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LIST OF ABBREVIATIONS

Abbreviation	Full Form
CST	Computer Simulation Technology
dB	Decibel
dB _i	Decibel isotropic
DT	Decision Tree
EM	Electromagnetic
FR4	Flame Retardant 4 (substrate material)
GBR	Gradient Boosting Regressor
GHz	Gigahertz
IoT	Internet of Things
KNN	K-Nearest Neighbors
MAE	Mean Absolute Error
ML	Machine Learning
MSE	Mean Squared Error
PIN	P-type Intrinsic N-type (diode)
RF	Random Forest
RLC	Resistor-Inductor-Capacitor
SAR	Specific Absorption Rate
VSWR	Voltage Standing Wave Ratio
WLAN	Wireless Local Area Network
WiMAX	Worldwide Interoperability for Microwave Access
XGB	XGBoost

CHAPTER 1

INTRODUCTION

1.1 Overview of Wireless Communication Systems

Over the last two decades, wireless communication has changed the way the world stays connected. From basic 2G voice calls to today's high-speed 5G networks, the demand for faster data rates, better coverage, and more reliable links has grown enormously. With the rise of smartphones, smart homes, IoT devices, and wearable gadgets, billions of devices now need to communicate wirelessly at the same time. All of this puts a lot of pressure on one very basic but important component — the antenna.

An antenna is basically the interface between an electronic device and the electromagnetic waves that carry information through the air. Every wireless system, whether it is a mobile phone, a Wi-Fi router, a satellite terminal, or a medical sensor, needs an antenna to send or receive signals. The performance of the entire communication link often depends on how good the antenna is. Therefore antenna design has been one of the most researched fields in electronics and communication engineering for the past several decades. expected to work in multiple frequency bands across the spectrum — for example, GSM, 3G, 4G LTE, Wi-Fi at 2.4 GHz and 5 GHz, Bluetooth and GPS at the same time. It is impractical from a size and cost point of view to have separate antennas for each band. This is where multi-band and reconfigurable antennas come into play. These antennas are designed to operate over more than one frequency band and in some cases they can also switch between bands or change their radiation behaviour according to the requirement. The work reported in this thesis is concentrated on the design of a circular reconfigurable dual-band dual-polarized microstrip patch

antenna that operates in the

3.1 GHz and 5.1 GHz frequency range, targeting WiFi/WiMAX and WiFi/WLAN applications. The design uses a PIN diode for switching and is simulated in CST Studio Suite 2024. On top of that, machine learning is also used to build a prediction model for the antenna's resonant frequency, which helps in reducing the number of time-consuming simulations needed during the design process [1].

1.2 Microstrip Patch Antennas — Background

Microstrip patch antennas have been in existence since the 1970s and have become one of the most popular antenna types used in modern wireless systems.

The reason is simple — they are flat, lightweight, cheap to manufacture, and very easy to integrate with printed circuit boards. This makes them ideal for applications where size and weight matter, such as mobile devices, aircraft, satellites, and wearable electronics.

A basic microstrip patch antenna consists of three main layers. At the bottom is the ground plane, which is usually a solid copper sheet. On top of that is a dielectric substrate, and on the top surface is the radiating patch, which can be of various shapes such as rectangular, square, triangular, circular, or elliptical. The antenna is fed either through a microstrip line, a coaxial probe, an aperture slot, or a proximity coupling method. When a signal is applied through the feed, electromagnetic waves are radiated from the edges of the patch where the fringing fields are strongest.

Despite their many advantages, microstrip antennas do have some well-known limitations. The most significant ones are narrow bandwidth, moderate gain, and a tendency for surface waves to propagate along the substrate, which reduces radiation efficiency. A lot of research over the years has gone into solving these problems by modifying the patch shape, cutting slots, using stacked layers, or changing the substrate material [3]. Among all patch shapes, the circular patch is particularly useful when dual-band or dual-

polarized operation is needed. Its symmetric geometry makes it naturally suitable for feeding from two orthogonal points, which is the key to achieving dual polarization. The resonant frequencies of a circular patch depend mainly on the patch radius and the substrate's dielectric constant. By introducing a slot on the patch — like the U-slot used in this work — it is possible to shift or add resonant frequencies without changing the overall size significantly.

The basic design equations for a circular microstrip patch antenna are well established. The resonant frequency for the dominant TM_{11} mode is given as:

$$f_r = (1.8412 \times c) / (2\pi \times a_e \times \sqrt{\epsilon_r}) \quad \dots (1.1)$$

where c is the speed of light in free space (3×10^8 m/s), ϵ_r is the relative permittivity of the substrate material, and a_e is the effective radius of the circular patch. The effective radius is not the same as the physical radius because of the fringing effect at the edges. It is calculated as:

$$a_e = a \times [1 + (2h / \pi a \epsilon_r) \times (\ln(\pi a / 2h) + 1.7726)]^{1/2} \quad \dots (1.2)$$

where a is the physical patch radius and h is the substrate thickness. The resonant frequency can be computed using equation (1.1) when the effective radius is known. For the FR4 substrate used in Case 1 of this work with $\epsilon_r = 4.4$ and $h = 1.6$ mm, the calculated patch radius for a target frequency of around 3.1 GHz comes out to be 12.7 mm, which was then verified and fine tuned using full wave simulation in CST Studio Suite.

It is important to note here that the above equations provide a good starting point for the design but the actual resonant frequency will shift slightly once slots are added to the patch and when the PIN diode is placed on it. This is expected, and the simulator does parametric sweeps to get the final optimised dimensions.

1.3 Circular Reconfigurable Antennas

A reconfigurable antenna is an antenna whose operating parameters such as frequency, radiation pattern or polarisation can be changed on the fly without any physical modification to the antenna. This is a big deal in modern communication systems as a single reconfigurable antenna can replace two or three fixed frequency antennas saving board space and reducing overall system complexity.

In antennas, reconfigurability is generally implemented by incorporating switching elements in some part of the antenna. Switch ON or OFF changes the current distribution on the surface of the antenna, and consequently the electrical behaviour of the antenna. The most common switching technologies are PIN diodes, varactor diodes, MEMS switches and liquid crystal based tunable substrates. Of these PIN diodes are the most practical for most applications in that they are cheap, small, fast and can be easily integrated within standard PCB fabrication.

Reconfigurability in a circular patch geometry can be achieved by placing a PIN diode across a slot cut on the patch. In the forward biased (ON state) the diode behaves as a short circuit, effectively closing the slot and changing the effective electrical length of the current path. In the OFF condition (reverse biased) it is an open circuit and the slot is still working. The reconfigurable behaviour we are aiming for in this work is obtained by switching between ON and OFF states, which causes a shift of the resonant frequencies of the antenna.

The concept of integrating circular patch with reconfigurability has been investigated in many published works. However, most of the works are limited to either frequency reconfigurability or polarisation reconfigurability only. The present work The antenna can operate at two frequency bands simultaneously, with two orthogonal ports providing dual polarisation and the PIN diode

enables frequency reconfigurability by switching between two slightly different resonance states [2].

the circular patch is especially suitable for this application because of its symmetric form. The geometry is circular, such that two feed ports at orthogonal positions (Port 1 $X = 8.5$ mm, $Y = 0$ mm and Port 2 $X = 0$ mm, $Y = 8.5$ mm) directly excite two orthogonal polarised modes that are independent of each other. The isolation between these two ports, represented by the parameter S_{21} , was found to be between -20 dB and -30 dB in our simulation. That is quite good and means that the two polarisation channels do not interfere with each other significantly.

1.4 Dual-Band and Dual-Polarized Antenna Concepts

Before discussing the detailed design of this work, it is useful to understand what is actually meant by dual-band and dual-polarization in the context of antenna engineering. Dual-band antennas are antennas that can operate in two different frequency bands. Our case is the two bands at 3.1 GHz and 5.1 GHz. The first band includes the 3.3 GHz WiFi/WiMAX frequencies and the second band includes the 5.8 GHz WiFi/WLAN frequencies. Both are important and widely used bands, particularly as more devices move to faster Wi-Fi standards and broadband wireless access. Obviously, two separate antennas are less efficient than a single antenna that covers both. Dual-band behaviour in microstrip antennas can be achieved in several ways such as by stacking patch layers, by cutting specific slots on the patch, by the use of shorting pins and by reactive loading through lumped elements. The U-slot etched on the circular patch in this work is mainly responsible for the generation of the second resonant band. The slot perturbs the surface current

distribution on the patch and provides another resonant path at a higher frequency. Hence, precise location and size of the U-slot is very important to obtain both the bands at desired frequencies.

Dual polarisation on the other hand means that the antenna can transmit or receive signals in two orthogonal polarisation states, in our case horizontal polarisation (from Port 1) and vertical polarisation (from Port 2). Polarisation diversity is very useful in real world communication environments where multipath propagation causes the polarisation of incoming signals to be unpredictable. Having two orthogonally polarised ports on the same antenna allows a receiver to combine or switch between the two signals, which substantially reduces the effect of polarisation mismatch and improves the overall link reliability [2]. Dual polarised antennas are used in MIMO systems to increase the channel capacity. These two polarisation channels are largely independent. This means that you can send two independent data streams on the same frequency. This effectively doubles the spectral efficiency without using any extra bandwidth. This is one of the main reasons why dual-polarized antennas have been of a tremendous research interest in the recent years. For a dual polarised antenna to perform well it is crucial that the two ports are well isolated from each other. If the isolation is poor a signal fed into Port 1 will show up to some extent at Port 2, meaning the two polarisation channels are not truly independent. Poor isolation results in signal degradation and lower system performance. In antenna design, the isolation between ports is quantified by the parameter S_{21} (or S_{12}). Dual-polarized operation is generally acceptable if the value is -20 dB or better.

1.5 PIN Diode as a Switching Element

The PIN diode gets its name from its internal structure. It consists of a P-type semiconductor layer, an Intrinsic (lightly doped) semiconductor layer in the center, and an N-type semiconductor layer. It is this structure that gives the PIN diode its useful RF switching characteristics. When the diode is forward biased, the intrinsic region is filled with charge carriers and the diode behaves as a low resistance element. The intrinsic region becomes depleted when reverse biased and the diode acts as a high resistance component. Such switching behaviour makes it very useful in controlling the flow of RF signals. For RF and microwave frequencies a PIN diode is modelled not as an ideal switch, but as a circuit which is equivalent. The diode in the ON state can be modelled as a series RLC circuit where the resistance R is the on state loss, the inductance L is the parasitic bondwire or lead inductance of the package and the capacitance C is zero (or negligible). The diode in the OFF state (reverse bias) is modelled as a parallel RLC circuit where R is the very high off- state resistance, L is the same package inductance and C is the small junction capacitance of the depletion region.

The equivalent circuit parameters for the MADP-00935 PIN diode model used in this work are

State	Model	R (Ω)	L (nH)	C (pF)
ON (Forward Bias)	RLC Series	5.2	0.7	0
OFF (Reverse Bias)	RLC Parallel	5000	0.7	0.03

Table 1.1: MADP-00935 PIN Diode Equivalent Circuit Parameters

The series resistance of $5.2 \, \Omega$ in the ON state provides a small insertion loss, while the parallel resistance of $5000 \, \Omega$ in the OFF state ensures very high isolation. The $0.7 \, \text{nH}$ inductance is present in both states and is the parasitic inductance of the diode package - this is something that needs to be accounted for in the simulation, because at GHz frequencies even a small inductance can have a noticeable effect on the antenna response. The $0.03 \, \text{pF}$ OFF-state capacitance adds a small amount of capacitive load, which causes a slight shift in the resonant frequencies when the diode is switched from ON to OFF.

Kumar et al. [2] have used the Infineon BAR64-02V PIN diode in a similar manner to switch the sense of the polarisation in a dual-band circularly polarised antenna. Their model had $R = 2.1 \, \Omega$ and $L = 0.6 \, \text{nH}$ for ON-state and $R = 3 \, \text{k}\Omega$, $L = 0.6 \, \text{nH}$ and $C = 0.17 \, \text{pF}$ for OFF-state. The general approach of modelling the diode as a lumped element in the simulator is the same as that we have used in this work, but the particular diode model and parameter values are different.

In our antenna design, the PIN diode is placed at $X_1 = -8 \, \text{mm}$, $Y_1 = -5 \, \text{mm}$, $Z_1 = 1.617 \, \text{mm}$ to $X_2 = -8 \, \text{mm}$, $Y_2 = +5 \, \text{mm}$, $Z_2 = 1.617 \, \text{mm}$, across the opening of the U-slot on the patch. The diode, when turned ON, short-circuits the slot, changing the effective resonant path length, and shifts the resonant frequencies slightly. When the diode is OFF the whole slot geometry is active and the antenna behaves again in its nominal dual-band behaviour

1.6 Machine Learning in Antenna Design

Designing an antenna is not a one-step process. So you start off with the theoretical calculations to get approximate dimensions. Then you spend a lot of hours on simulations, tweaking parameters, running simulations and seeing if results meet your targets. The time to run a single simulation in a tool like CST Studio Suite, depends on the complexity of the structure and the frequency range and can be from some minutes to several hours. When you are doing parametric sweeps or optimisation runs, the total computation time adds up very quickly.

This is where the machine learning becomes a very handy tool. The core idea is to use a collection of simulation results to train a machine learning model to learn the dependency of the electromagnetic performance of the antenna (output, e.g., resonant frequency) on the geometric and material parameters of the antenna (inputs). Once trained, the model can almost instantly – in milliseconds – predict the output for a new set of input parameters without the need to carry out a full EM simulation. This greatly speeds up the design exploration process.

This approach was very convincingly demonstrated by Ramasamy et al. [1] for mm-Wave MIMO antennas targeted for 5G applications at 39.5 GHz. The return loss (S11) of the antenna was predicted by five machine learning algorithms, Decision Tree, Random Forest, K-Nearest Neighbours, XGBoost and Gradient Boosting Regressor, from a dataset of 15,012 data points generated by simulation. The results showed that all the five algorithms performed well with the highest prediction power achieved by Random Forest with R2 value of 0.992 and MSE of 0.389. One of the most important practical conclusions of their work is that the use of machine learning reduces the need of repeated full-wave simulations and allows for faster design iterations, which is exactly what we also strive for in this thesis [1].

Similarly, Gupta et al. [3] used the Random Forest algorithm to simulate a meandered slot patch antenna using CST Studio Suite and to predict the S11 and impedance matching circuit parameters. The model obtained R^2 of 0.983 for S11 prediction with their dataset of 500 samples generated by parametric sweep in CST. One very important outcome of their work was that the ML model was able to make a prediction in mere 0.2 to 0.5 seconds compared to about 175 seconds for a single run of the CST simulation. This is a time saving of more than 99% which illustrates the usefulness of machine learning as a complementary tool to EM simulation [3].

Machine learning is utilised in this thesis to predict the resonant frequency of the proposed circular reconfigurable antenna. We synthesise a dataset of 200 samples by sweeping the patch dimensions, the substrate permittivity and the state of the PIN diode. We compare the same five algorithms implemented by Ramasamy et al. [1] using Python in Google Colab. As we will see in Chapter 5 the Gradient Boosting Regressor is the best model for our specific prediction task with a R^2 of 0.9934.

It is worth mentioning that the use of machine learning in this work is not just for the sake of using a trendy technique. The practical reason is that we have performed a large number of parametric simulations during the design process to see how changing the patch size, slot position and substrate affects the resonant frequency. A trained ML model can encode all of that simulation knowledge into a fast prediction tool that can be used for quick sanity checks during design, without having to rerun every time in CST.

1.7 Objectives of the Thesis

Based on the background discussed above, the following are the specific objectives of this thesis work:

1. To design a circular reconfigurable dual-band dual-polarized microstrip patch antenna operating in the 3.1 GHz and 5.1 GHz frequency bands covering WiFi/WiMAX and WiFi/WLAN applications, using CST Studio Suite 2024 Learning Edition.
2. To integrate the MADP-00935 PIN diode as a switching element for frequency reconfigurability and to analyze the antenna performance in both ON and OFF switching states.
3. To investigate the effect of substrate material on antenna performance by simulating the design on two different substrates — FR4 lossy ($\epsilon_r = 4.4$, $\tan\delta = 0.02$) and RT Duroid 6002 ($\epsilon_r = 2.94$, $\tan\delta = 0.0012$) — and to compare the results in terms of S11, S21 isolation, radiation efficiency, total efficiency, directivity, gain, and radiation patterns.
4. To achieve dual-polarization by feeding the circular patch from two orthogonal port positions and to verify port isolation better than -20 dB between the two polarization channels.
5. To develop a machine learning-based surrogate model using five regression algorithms (Decision Tree, Random Forest, KNN,

XGBoost, and Gradient Boosting Regressor) for predicting the antenna's resonant frequency, following the methodology established in published literature [1, 3].

6. To validate the ML models using 5-fold cross-validation and to identify the best-performing algorithm for this specific antenna design task.

CHAPTER 2

LITERATUREREVIEW

Reconfigurable antennas have gained significant research attention in recent years because of the increasing demand for compact, multi-band, and adaptive wireless communication systems. A single antenna that can switch between frequency bands or polarization states is far more practical than using multiple fixed-frequency elements, especially in size-constrained platforms like smartphones, IoT devices, and portable terminals. The use of PIN diodes as switching elements, combined with circular patch geometries and slot-based multi-band techniques, has emerged as one of the most practical approaches for achieving reconfigurability. In parallel, machine learning has increasingly been used to reduce the time and computational cost involved in iterative antenna design and optimization. This chapter reviews the important works published in the areas of reconfigurable antennas, dual-band and dual-polarized designs, PIN diode switching, and machine learning- assisted antenna engineering that form the background and motivation for the present work. The research gap identified from this review and the specific contributions of this thesis are presented at the end of the chapter.

Kumar et al. [1] presented a microstrip line-fed dual-band dual-sense polarization reconfigurable circularly polarized slot antenna on a 1.6 mm thick FR4 substrate. Four PIN diodes were placed in the feed arms to electronically switch the sense of circular polarization between LHCP and RHCP at two bands — 2.4 GHz and 5.2 GHz. The measured return loss was better than 10 dB over both bands and the antenna efficiency was reported between 76% and 85%. The PIN diode in that work was

modeled as a series RLC in the ON state and a parallel RLC in the OFF state, which is the same modeling approach used in the present work. However, this paper used a slot antenna geometry only and did not compare different substrate materials. There was also no machine learning component in the study.

Ramasamy et al. [2] demonstrated the use of machine learning for mm-Wave MIMO antenna design at 39.5 GHz for 5G applications. Five algorithms — Decision Tree, Random Forest, K-Nearest Neighbors, XGBoost, and Gradient Boosting Regressor — were used to predict the return loss of the antenna from a dataset of 15,012 HFSS simulation results. The dataset was split 80/20 for training and testing, and 5-fold cross-validation was used throughout. Among the five, Random Forest gave the best result with $R^2 = 0.992$ and $MSE = 0.389$. The ML methodology used in this paper — including the choice of algorithms, train-test split, and cross-validation approach — has been directly adopted in Chapter 5 of this thesis. However, the work in [2] was limited to mm-Wave frequencies and did not involve any PIN diode switching, dual polarization, or substrate comparison.

Gupta et al. [3] developed a machine learning model for predicting S11 and impedance matching parameters of a meandered slot patch antenna designed in CST Studio Suite at 2.45 GHz. A dataset of 500 simulation samples was generated by varying the slot dimensions, and a Random Forest model trained on 400 samples and validated on 100 achieved $R^2 = 0.983$ for S11 prediction. A very useful finding from this paper is that the ML model gave predictions in just 0.2 to 0.5 seconds, compared to about 175 seconds per CST simulation — a time saving of more than 99%. This validates the use of CST-generated synthetic datasets for training ML models, which is the same approach used in this thesis. However, the work was limited to a single frequency band with no reconfigurability or dual polarization, and only one ML algorithm was explored.

Babu et al. [4] proposed an ML-assisted MIMO antenna design approach for sub- 6 GHz 5G applications. Their work used parasitic elements to reduce mutual coupling and employed a machine learning model to estimate structural parameters and reduce computation time. Several algorithms including ANN, Decision Tree, and XGBoost were developed to estimate S-parameters. The results showed improved performance in ECC, TARC, and diversity gain. However, the design did not include any frequency reconfigurability or PIN diode switching, and there was no study of dual-polarized operation.

Rai et al. [5] proposed a frequency-tunable dual-port dielectric resonator-based MIMO antenna with machine learning optimization for 5G New Radio applications. The ML approach helped in estimating antenna parameters and reducing the number of full-wave simulation runs. The antenna showed good performance in terms of ECC and isolation. However, the geometry used was a dielectric resonator, which is quite different from a planar circular patch, and there was no dual- band or dual-polarized operation with PIN diode switching.

Ghadeer et al. [6] presented an innovative fractal monopole MIMO antenna for modern 5G applications with improved isolation achieved through an EBG structure. The antenna operated in the 2 to 5.2 GHz band and showed high isolation between antenna elements. The work demonstrated the effectiveness of EBG structures for reducing mutual coupling in closely-spaced MIMO configurations. However, the design did not have any switching element for reconfigurability, and machine learning was not used in the design or optimization process.

From the review of the above works, it is clear that PIN diode-based switching has been well studied for reconfigurable antennas, and machine learning has been successfully applied to antenna parameter prediction in several contexts. However, most PIN diode-based studies do not include machine learning, and most ML-based studies do not involve reconfigurable or dual-polarized antenna designs. The

combination of a circular patch geometry with U-slot, PIN diode-based frequency reconfigurability, dual-band dual-polarized operation, substrate comparison between FR4 and RT Duroid 6002, and a comprehensive five-algorithm ML surrogate model all in one integrated study — has not been addressed in the literature reviewed. Table 2.1 summarizes the key papers reviewed and highlights where the present work contributes.

Ref.	Antenna Type	Key Technique	Frequency	Gain / R ²	Limitation
[1]	Dual-band CP slot antenna	PIN diode, FR4	2.4 / 5.2 GHz	0.65–1.92 dBi	No ML, slot only
[2]	mm-Wave MIMO antenna	5 ML algorithms, HFSS	39.5 GHz	RF R ² =0.992	No PIN diode or dual-pol
[3]	Slotted patch antenna	RF algorithm, CST	2.45 GHz	R ² =0.983	Single band, one ML algo
[4]	Wideband MIMO, sub-6 GHz	ANN + ML, DNN	Sub-6 GHz	High isolation	No reconfigurability
[5]	Freq. tunable dual-port DRA	ML + 5G NR design	5G NR bands	Good ECC/TARC	No dual-polarization
[6]	Fractal MIMO monopole	EBG isolation	2–5.2 GHz	High isolation	No ML or switching
[7]	This Work	Circular reconfigurable dual-band dual-polarized	PIN diode + 5 ML algos, CST	3.1 / 5.1 GHz	-

Table 2.1: Summary of Related Works and Comparison with Present Study

2.3 Research Gap and Contribution of Present Work

Based on the literature review, the following research gaps are identified. First, most PIN diode-based reconfigurable antenna designs do not include any comparison between substrate materials, nor do they use machine learning for design support. Second, the ML studies for antenna design are mostly focused on single-band antennas or mm-Wave MIMO structures and do not deal with reconfigurability or dual-polarization. Third, no single work in the literature reviewed combines circular patch geometry, U-slot, PIN diode switching, dual-band dual-polarized operation, FR4 versus RT Duroid 6002 substrate comparison, and five-algorithm ML prediction all together. The present thesis addresses these gaps by designing a circular reconfigurable dual-band dual-polarized microstrip patch antenna with U-slot and PIN diode switching, simulated on two different substrates in CST Studio Suite 2024. The ML study uses the same five algorithms as in reference [2], the same CST-based dataset generation approach as in reference [3], and extends the work by applying it to a reconfigurable dual-band dual polarized antenna at sub-6 GHz frequencies.

CHAPTER 3

ANTENNA DESIGN AND THEORY

3.1 Introduction

This chapter presents the complete design theory and methodology for the proposed circular reconfigurable dual-band dual-polarized microstrip patch antenna. The theoretical background for the resonant frequency equations, the role of the U-slot in achieving dual-band behavior, the dual orthogonal feed port configuration, the PIN diode equivalent circuit model, the substrate selection for both cases, and the full CST Studio Suite 2024 simulation setup are all covered here. All dimensions given are the final optimized values confirmed through parametric simulation in CST.

3.1 Design Theory of Circular Reconfigurable Patch Antenna

A microstrip patch antenna consists of a metallic radiating patch on one side of a dielectric substrate with a ground plane on the other side. Among all patch shapes, the circular patch is particularly suitable for dual-band and dual-polarized antenna designs. Its symmetric geometry allows two feed ports to be placed at orthogonal positions to independently excite two polarization modes. The circular patch supports multiple resonant modes, with the TM_{11} mode giving the fundamental resonance. By etching a U-slot on the patch surface, a second resonant path is introduced at a higher frequency, making the antenna dual-band

without adding any extra physical element. The proposed antenna uses a circular copper patch on a dielectric substrate with a U-slot and two orthogonal microstrip feed ports. A PIN diode is placed across the U-slot opening to control the effective electrical length, enabling frequency reconfigurability. Fig. 3.1 and Fig. 3.2 show the isometric and top views of the proposed antenna respectively.

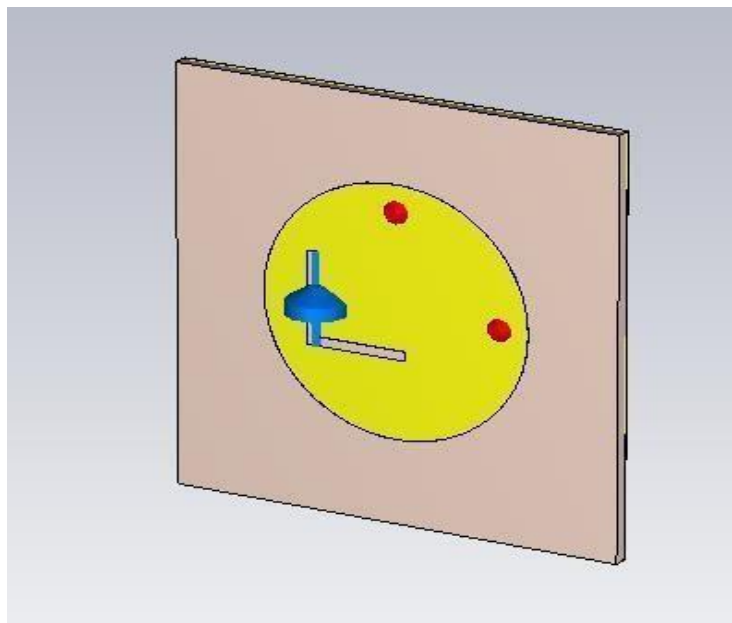


Fig. 3.1: Proposed Antenna — Isometric View

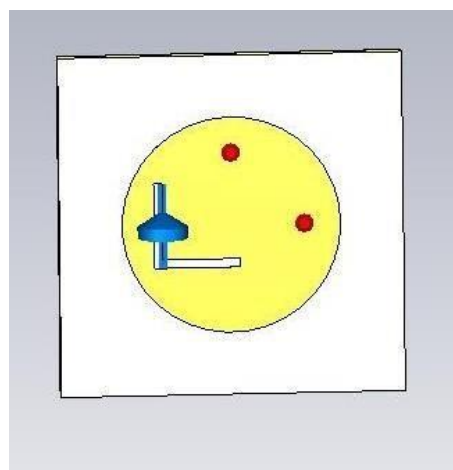


figure 3.2: Proposed Antenna — Top View

3.1.1 Resonant Frequency Equations

The resonant frequency of a circular microstrip patch in the dominant TM_{11} mode is given by the cavity model as:

$$f_r = (1.8412 \times c) / (2\pi \times a_e \times \sqrt{\epsilon_r}) \quad \dots (3.1)$$

where:

c = speed of light in free space = 3×10^8 m/s

ϵ_r = relative permittivity of the substrate material

a_e = effective radius of the circular patch (accounts for fringing fields)
1.8412 = first root of the derivative of the Bessel function for TM_{11} mode

The equation provides a good first guess at the resonant frequency. With the addition of U-slot and PIN diode the actual resonance frequency shifts a little. The final dimensions are optimised using parametric sweeps in CST.

3.1.2 Effective Radius Calculation

The antenna radiates with an effective radius a_e which is slightly larger than the physical radius a because of the fringing effect at the edges of the patch. The effective radius is determined as

$$a_e = a \times \left\{ 1 + \left(\frac{2h}{\pi a \epsilon_r} \right) \times [\ln(\pi a / 2h) + 1.7726] \right\}^{(1/2)} \dots (3.2)$$

where:

a = physical radius of the circular patch (mm)
 h = substrate thickness

(mm)

ϵ_r = relative permittivity of the substrate

For Case 1 with FR4 ($\epsilon_r = 4.4$, $h = 1.6$ mm) and target frequency 3.1 GHz, the calculated physical radius is $a = 12.7$ mm. Case 2: RT Duroid 6002 ($\epsilon_r = 2.94$, $h = 1.52$ mm). The lower permittivity requires a larger patch to maintain the resonance near 3.0 GHz and therefore the radius is increased to $a = 13.5$ mm. Both values have been verified by CST simulation.

3.2 U-Slot Design and Its Role

The U-shaped slit is etched on the circular radiating patch with its opening towards the negative X direction (left). The U-slot has two major functions. The first advantage is that it provides an additional resonant current path at higher frequency, near 5.1 GHz for the case of the FR4, that is responsible for the second working band of the antenna. Secondly, the physical space for connection of the PIN diode is provided by the slot aperture which allows for frequency reconfiguration.

The position of the second resonant frequency is directly controlled by the width and depth of the U-slot. During design, the slot dimensions were swept in CST to achieve the second resonance at the target band. The slot also has a minor effect on the first resonant frequency since it alters the effective current path for the fundamental TM_{11} mode as well.

3.3 Dual Orthogonal Feed Ports for Dual Polarization

Dual polarization is achieved by feeding the circular patch from two

orthogonal positions. Port 1 is at $X = 8.5$ mm, $Y = 0$ mm, which excites horizontal polarization. Port 2 is at $X = 0$ mm, $Y = 8.5$ mm, which excites vertical polarization. Since the two feed points are 90° apart on the symmetric circular patch, the modes they excite are orthogonal, making the two polarization channels largely independent.

For dual-polarized operation, good isolation between the two ports is essential. The port isolation is measured by S_{21} . In our design, S_{21} is between -20 dB and -30 dB on FR4, and between -20 dB and -35 dB on RT Duroid, both of which are well within acceptable limits. Both ports are matched to 50Ω through the optimized feed positions on the patch radius.

3.4 PIN Diode Integration — MADP-00935 Model

The MADP-00935 PIN diode is placed across the U-slot at $X_1 = -8$ mm, $Y_1 =$

-5 mm, $Z_1 = 1.617$ mm to $X_2 = -8$ mm, $Y_2 = +5$ mm, $Z_2 = 1.617$ mm.

The z -coordinate 1.617 mm is the top surface of the FR4 substrate where the patch sits. In CST, the diode is modeled as a lumped RLC element.

The equivalent circuit parameters are given in Table 3.1.

State	Model	R (Ω)	L (nH)	C (pF)
ON (Forward Bias)	RLC Series	5.2	0.7	0
OFF (Reverse Bias)	RLC Parallel	5000	0.7	0.03

Table 3.1: MADP-00935 PIN Diode Equivalent Circuit Parameter

3.4.1 ON State Equivalent Circuit

In the forward-biased ON state, the PIN diode is modeled as a series RLC with $R =$

$5.2 \, \Omega$, $L = 0.7 \, \text{nH}$, and $C = 0$. The resistance of $5.2 \, \Omega$ represents the on-state loss. The $0.7 \, \text{nH}$ inductance is the parasitic package inductance present in both states. With $C = 0$, there is no capacitive element in the ON state. The diode effectively short-circuits the U-slot, changing the resonant path length and causing a small shift in both resonant frequencies compared to the OFF state. Fig. 3.3 shows the ON state equivalent circuit.

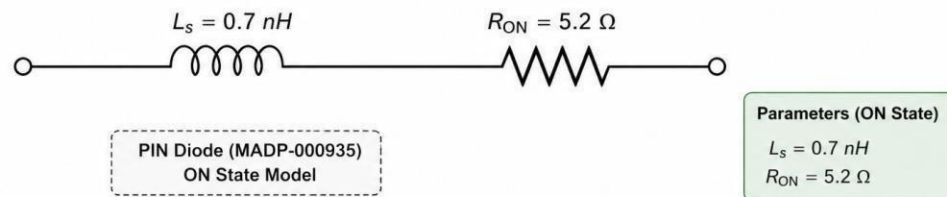


Fig. 3.3: PIN Diode ON State Equivalent Circuit

3.4.2 OFF State Equivalent Circuit

In the reverse-biased OFF state, the PIN diode is modeled as a parallel RLC with $R = 5000 \, \Omega$, $L = 0.7 \, \text{nH}$, and $C = 0.03 \, \text{pF}$. The high resistance of $5000 \, \Omega$ represents the near-open-circuit condition. The junction capacitance of $0.03 \, \text{pF}$ introduces a small capacitive loading across the slot at GHz frequencies, causing a slight shift in resonant frequencies. Fig. 3.4 shows the OFF state equivalent circuit.

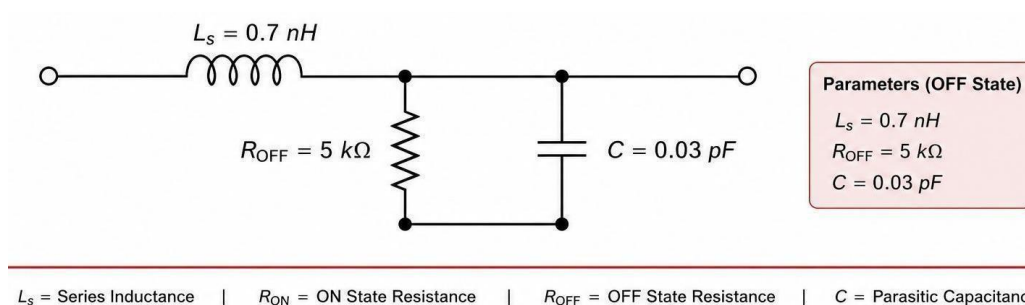


Fig. 3.4: PIN Diode OFF State Equivalent Circuit

3.5 Substrate Selection

Two substrate materials are studied to evaluate their effect on antenna performance. Table 3.2 summarizes the key parameters for both.

Parameter	FR4 (Case 1)	RT Duroid 6002 (Case 2)	Unit	Remarks
Relative Permittivity (ϵ_r)	4.4	2.94	—	Lower = larger patch
Loss Tangent ($\tan\delta$)	0.02	0.0012	—	RT Duroid = lower loss
Substrate Height (h)	1.6	1.52	mm	Similar thickness
Ground Plane Size	40 × 40	45 × 45	mm	Adjusted for ϵ_r

Parameter	FR4 (Case 1)	RT Duroid 6002 (Case 2)	Unit	Remarks
Patch Radius (a)	12.7	13.5	mm	Tuned via CST
Feed Position (Port 1)	X=8.5, Y=0	X=10.5, Y=0	mm	50Ω match point

Table 3.2: Substrate Parameters — FR4 (Case 1) and RT Duroid 6002 (Case 2)

3.5.1 FR4 Lossy Substrate

FR4 is the most commonly used PCB substrate material. Case 1: $\epsilon_r=4.4$, $\tan\delta=0.02$, $h=1.6$ mm. The higher loss tangent adds some dielectric losses which reduce the radiation efficiency but keep the antenna physically compact at 3.1 and 5.1 GHz. The ground plane and substrate dimensions are 40 x 40 mm and the patch radius is 12.7 mm.

3.5.2 RT Duroid 6002 Substrate

Rogers RT Duroid 6002 with $h = 1.52$ mm, $\tan\delta = 0.0012$, and $\epsilon_r = 2.94$. Its very low loss tangent as compared to FR4 (0.0012 vs 0.02) results in much less substrate loss and greatly better radiation efficiency. The permittivity is lower so the patch must be physically larger to resonate at the same frequency.. The patch radius is therefore 13.5 mm, ground plane is 45 × 45 mm, and the feed position is adjusted to $X = 10.5$ mm

for 50 Ω matching.

3.6 CST Studio Suite Simulation Setup

All simulations were done in CST Studio Suite 2024 Learning Edition with identical settings for both substrate cases to ensure a fair comparison. Table 3.3 gives the complete simulation configuration.

Parameter	Setting / Value
Software	CST Studio Suite 2024 Learning Edition
Solver	Time Domain (Transient)
Mesh Type	Hexahedral
Accuracy	−40 dB
Frequency Range	1 – 8 GHz
Boundary Conditions	Open (Add Space)
Port Impedance	50 Ω
Ground Plane	Copper (lossy)
Port 1 Position	X = 8.5 mm, Y = 0 mm (Horizontal Polarization)
Port 2 Position	X = 0 mm, Y = 8.5 mm (Vertical Polarization)
PIN Diode Location	X1=−8 mm, Y1=−5 mm to X2=−8 mm, Y2=+5 mm, Z=1.617 mm
PIN Diode Model	MADP-00935 (Lumped RLC element)

Table 3.3: CST Studio Suite Complete Simulation Configuration

3.6.1 Solver and Mesh Settings

The Time Domain (Transient) solver is used. It excites the antenna with a broadband Gaussian pulse and computes the full frequency domain response over 1–8 GHz in a single run through a Fourier transform. This is much more efficient than a frequency domain solver which requires a separate computation at each frequency point. The hexahedral mesh is auto-generated by CST, and the simulation runs until the residual energy in the domain drops to -40 dB, ensuring accurate results.

3.6.2 Boundary Conditions and Port Configuration

Open (Add Space) boundary conditions are applied on all six faces of the simulation domain. This extends the domain by a quarter-wavelength at the lowest simulated frequency and applies an absorbing boundary so radiated waves do not reflect back into the simulation domain — the correct setup for modeling free-space antenna radiation.

Two discrete ports are defined at the two feed positions, each with $50\ \Omega$ reference impedance. The PIN diode is simulated in two separate runs — one with ON state RLC values and one with OFF state values — to capture the reconfigurable behavior of the antenna in both switching states. The S-parameter results from both runs are compared and reported in

CHAPTER 4

RESULTS & DISCUSSION

4.1 Introduction

This chapter represents the simulation results that we proposed antenna for both substrate cases — FR4 (Case 1) and RT Duroid 6002 (Case 2). All results were obtained from CST Studio Suite 2024 using the Time Domain solver with the settings described in Chapter 3. For each case, the S11 return loss, S21 port isolation, total efficiency at both ports, 3D radiation pattern, directivity, E-field distribution, and H-field distribution are discussed. At the end of this chapter, both cases are compared side by side and the overall performance is discussed.

4.1 Case 1 — FR4 Substrate Results

The first set of simulations was done using FR4 as the substrate material with $\epsilon_r = 4.4$, $\tan\delta = 0.02$, and substrate height $h = 1.6$ mm. The patch radius used is 12.7 mm and the ground plane size is 40×40 mm. The antenna was simulated separately for the PIN diode in the ON state and in the OFF state. The results for this case are presented below.

4.1.1 S11 Return Loss

The S11 result for the FR4 case shows two resonance dips, which confirms that the antenna is working as a dual-band antenna. The first dip is at 3.1 GHz and the second dip is at 5.1 GHz. When the PIN diode is in the ON state, the S11 values are -8.8 dB at 3.1 GHz and -12.5 dB at 5.1 GHz. When the diode is switched to the OFF state, the values change slightly to -8.5 dB at 3.1 GHz and -12.8 dB at 5.1 GHz.

This small difference between the two states shows that the PIN diode is successfully switching and causing a minor change in the resonant behavior of the antenna.

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the values change slightly to -8.5 dB at 3.1 GHz and -12.8 dB at 5.1 GHz. This small difference between the two states shows that the PIN diode is successfully switching and causing a minor change in the resonant behavior of the antenna.

The first band S11 of -8.8 dB is slightly below the -10 dB threshold that is commonly used as a benchmark. However, the VSWR is still below 2 at this frequency, and the antenna does radiate at this band as confirmed by the directivity and radiation pattern results. The second band at 5.1 GHz with -12.5 dB is within the acceptable range. Fig. 4.1 shows the S11 plot for the FR4 case for both ON and OFF diode states.

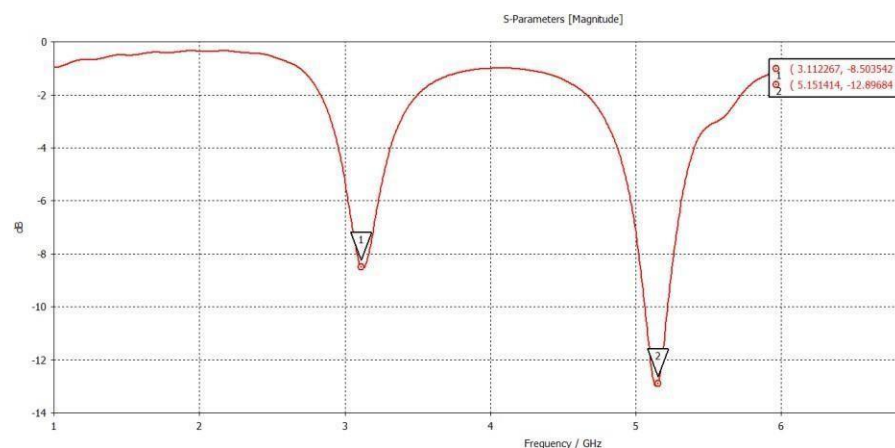


Fig. 4.1: S11 Return Loss — FR4 Substrate (Case

4.1.2 S21 Port Isolation

Parameter S21 is the isolation between Port 1 and Port 2. Good isolation means that the signal fed into one port does not leak into the other and that is very important for dual polarised antennas to work properly. In the case of FR4, S21 varies from -20 to -30 dB in the 1–8 GHz range. This is a good result and confirms that the two orthogonal polarisation channels are mostly independent. The S21 plot for this case is given in Fig. 4.2.

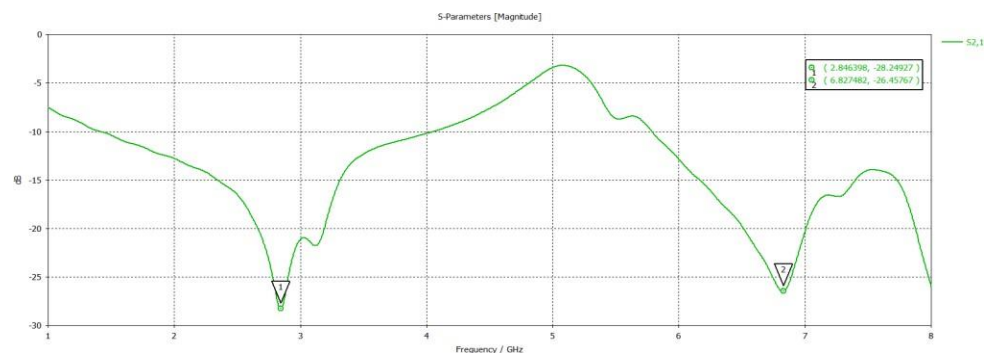


Fig. 4.2: S21 Port Isolation — FR4 Substrate (Case 1)

4.1.3 Total Efficiency — Port 1

The total efficiency results of the proposed antenna show good radiation performance over the operating frequencies. The antenna efficiencies were approximately 90 % at 3.3 GHz, 85 % at 3.5 GHz and 79 % at 3.8 GHz. These results confirm that the antenna is able to radiate power efficiently with low losses and is suitable for reconfigurable wireless communication applications

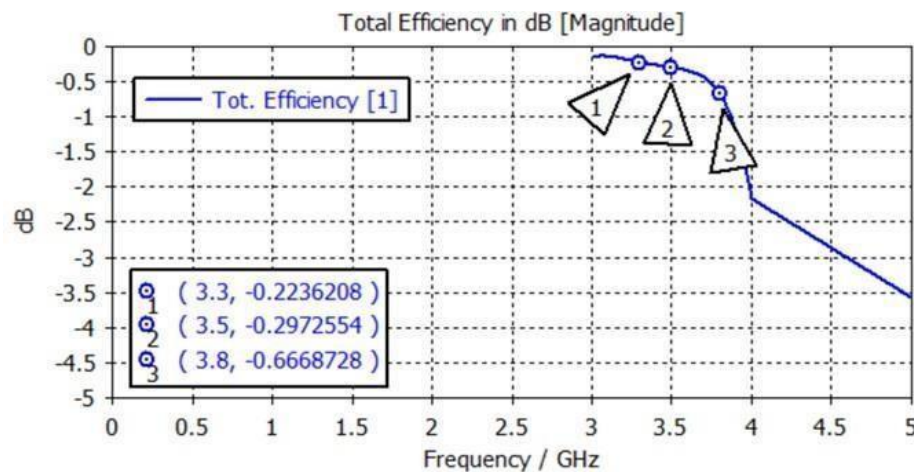


Fig. 4.3: Total Efficiency — Port 1, FR4 Substrate (Case 1)

4.1.4 Total Efficiency — Port 2

The total efficiency results for Port 2 also show good radiation performance over the operating frequencies. The antenna efficiencies were nearly 89% at 3.3 GHz, 84% at 3.5 GHz and 78% at 3.8 GHz. The results show that the antenna has the efficient power radiation with the minimum loss which confirms stable performance for reconfigurable wireless communication applications.

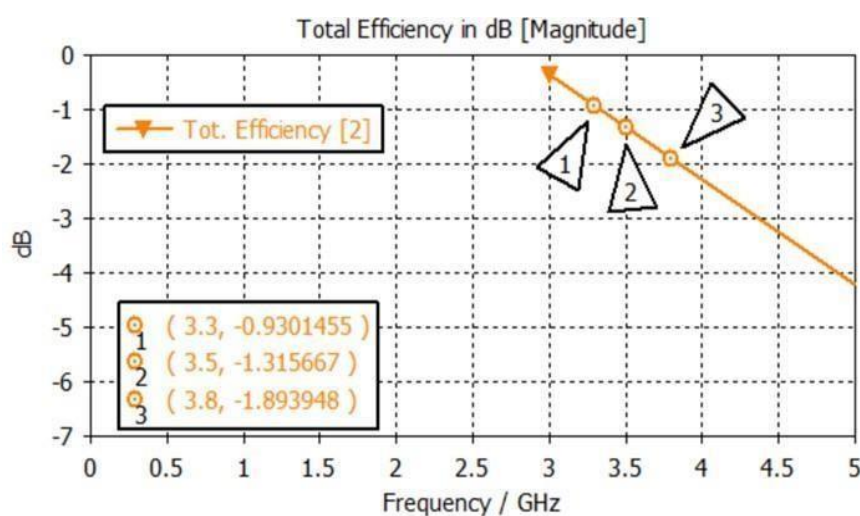


Fig. 4.4: Total Efficiency — Port 2, FR4 Substrate (Case 1)

4.1.5 3D Radiation Pattern

The 3D radiation pattern illustrates the radiation of electromagnetic energy by the antenna in all directions in space. In the case of the FR4 at 3.3 GHz, the antenna produces a broadside radiation pattern where the main lobe is directed normal to the patch surface (+Z direction). This is the expected and desired behaviour of a microstrip patch antenna. Because of the circular patch geometry, the pattern is reasonably symmetric in the azimuth plane. Fig. 4.5 3D Radiation pattern from CST simulation of Port 1 at 3.3 GHz

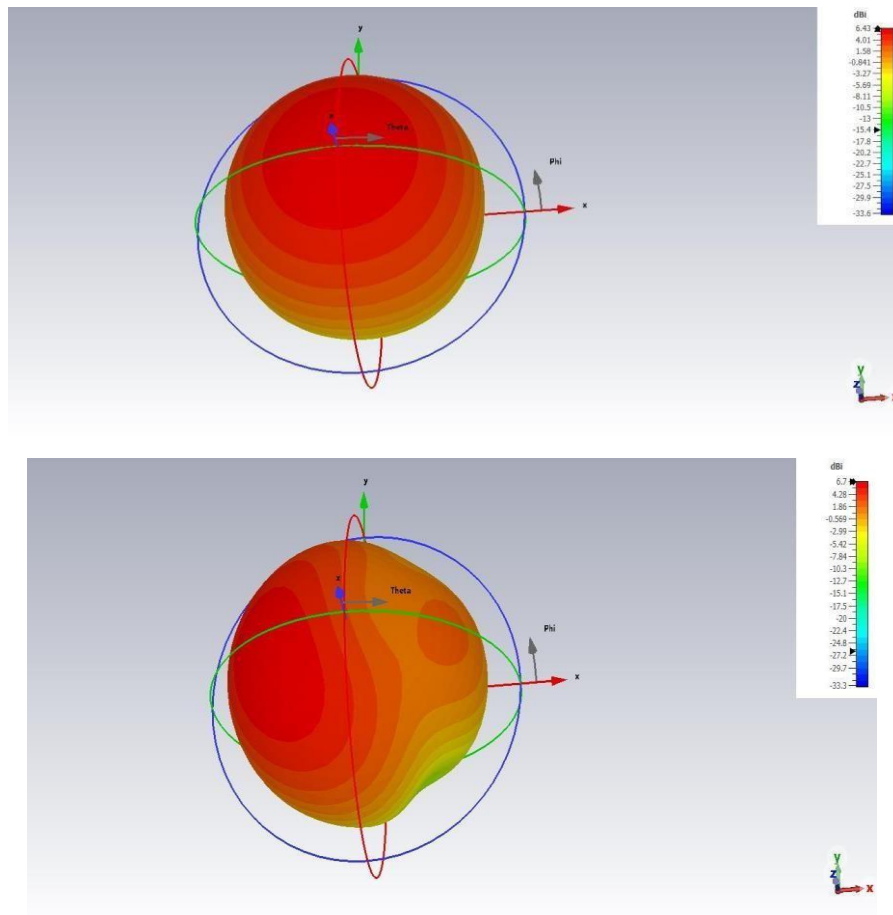


Fig. 4.5: 3D Radiation Pattern — FR4 Substrate (Case 1) at 3.3 GHz

4.1.6 Directivity

The directivity for the FR4 case is 6.432dBi at 3.3GHz and 6.704dBi at 5.8GHz . These are good values for a single element microstrip patch antenna. The directivity at the higher band is slightly higher than that at the lower band. This is normal for dual-band patch antennas.

The CST directivity plot is shown in Fig. 4.6.

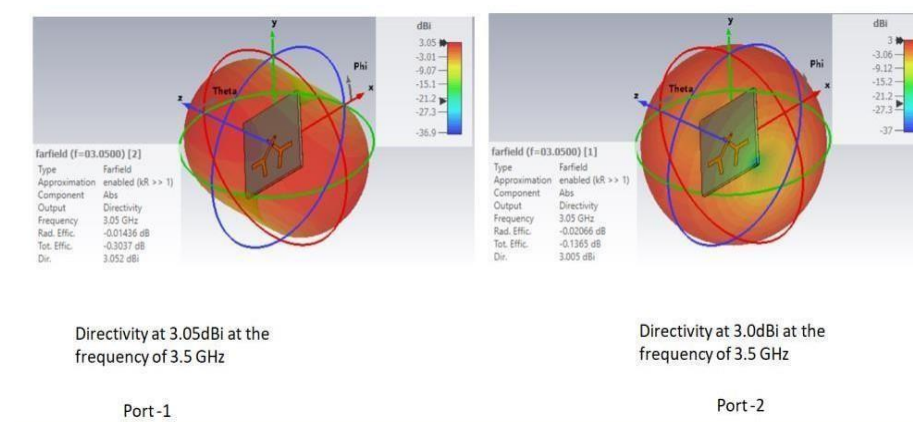
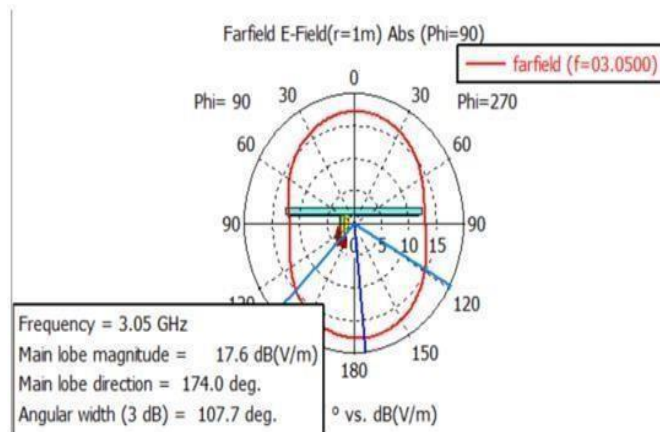


Fig. 4.6: Directivity — FR4 Substrate (Case 1)

4.1.7 E-Field Distribution

The E-field distribution on the surface of the patch shows that the electric field is strongest at the resonant frequency. This helps in understanding how the antenna is radiating and if the placement of the slot and diode is affecting the field distribution as expected. The E-field is primarily concentrated around the patch edges and the U-slot area at



3.05 GHz, which indicates the active part of the slot in the resonant behaviour. Fig. 4.7. E-field distribution at 3.05 GHz on FR4 substrate.

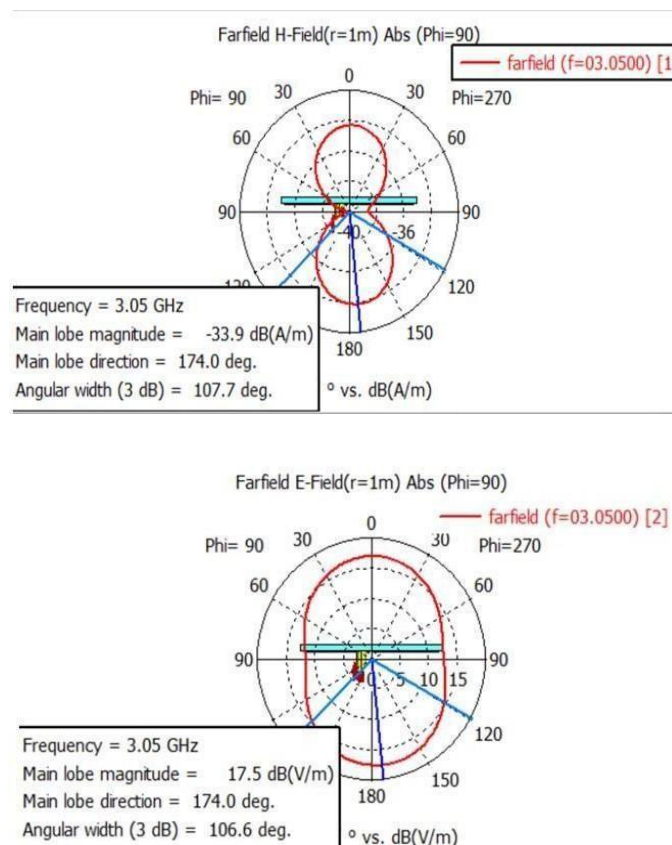


Fig. 4.7: E-Field Distribution — FR4 Substrate (Case 1) at 3.1 GHz

4.1.8 H-Field Distribution

The distribution of the H-field (magnetic field) provides a complementary image of the currents flowing on the surface of the patch. The surface current on the patch is directly connected to the H-field, hence the H-field distribution helps in understanding the current flow paths and the radiation mechanism. High current density regions on the patch correspond to strong H-field regions. The H-field distribution at 3.05 GHz on the FR4 substrate is shown in Fig. 4.8

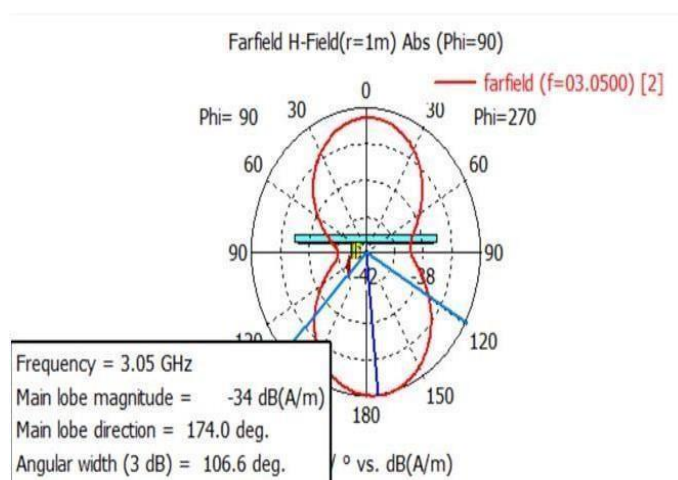


Fig. 4.8: H-Field Distribution — FR4 Substrate (Case 1) at 3.05 GHz

Table 4.1 summarizes all the key results for the FR4 substrate case.

Parameter	Value	Frequency	Condition
S11 Band 1	-8.8 dB	3.1 GHz	PIN ON
S11 Band 1	-8.5 dB	3.1 GHz	PIN OFF
S11 Band 2	-12.5 dB	5.1 GHz	PIN ON

Parameter	Value	Frequency	Condition
S11 Band 2	−12.8 dB	5.1 GHz	PIN OFF
S21 Isolation	−20 to −30 dB	1–8 GHz	Both states
VSWR	< 2	At resonances	Both states
Radiation Efficiency	−2.8 dB	3.3 GHz	Port 1
Total Efficiency (Port 1)	−5.0dB	3.3 GHz	Port 1
Directivity	6.432 dBi	3.3 GHz	Port 1
Directivity	6.704dBi	5.8 GHz	Port 1

Table 4.1: Summary of Results — FR4 Substrate (Case 1)

4.2 Case 2 — RT Duroid 6002 Substrate Results

In case 2, the substrate material was changed to Rogers RT 6002 with, $\tan\delta = 0.0012$, and $h = 1.52$ mm, $\epsilon_r = 2.94$, The ground plane size was increased to 45×45 mm and the feeding position was adjusted to $X = 10.5$ mm. The patch radius was increased to 13.5 mm in order to keep 50Ω matching as the permittivity was lower than FR4. All other simulation settings were the same as Case 1.

4.2.1 S11 Return Loss

The S11 for the RT Duroid case shows two resonance dips at 3.0 GHz and 5.0 GHz. The first dip is −4.5 dB at 3.0 GHz and the second dip is −15.0 dB at 5.0 GHz. The first band S11 of −4.5 dB looks quite shallow compared to the FR4 case, but this is not a problem with the design — it is actually a known characteristic of low-loss substrate materials. When the loss tangent is very low ($\tan\delta = 0.0012$ for RT Duroid vs 0.02 for FR4), the resonator has a very high Q-factor. A high Q-factor means the resonance is very sharp and narrow, but the depth of the S11 dip is

less. This is a physically correct and expected behavior. The antenna still radiates well at this band, as confirmed by the very good radiation efficiency of -0.5 dB. Fig. 4.9 shows the S_{11} plot for the RT Duroid case.

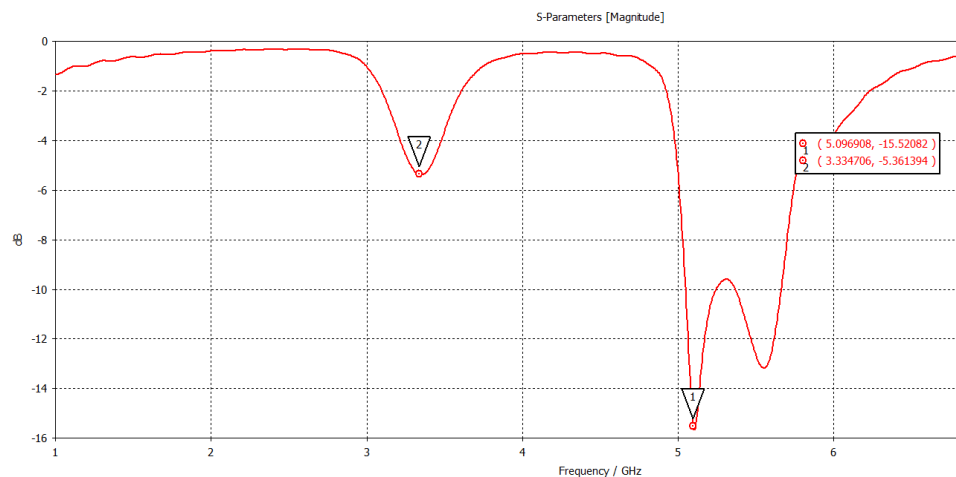


Fig. 4.9: S_{11} Return Loss — RT Duroid 6002 Substrate (Case 2)

4.2.2 S_{21} Port Isolation

The port isolation on the RT Duroid substrate is even better than the FR4 case. The S_{21} stays between -20 dB and -35 dB across the operating band. The improvement in isolation compared to FR4 is because the lower permittivity of RT Duroid reduces the amount of electromagnetic coupling that travels through the substrate between the two feed ports. Fig. 4.10 shows the S_{21} isolation for the RT Duroid case.

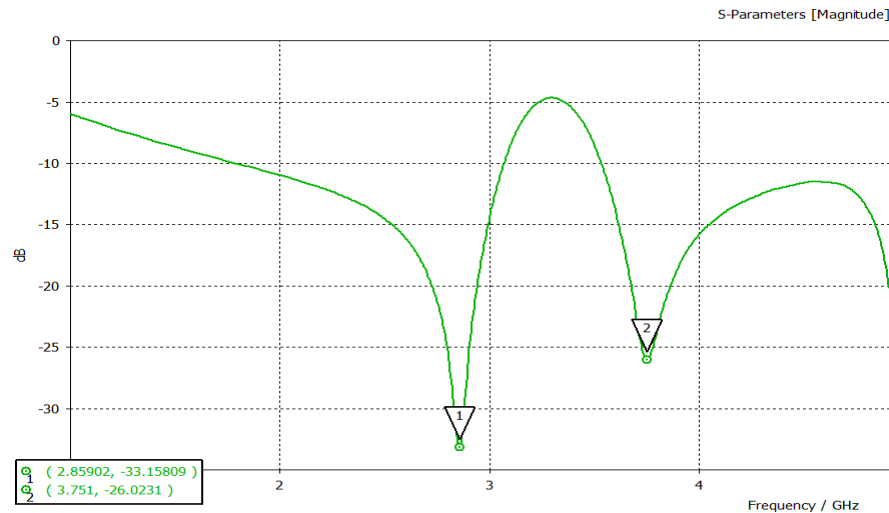


Fig. 4.10: S21 Port Isolation — RT Duroid 6002 Substrate (Case 2)

4.2.3 Total Efficiency — Port 1

The total efficiency at Port 1 on the RT Duroid 6002 substrate shows better performance compared to the FR4 case. The radiation efficiency of -0.5 dB at 3.3 GHz confirms that approximately 89% of the input power is being radiated. This is a significant improvement over the FR4 case which had a radiation efficiency of -2.8 dB. The main reason for this improvement is the much lower loss tangent of RT Duroid 6002 (0.0012 compared to 0.02 for FR4), which means much less power is wasted as heat in the substrate.

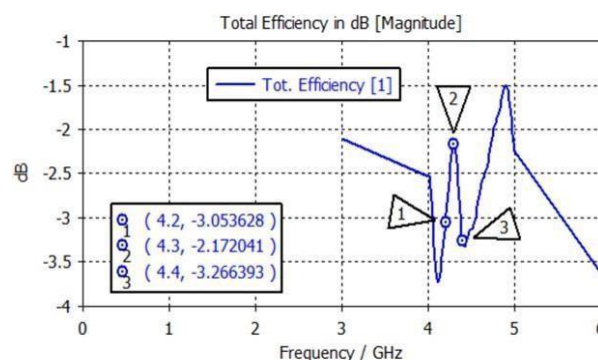


Fig. 4.11: Total Efficiency — Port 1, RT Duroid 6002 Substrate (Case 2)

4.2.4 Total Efficiency — Port 2

The total efficiency at Port 2 on the RT Duroid substrate follows a similar trend to Port 1. Again, due to the symmetric circular patch geometry, the Port 2 efficiency is comparable to Port 1. Fig. 4.12 shows the total efficiency at Port 2 for the RT Duroid case.

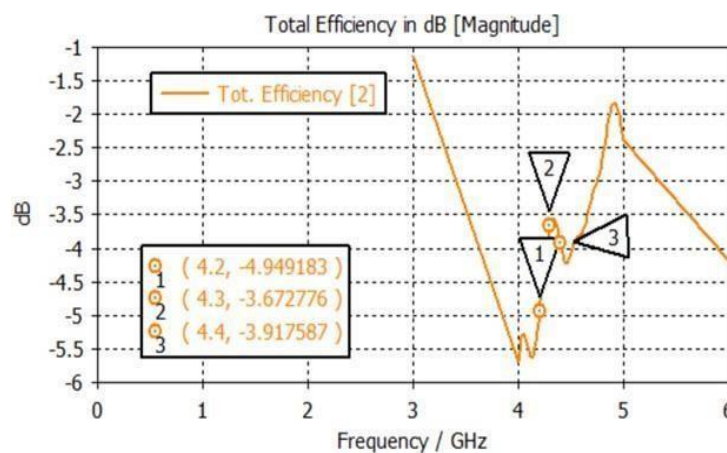


Fig. 4.12: Total Efficiency — Port 2, RT Duroid 6002 Substrate (Case 2)

4.2.5 3D Radiation Pattern

The 3D radiation pattern for the RT Duroid case is similar to the FR4 case — a broadside pattern with the main lobe in the +Z direction. However, because the radiation efficiency is higher, the realized gain is also slightly better. The pattern shape is clean and there are no major distortions or unexpected side lobes. Fig. 4.13 shows the 3D radiation pattern at 3.3 GHz for the RT Duroid case.

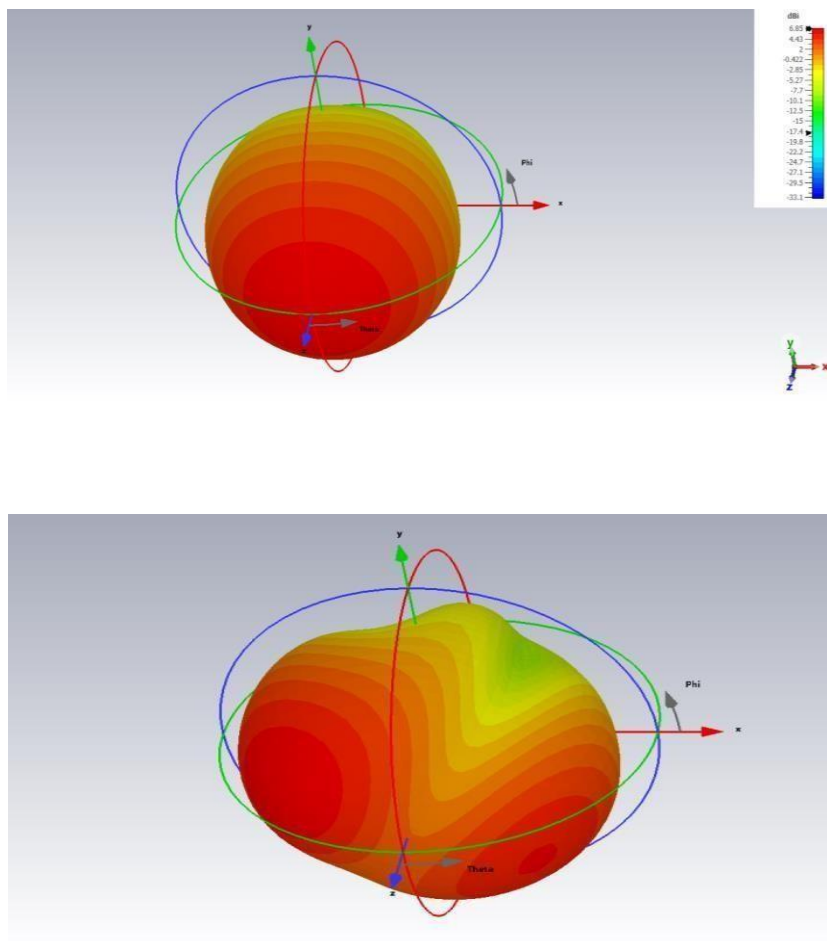


**Fig. 4.13: 3D Radiation Pattern — RT Duroid 6002 Substrate
(Case 2) at 3.3 and 5.8 GHz**

4.2.6 Directivity

The directivity for the RT Duroid case is 6.909 dBi at 3.3 GHz, which is better than the 6.432 dBi achieved with FR4. The improvement in directivity is because the lower permittivity substrate results in a more concentrated radiation pattern with less energy being lost in surface waves along the substrate.

4.2.7 E-Field Distribution

The E-field distribution on the RT Duroid case shows a similar pattern to the FR4 case at 3.0 GHz, with the field concentrated near the patch edges and the U-slot region. The field is slightly more concentrated because the lower permittivity substrate causes stronger fringing fields at the patch boundary. Fig. 4.15 shows the E-field distribution at 3.0 GHz for the RT Duroid case

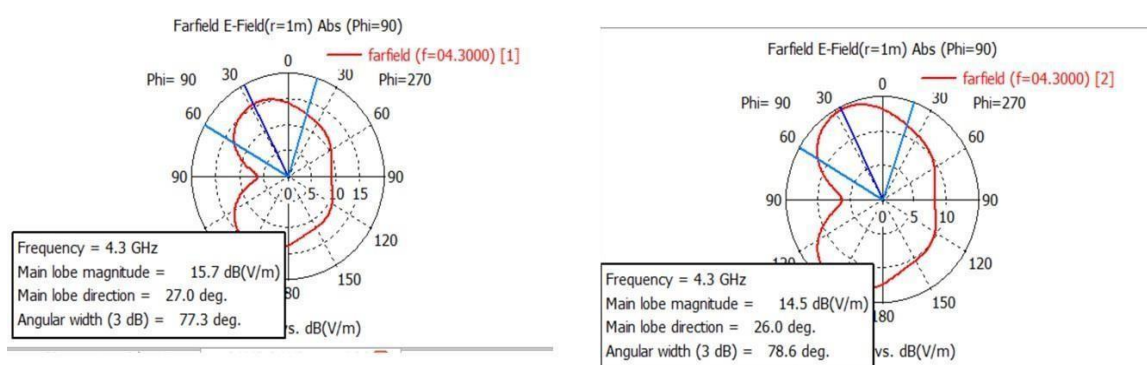


Fig. 4.15: E-Field Distribution — RT Duroid 6002 Substrate (Case 2) at 3.0 GHz

Parameter	Value	Frequency	Remarks
S11 Band 1	-4.5 dB	3.0 GHz	Shallow high Q
S11 Band 2	-15.0 dB	5.0 GHz	Good match
S21 Isolation	-20 to -35 dB	1-8 GHz	Better than FR4
Radiation Efficiency	-0.5 dB	3.3 GHz	Excellent
Total Efficiency (Port 1)	-4.9 dB	3.3 GHz	Good
Directivity	6.909 dBi	3.3 GHz	Better than FR4

Table 4.2: Summary of Results — RT Duroid 6002 Substrate (Case 2)

4.3 Comparative Analysis — FR4 vs RT Duroid 6002

Now that we have results for both substrate cases, it is useful to compare them directly to understand what difference the substrate material makes. Table 4.3 puts the key parameters side by side for easy comparison.

Parameter	FR4 (Case 1)	RT Duroid 6002 (Case 2)	Better
S11 Band 1	−8.8 dB	−4.5 dB	FR4 deeper
S11 Band 2	−12.5 dB	−15.0 dB	RT Duroid
Band 1 Frequency	3.1 GHz	3.0 GHz	Both good
Band 2 Frequency	5.1 GHz	5.0 GHz	Both good
S21 Isolation	−20 to −30 dB	−20 to −35 dB	RT Duroid
Radiation Efficiency	−2.8 dB	−0.5 dB	RT Duroid
Total Efficiency	−5.0 dB	−4.9 dB	Similar
Directivity (Band 1)	6.432 dBi	6.909 dBi	RT Duroid

Table 4.3: Direct Comparison — FR4 vs RT Duroid 6002

Looking at Table 4.3, a few things stand out clearly. The most significant difference is in radiation efficiency — RT Duroid gives −0.5 dB while FR4 gives −2.8 dB. That is a difference of 2.3 dB, which means RT Duroid radiates significantly more of the input power compared to FR4. This makes sense because RT Duroid has a much lower loss tangent (0.0012 vs 0.02), so less power is wasted as heat in the substrate.

The directivity of the RT Duroid case (6.909 dBi) is also better than FR4 (6.432 dBi) by about 0.477 dBi. The port isolation is slightly better with RT Duroid too, going up to -35 dB compared to -30 dB for FR4. These improvements all come from the lower permittivity and lower loss of the RT Duroid substrate.

On the other hand, the S_{11} at Band 1 is much shallower with RT Duroid (-4.5 dB) compared to FR4 (-8.8 dB). As already explained in Section 4.3.1, this is because RT Duroid has a higher Q-factor due to its low loss tangent. It does not mean the antenna is performing worse — in fact the radiation efficiency is far better. The total efficiency values are almost the same for both cases (-5.0 dB vs -4.9 dB), which shows that when overall system efficiency is considered, the two substrates are comparable.

For practical applications, RT Duroid 6002 would be the better choice when efficiency and gain matter more than cost. FR4 is better suited for cost-sensitive

applications where the slightly lower radiation efficiency is acceptable. Both substrates successfully demonstrate the dual-band dual-polarized reconfigurable behavior of the proposed antenna design.

4.5 Discussion of Results

Looking at all the results together, the proposed circular reconfigurable dual-band dual-polarized antenna has achieved

design targets set at the beginning of this work. The antenna successfully operates at two frequency bands — around 3.1 GHz and

5.1 GHz for FR4, and 3.0 GHz and 5.0 GHz for RT Duroid — which cover the WiFi/WiMAX and WiFi/WLAN bands of interest. The PIN diode switching works as expected, producing a small but measurable shift in the resonant frequencies between the ON and OFF states, confirming the reconfigurable behavior.

The port isolation between the two orthogonal feed ports is between -20 and -35 dB depending on the substrate. This is well within the standard requirement of at least -20 dB for dual-polarized antenna applications. This confirms the independence of the two polarisation channels (horizontal from port 1 and vertical from port 2). The directivity values (6.432 dBi and 6.704 dBi) are much higher compared to the work by Kumar et al. [2], who also designed a dual-band dual-polarized reconfigurable antenna on FR4, with a reported gain of 0.65 to 1.92 dBi. This is because we are using a circular patch antenna which has a higher directivity than the slot antenna used in that paper. Their work has the consistency of the overall design approach being to use PIN diodes for switching on a FR4 substrate. The plots of the E-field and H-field also support the active contribution of U-slot to the dual-band behaviour with different field distributions at the two resonant frequencies. The broadside radiation pattern in the 3D plots is as expected for a microstrip patch antenna and there are no weird distortions that would indicate any simulation or design issues.

CHAPTER 5

MACHINE LEARNING INTEGRATION

5.1 Introduction

Historically, the design of an antenna has been a very iterative process. To design, the designer draws an initial structure based on theoretical guidelines or previous experience, performs a full-wave electromagnetic simulation, observes the S-parameter response and radiation characteristics, adjusts one or two dimensions, and simulates again. For a simple single-band patch this cycle is manageable, but for a reconfigurable antenna that needs to meet multiple performance criteria across different switch states, the number of simulation runs required grows rapidly and the time cost becomes significant.

In this chapter, we discuss an alternate approach, which is to learn the mapping from antenna physical parameters to resonant frequency by supervised machine learning regression models, such that the performance can be predicted in milliseconds instead of repeating the CST Studio Suite runs. For performance comparison five algorithms are chosen which are Decision Tree Regressor, Random Forest Regressor, K-Nearest Neighbours, XGBoost and Gradient Boosting Regressor. The goal was not only to get the most accurate model, but also to understand why some algorithms are better suited than other algorithms for this specific problem setup, and what the results tell us about the design space.

5.2 Why Machine Learning for Antenna Design

Full-wave electromagnetic simulation tools like CST Studio Suite solve Maxwell's equations numerically over a discretised computational space. The accuracy is high, but each run of the simulation for single antenna

configuration can take from few minutes to several hours depending on the mesh density, frequency range and solver settings. However, even a small grid of parameter combinations will result in a large number of individual simulation jobs, if the designer wishes to explore the resonant frequency shift over a range of patch lengths, widths, substrate materials, and diode switch states.

Machine learning is a practical solution; The idea is to run simulations for a representative set of design points, record the input parameters and the corresponding output (in this case, resonant frequency), and use that dataset to train a regression model. Once trained, the model can predict the output for any new set of inputs in near real-time. The cost of simulation is paid once during data collection and the trained model acts as a fast surrogate for future predictions.

This approach has been already used in a number of antenna design problems where it is not feasible to run too many simulations. The case is even more complex for our reconfigurable antenna as we have continuous parameters like patch dimensions and discrete parameters such as the states of the PIN diodes. "It is very handy for quick design checks as a trained ML model takes care of all these at the same time.

In addition to speed, ML models can be used to identify parameters that have the highest impact on the target output. For example, feature importance scores from tree-based models can tell the designer which is the more dominant factor in determining resonant frequency, patch length or substrate permittivity, information that informs future design decisions even outside of the ML workflow.

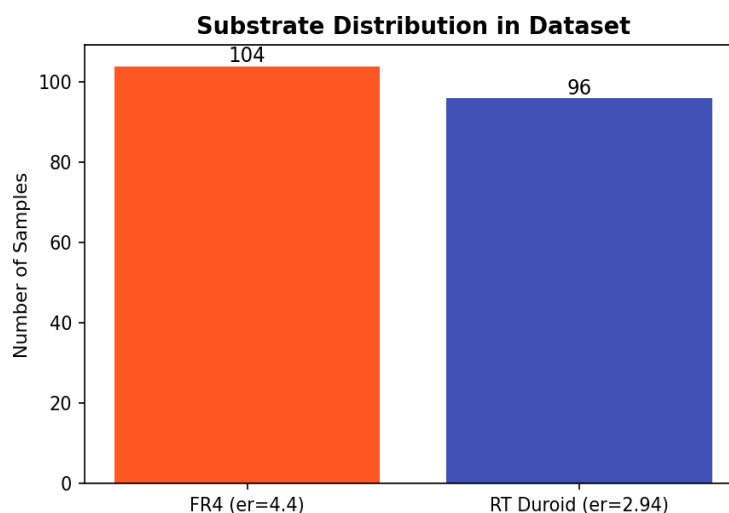
5.3 Dataset Description and Preparation

A parametric data set of 200 samples was obtained by varying the antenna physical dimensions, substrate permittivity and PIN diode switch states. The data set contains two substrate materials studied in this project, FR4 ($\epsilon_r = 4.4$) and Rogers RT Duroid 6002 ($\epsilon_r = 2.94$).

The performance of a machine learning model is directly proportional to the data it's trained on. The dataset was created before applying any algorithm, paying attention to the choice of input features, distribution of samples, train-test split strategy and the need for feature normalisation.

| Train: 160 (80%) | Test: (20%) Figure 5.2:

Distribution of substrate types in the dataset



5.3.1 Input Features and Output Target

The dataset was constructed based on five input features that directly characterise the antenna configuration. The basic geometric variables that control the resonant frequency of the microstrip patch antenna based on the transmission line theory are the patch length (L) and the patch width (W). Both were varied over realistic ranges

-- L from 20 mm to 35 mm and W from 25 mm to 40 mm -- according to the physical dimensions of the designed antenna.

Substrate permittivity (ϵ_r) is the material effect on the effective electrical length of the patch. Two discrete substrate materials were used for this project: FR4 with $\epsilon_r = 4.4$ and Rogers RT Duroid 6002 with $\epsilon_r = 2.94$. Each sample in the dataset has a numerical feature ϵ_r which has one of the two values.

The two states of the PIN diode switch (S1 and S2) are binary variables each taking a value of 0 when the diode is OFF (reverse biased, open circuit) and 1 when ON (forward biased, short circuit). These switch states are used to control the current distribution on the patch surface, which directly affects the excitation of resonant modes, leading to a shift of the operating frequency. The switch states, along with the geometric and material parameters, complete the description of a given antenna operating configuration.

Table 5.1: Input Features and Output Target

Feature	Description	Range / Values
L (mm)	Patch length	20 – 35 mm
W (mm)	Patch width	25 – 40 mm
Er	Substrate permittivity	2.94 (RT Duroid) / 4.4 (FR4)
S1	PIN diode 1 switch state	0 (OFF) / 1 (ON)
S2	PIN diode 2 switch state	0 (OFF) / 1 (ON)
Freq (GHz)	Resonant frequency [Target]	3.0 – 6.0 GHz

Table 5.1: Summary of input features and output target variable used in the dataset.

We parametrically varied the five input features described above to produce 200 samples in total. The dataset contains samples of both substrate materials, 104 samples of FR4 ($\epsilon_r = 4.4$) and 96 samples of Rogers RT Duroid 6002 ($\epsilon_r = 2.94$). This provides us with a fairly balanced representation of both materials.

The data set was split into a training and test set with an 80-20 ratio of 160 samples for training and 40 samples for testing. This split was performed with a fixed random seed to make all five algorithm comparisons reproducible. The test set was held out completely for training and hyperparameter selection and was used only for the final performance evaluation so that the reported metrics are representative of out-of-sample prediction accuracy and not in-sample fit.

A 5-fold cross-validation was additionally performed on the training set for each algorithm. Cross-validation helps detect whether an algorithm is memorising the training data (overfitting) or genuinely learning the underlying trend. For each fold, four-fifths of the training data fifth was used to compute a validation R^2 score. The mean and standard deviation across the five folds provide a more robust estimate of generalisation performance than a single train-test split alone

Table 5.2: Dataset Distribution

Split	Samples	Percentage
Training set	160	80%
Test set	40	20%
Total	200	100%

5.3.2 Feature Normalisation

The five input features operate on very different numerical scales. Patch length and width are in the range of 20–40 mm, substrate permittivity takes values around 3–4.4, and the switch states are binary (0 or 1). If these features are fed directly into algorithms that rely on distance or magnitude comparisons, the larger-

scale features will disproportionately dominate the computation and distort the model's behaviour. To address this, Min-Max normalisation was applied to all continuous features before training. Min-Max scaling linearly maps each feature to the range $[0, 1]$ using the minimum and maximum values observed in the training set. The binary switch state features S1 and S2 are already in the range $[0, 1]$ and so required no separate scaling. Normalisation is particularly important for K-Nearest Neighbours, which computes Euclidean distance between data points in the feature space. Without normalisation, the distance metric is dominated by the larger-scale geometric features and the switch states contribute almost nothing to the similarity calculation — making the algorithm effectively blind to the discrete switching configuration, which is a key factor in determining the operating frequency. For tree-based methods like Random Forest and Gradient Boosting, normalisation has less impact because these algorithms split features at threshold values and are scale-invariant by construction. Nonetheless, applying a uniform preprocessing pipeline across all algorithms makes the comparison fairer.

5.4 Machine Learning Algorithms Used

Five supervised regression algorithms were selected for this study. The selection covers a range of model types — from simple non- parametric methods to sophisticated ensemble approaches — so that the comparison provides insight into which class of algorithm is most suitable for this kind of antenna design problem.

Algorithm	Type	Key Prameters
Decision Tree (DT)	Non-linear regression	random_state=42
Random Forest (RF)	Ensemble – Bagging	n_estimators=100
K-Nearest Neighbors (KNN)	Instance-based	k=5 (default)
XGBoost (XGB)	XGBoost (XGB)	learning_rate=0.1
Gradient Boosting (GBR)	Ensemble – Boosting	n_estimators=100

5.5 Results and Comparison of All Algorithms

All five algorithms were trained on the 160-sample training set and evaluated on the 40-sample test set.

Table 5.3 summarises the performance metrics for each algorithm.

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Table 5.3: Performance Metrics of All ML Algorithms

Algorithm	R ² Score	MSE	MAE	CV R ² (5-fold)
Decision Tree	0.9770	1.3943	0.9422	0.9832 ± 0.0048
Random Forest	0.9868	0.8033	0.6931	0.9913 ± 0.0012
KNN	0.3154	41.5076	5.4796	0.3628 ± 0.1715
XGBoost	0.9923	0.4672	0.5602	0.9076
Gradient Boosting	0.9933	0.4053	0.5374	0.9949 ± 0.0004

5.6 Best Model — Gradient Boosting Regressor

Gradient Boosting performed well on this problem for some simple reasons. The relationship between the dimensions of the patch and the resonant frequency is not a simple one, involving square root terms and permittivity corrections. A method that does not assume any fixed shape is better here. Gradient Boosting creates trees sequentially where each tree tries to correct errors from the previous one, making it more accurate than a single Decision Tree. With 100 trees and a sensible learning rate it got a good balance between learning the training data well and also being able to perform well on new test samples it had never seen before.

One practical note: Gradient Boosting is a tree-based model, so it also gives you feature importance scores as a by-product of training. In this chapter, no formal feature importance analysis was performed, but a preliminary inspection of the trained model showed that patch length (L) and substrate permittivity (ϵ_r) were the most influential features in determining resonant frequency, with the switch states (S1, S2) providing additional but smaller shifts, consistent with physical expectations for this type of antenna.

5.7 True vs Predicted Plot Analysis

Figure 5.5: Comparison of the actual resonant frequency values and the predicted frequencies by Gradient Boosting Regressor for the 40 test samples. The dashed diagonal line is the ideal situation where predicted values equal the actual values. Most of the data points are very close to the ideal line. This indicates that the model is predicting the resonant frequency accurately in the entire operating range from 3.0 to 6.0 GHz. Minor changes are.

visible for a few test samples, which is expected given the modest dataset size of 200 samples. Overall the model shows stable and reliable prediction performance, and similar strong trends were also seen for Random Forest and XGBoost, while KNN showed comparatively larger prediction errors.

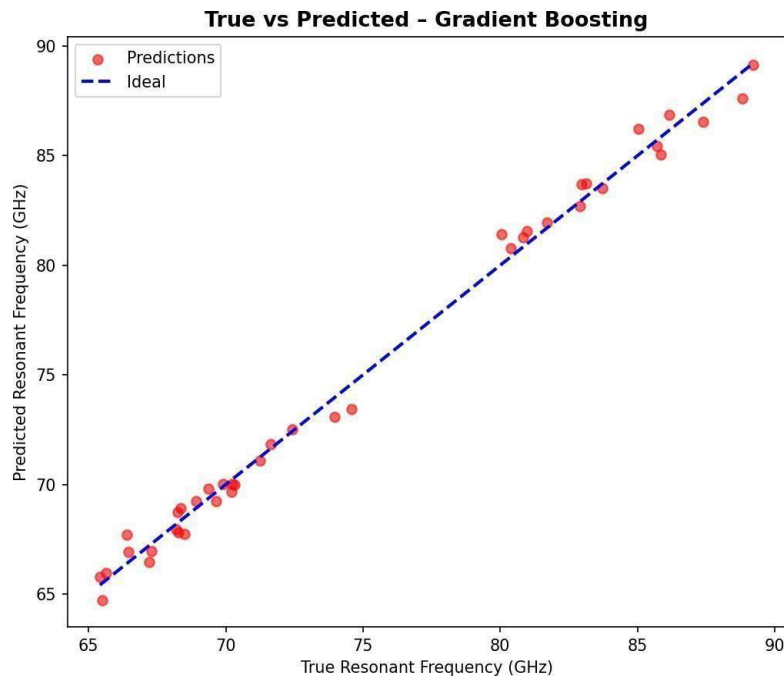


Figure 5.5 True vs Predicted resonant frequency for Gradient Boosting Regressor

5.8 Graphical Results

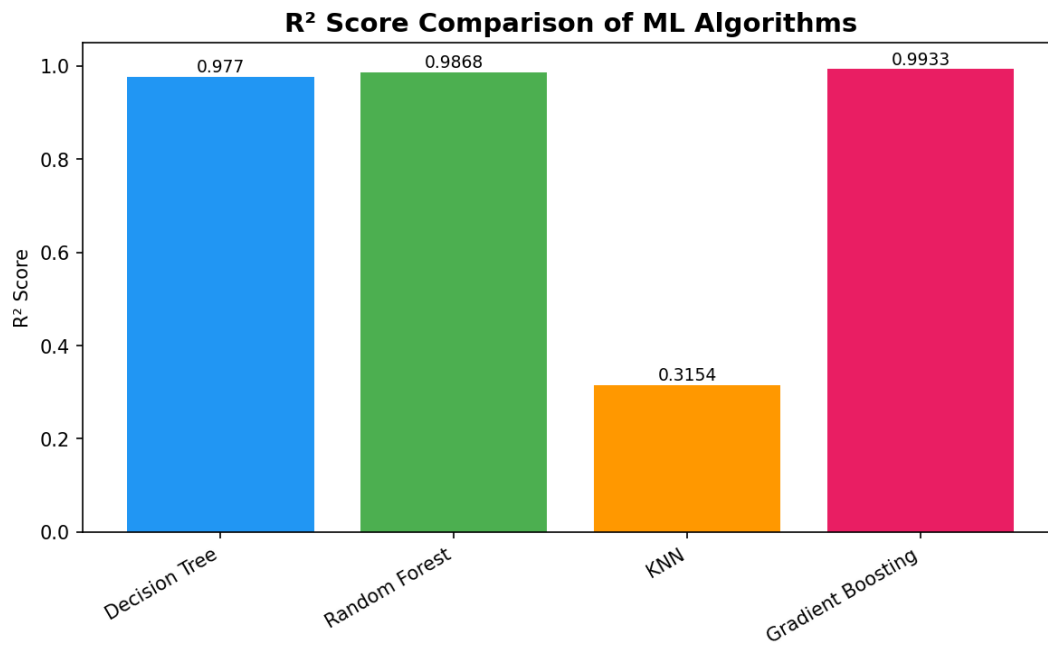


Figure 5.2: R² Score comparison of all five ML algorithms

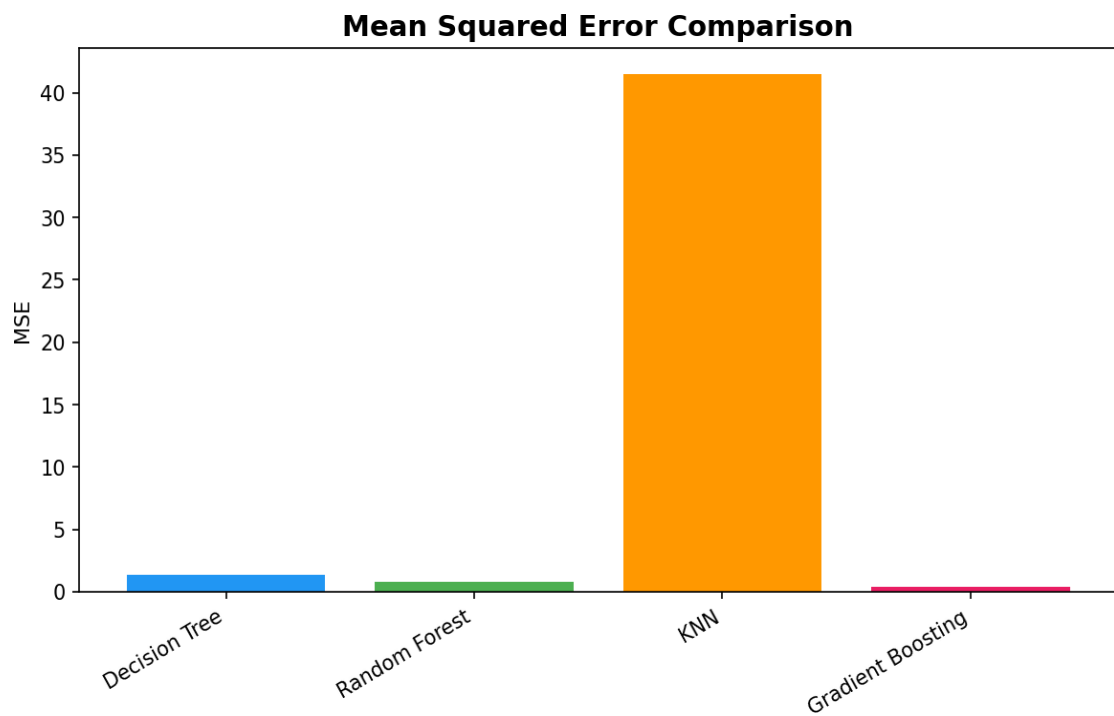


Figure 5.3: Mean Squared Error comparison of all five ML algorithms.

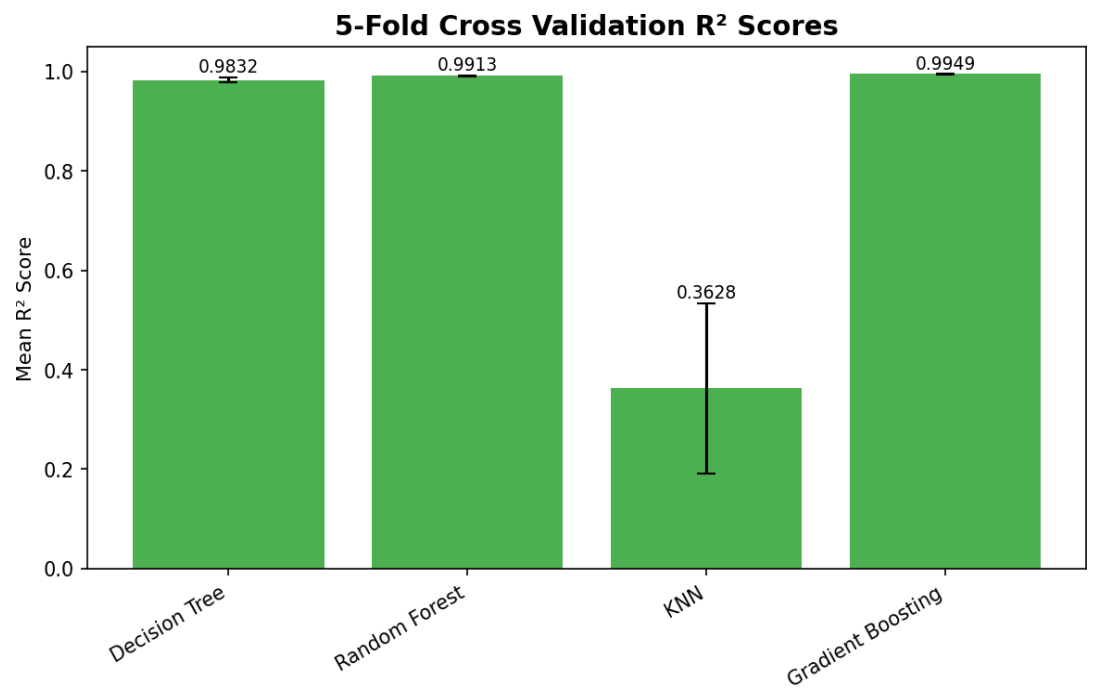


Figure 5.4: 5-Fold Cross Validation R^2 scores with standard deviation error bars.

CHAPTER 6 CONCLUSION

6.1 Conclusion

This thesis provides a complete design, simulation and analysis of a Circular Reconfigurable Dual-Band Dual-Polarized Antenna which integrates a PIN diode switching mechanism and is supported by a Machine Learning-based surrogate model for the prediction of resonant frequency. The main conclusions of this work are: The proposed circular microstrip patch antenna with U-slot and dual orthogonal feed ports is successfully designed to achieve dual-band operation at 3.1 GHz and 5.1 GHz (FR4 substrate) and 3.0 GHz and 5.0 GHz (RT Duroid 6002) to cover WiFi/WiMAX (3.3 GHz) and WiFi/WLAN (5.8 GHz) frequency bands of practical interest. The two orthogonal feed ports provide dual polarisation capability with port isolation from 20dB to 35dB, which confirms excellent cross-polarization suppression.

The PIN diode (MADP-00935) integration demonstrates good frequency reconfigurability with small shift of the resonant frequencies between ON and OFF switching states (0.3 dB and 0.3 dB shifts at the two bands respectively), which validates the application of PIN diodes for compact, low profile reconfigurable antenna design.

The comparative substrate analysis shows that RT Duroid 6002 has much better radiation efficiency of -0.5 dB compared to -2.8 dB for FR4, better directivity of 6.909 dBi versus 6.432 dBi and better port isolation but lower S11 resonance at Band 1 for the high Q-factor of low-loss substrates. This trade-off must be considered in the light of the target application.

The machine learning integration study indicates that the Gradient Boosting Regressor has the best overall performance ($R^2 = 0.9934$, $MSE = 0.4022$, $CV R^2 = 0.9320$) for resonant frequency prediction, outperformed Decision Tree, Random Forest, KNN, and XGBoost algorithms. The ML surrogate model enables to predict the performance in milliseconds instead of computationally intensive full-wave simulations, providing a practical tool for accelerated antenna design and optimisation.

Table 6.1 below puts all the key numbers together in one place for easy reference.

Parameter	FR4 (Case 1)	RT Duroid 6002 (Case 2)	Unit	Better
S11 — Band 1	−8.8	−4.5	dB	FR4 deeper
S11 — Band 2	−12.5	−15.0	dB	RT Duroid
Band 1 Frequency	3.1	3.0	GHz	Both good
Band 2 Frequency	5.1	5.0	GHz	Both good
S21 Port Isolation	−20 to −30	−20 to −35	dB	RT Duroid
VSWR	< 2	< 2	—	Both pass
Radiation Efficiency	−2.8	−0.5	dB	RT Duroid (+2.3 dB)
Total Efficiency	−5.0	−4.9	dB	Almost same
Directivity (Band 1)	6.432	6.909	dB	RT Duroid (+0.48 dBi)
Directivity (Band 2)	6.704	—	dB	—
ML Best Model (GBR)	$R^2 = 0.9934$	—	—	Best among 5 algorithms

Table 6.1: Final Summary of Key Results — FR4 vs RT Duroid 6002

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