

Design and Optimization of Reconfigurable Patch Antenna for Wireless Applications

A Thesis Submitted to Gujarat Technological University

for the Award of

Doctor of Philosophy

In

Electronics and Communication Engineering

By

Mansuri Sameer Hasanbhai

Enrollment No. 219999915009

Under supervision of

Dr. Shahidmohammed S. Modasiya



GUJARAT TECHNOLOGICAL UNIVERSITY

AHMEDABAD

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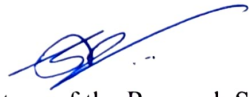
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ABSTRACT

The continuous evolution of wireless communication systems, from early cellular networks to fifth-generation (5G) and emerging 6G technologies, has significantly increased the number of standards modern devices must support, including LTE, WLAN, WiMAX, Bluetooth, IoT, and Wi-Fi 6E/7. Meeting these requirements with conventional fixed-frequency antennas demands multiple dedicated radiating elements, increasing hardware complexity, aperture congestion, and mutual coupling. Reconfigurable antennas overcome these limitations by electronically modifying frequency, radiation pattern, or polarization within a single compact structure.

This thesis presents the design, simulation, and experimental validation of compact reconfigurable microstrip antennas employing PIN diode-based switching. Three configurations are proposed: a frequency-reconfigurable antenna achieving multi-band operation through modified current paths; a frequency and pattern reconfigurable antenna using a single diode with reduced switching complexity; and a dual PIN diode circular antenna incorporating a defected ground structure for enhanced frequency agility. The designs primarily target the sub-6 GHz spectrum, extending select bands beyond 6 GHz for LTE, WLAN, 5G, and IoT applications.

Each design is evaluated through reflection coefficient, bandwidth, gain, and surface current analysis. Selected prototypes are fabricated and measured using a Vector Network Analyzer and anechoic chamber, showing good agreement with simulations and favorable comparison with existing reconfigurable antennas reported in the literature.

Keywords: Reconfigurable Antenna, PIN Diode, Frequency Reconfiguration, Radiation Pattern Reconfiguration, Microstrip Antenna, Defected Ground Structure (DGS), Sub-6 GHz, Multi-band Antenna, 5G/IoT Applications, Switching Mechanism

With heartfelt gratitude, I dedicate this

thesis to my Great Father

Late. Hasanbhai A. Mansuri

And

My Family Members

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List of Abbreviation

S.N.	Abbreviations	Full Form
1	1G	First Generation
2	5G	Fifth Generation
3	6G	Sixth Generation
4	AI	Artificial Intelligence
5	Bluetooth	Bluetooth Wireless Technology
6	C-Band	C-Band Frequency Spectrum
7	DGS	Defected Ground Structure
8	dBi	Decibels relative to an Isotropic Radiator
9	eMBB	Enhanced Mobile Broadband
10	F/B	Front-to-Back (Ratio)
11	GPS	Global Positioning System
12	GSM	Global System for Mobile Communications
13	IoT	Internet of Things
14	ISM	Industrial, Scientific, and Medical
15	ITS	Intelligent Transportation System
16	LTE	Long-Term Evolution
17	MIMO	Multiple-Input Multiple-Output
18	mmWave	Millimeter Wave
19	mMTC	Massive Machine-Type Communication
20	PIN	Positive–Intrinsic–Negative (Diode)
21	RF	Radio Frequency
22	RF-MEMS	Radio Frequency Micro-Electro-Mechanical Systems
23	SDR	Software-Defined Radio
24	SMA	SubMiniature Version A (RF Connector)
25	SNR	Signal-to-Noise Ratio
26	UWB	Ultra-Wideband
27	URLLC	Ultra-Reliable Low-Latency Communication
28	VNA	Vector Network Analyzer
29	Wi-Fi	Wireless Fidelity
30	WiMAX	Worldwide Interoperability for Microwave Access
31	WLAN	Wireless Local Area Network
32	ZigBee	ZigBee Wireless Communication Standard

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CHAPTER-1

Introduction

1.1 Evolution of Wireless Communications

Wireless communication forms the foundation of numerous services used in everyday life, ranging from mobile communication and broadband internet access to multimedia transmission and the rapidly growing Internet of Things (IoT). The widespread adoption of connected devices has paved the way for an unprecedented increase in wireless data traffic, placing greater demands on network performance. To satisfy these requirements, modern wireless systems must provide higher data rates, reliable connectivity, and efficient utilization of the available spectrum, which has driven continuous advancements in wireless communication technologies [1].

Wireless communication technology has continuously transitioned from the analog voice-based first-generation (1G) systems to the advanced fifth-generation (5G) networks currently in use. Unlike preceding generations of cellular technology, which were oriented primarily toward voice transmission and conventional data services, 5G has been envisioned to accommodate a far more diverse set of application requirements — encompassing enhanced Mobile Broadband (eMBB), Ultra-Reliable Low-Latency Communication (URLLC), and Massive Machine-Type Communication (mMTC). Integrating these diverse services within a single network requires efficient utilization of spectrum and network resources, making resource management a key requirement for present-day wireless communication systems [2], [3].

Figure 1.1 presents the how the wireless communication technologies have evolved and summarizes the key developments that have driven successive generations of wireless networks. It illustrates the transition from conventional voice-centric communication systems to intelligent wireless environments capable of supporting cognitive radio, artificial intelligence, IoT applications, and future 6G technologies.

Alongside these developments, the design of radio-frequency (RF) front-end systems has become increasingly challenging. Contemporary wireless devices are expected to operate across multiple communication standards, including LTE, WLAN, Bluetooth, various IoT

protocols, and several 5G frequency bands, while maintaining compact physical dimensions. Meeting these requirements using separate antennas for each wireless standard increases hardware complexity, occupies valuable antenna aperture space, and intensifies mutual coupling between radiating elements, which can ultimately reduce radiation efficiency. These challenges have encouraged the development of compact antenna structures capable of supporting multiple wireless services within a single radiating element [4].

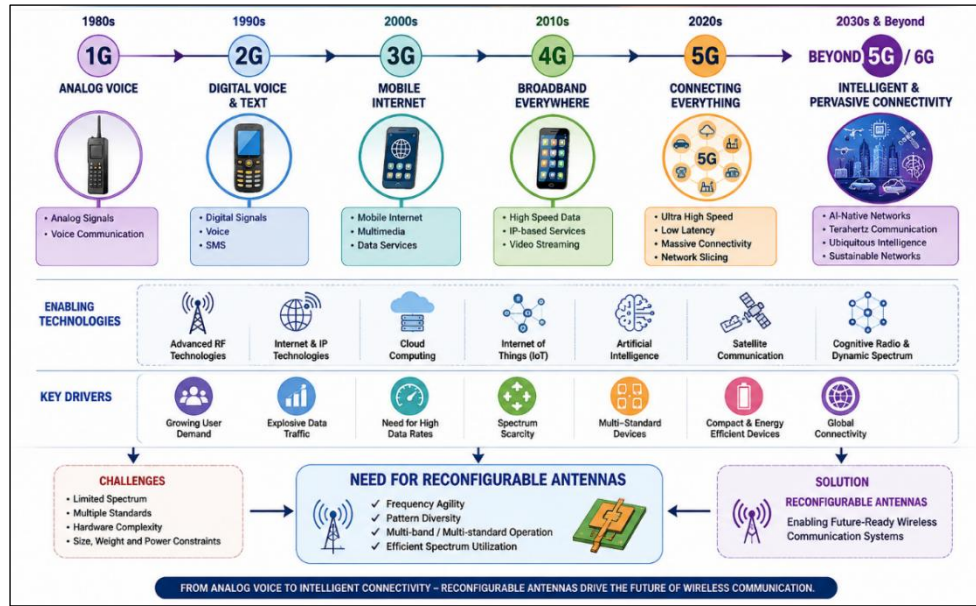


Figure 1.1 Progression of Wireless Communication Networks and the Role of Reconfigurable Antennas

Growing demands of modern wireless communication have exposed the limitations of conventional fixed antennas, driving significant research toward reconfigurable antenna technology. In contrast to fixed antennas with predetermined characteristics, reconfigurable antennas can electronically alter their operating behavior by adjusting frequency, radiation characteristics, or polarization to meet varying communication needs. As a result, a single antenna can perform multiple wireless functions, minimizing hardware requirements while improving system adaptability and overall spectrum efficiency [5].

Serving as a core element within the RF front-end, the antenna exerts considerable influence over communication performance and spectrum efficiency. As wireless systems continue to support an increasing number of services within compact devices, the development of multifunctional reconfigurable antennas has become an important research direction. Compact antenna structures capable of adapting to different operating conditions are particularly valuable for contemporary wireless communication platforms, including fifth-

generation (5G) networks, cognitive radio systems, and IoT applications, all of which demand effective spectrum management and adaptive system operation [6].

1.2 Motivation for Reconfigurable Antenna Design

The fast-paced evolution of wireless communication has substantially broadened the functional requirements of contemporary communication devices. Instead of operating within a single wireless standard, today's terminals are expected to provide compatibility with technologies such as GSM, LTE, WLAN, WiMAX, Bluetooth, GPS, IoT, and fifth-generation (5G) networks. Furthermore, the deployment of Wi-Fi 6E and the evolution toward Wi-Fi 7 have widened the operating spectrum, creating additional challenges in developing compact, high-performance radio-frequency (RF) front-end systems capable of supporting multiple services efficiently [1].

Traditionally, different wireless services have been accommodated using separate antennas, each optimized for a specific operating frequency band. While this approach satisfies the requirements of individual communication standards, it increases the overall hardware complexity of the device. The use of multiple dedicated antennas also contributes to larger physical dimensions, higher fabrication cost, and increased power consumption. As portable devices continue to become more compact while incorporating a greater number of wireless technologies, this conventional design strategy becomes progressively less practical [4].

Space limitation within modern communication devices introduces another important design challenge known as aperture congestion. Batteries, displays, processors, cameras, sensors, and RF circuitry occupy a significant portion of the available space, leaving limited room for antenna integration. Under such constraints, placing several antennas in close proximity increases electromagnetic interaction between radiating elements. The resulting mutual coupling degrades impedance matching, reduces radiation efficiency, and can adversely affect the way the multiple-input multiple-output (MIMO) system perform[3]. These limitations have encouraged the development of antenna architectures capable of supporting multiple communication bands without relying on separate radiating structures.

The demand for adaptable antenna systems has become even more pronounced with the widespread adoption of carrier aggregation, heterogeneous wireless networks, and cognitive radio technologies. Cognitive radio systems require antennas that can dynamically adjust

their operating frequencies as spectrum availability changes. Likewise, LTE and 5G networks often utilize multiple frequency allocations, making frequency-agile antennas essential for maintaining reliable communication across different operating bands [7].

Reconfigurable antennas address these limitations by allowing their electromagnetic behavior to be electronically controlled without altering the physical structure. This adaptability is realized by embedding controllable components, including PIN diodes, varactor diodes, or RF-MEMS switches, into the antenna geometry to modify the current distribution under different switching conditions. Consequently, one antenna structure can be electronically reconfigured to operate over several frequency bands while meeting diverse wireless communication requirements. Consequently, the number of antennas required in a communication device is reduced, leading to lower hardware complexity, improved spectrum utilization, reduced aperture congestion, and more compact system implementation [5].

The increasing use of software-defined radio (SDR) has further highlighted the importance of antenna adaptability. Although SDR platforms provide the flexibility to modify communication parameters through software, efficient system performance also depends on the capability of the antenna to respond to these changes. Reconfigurable antennas complement SDR technology by providing hardware-level frequency agility, allowing communication systems to utilize the available spectrum more effectively under varying operating conditions [3].

The growing demand for compact multi-standard wireless devices, together with the need for efficient spectrum utilization and adaptive communication systems, continues to drive research in reconfigurable antenna technology. By enabling multiple communication bands to be supported through a common radiating structure, reconfigurable antennas reduce hardware complexity while improving system integration and operational flexibility. These capabilities make reconfigurable antennas a key technology for future wireless infrastructures, particularly in cognitive radio and multifunctional communication systems supporting multiple standards [4], [5].

1.3 Advantages of Reconfigurable Antennas

The growing demands of modern wireless networks have increased the need for antenna systems capable of adapting to diverse operating conditions, making reconfigurable antennas an attractive alternative to conventional fixed designs. In contrast to antennas with fixed electromagnetic characteristics, reconfigurable antennas electronically adjust their operating frequency, radiation characteristics, or polarization according to application requirements. This capability allows a single antenna to perform multiple communication functions while enhancing spectrum efficiency, improving overall system performance, and reducing the complexity of RF hardware [6].

One prominent merit of reconfigurable antennas is their ability to selectively resonate within the intended frequency band. By limiting operation to the desired spectrum, unwanted signals are naturally suppressed, leading to reduced interference and betterment in signal-to-noise ratio (SNR). In addition to frequency agility, pattern reconfiguration allows the radiated energy to be directed toward the intended coverage region while minimizing radiation in undesired directions. Such beam control enhances communication reliability, extends coverage, and improves interference mitigation in wireless systems [8].

The capability of reconfigurable antennas extends beyond frequency and pattern adaptation. Since the operating band can be electronically selected, these antennas inherently suppress out-of-band signals before they reach the receiver. This frequency-selective behavior reduces the dependence on additional RF filtering circuitry and contributes to improved receiver performance. Such characteristics are particularly beneficial in cognitive radio and software-defined radio systems, where dynamic spectrum access is a fundamental requirement [7].

The compact nature of reconfigurable antennas represents another significant advantage for modern wireless devices. As portable communication equipment continues to integrate a larger number of electronic components within limited physical dimensions, accommodating multiple dedicated antennas becomes increasingly challenging. A reconfigurable antenna addresses this limitation by providing multi-band operation through a common radiating structure. Consequently, the overall antenna count can be reduced, leading to lower fabrication cost, simplified hardware implementation, and more efficient utilization of the available space.

The emergence of diverse wireless applications, ranging from IoT ecosystems to portable devices and multi-standard communication platforms, has intensified the need for antenna systems with adaptive operating capabilities. Reconfigurable antennas satisfy this requirement by enabling a single antenna structure to support multiple communication standards through electronic reconfiguration. This capability reduces hardware redundancy, improves overall system efficiency, and provides reliable operation across diverse wireless environments [9].

The combination of frequency agility, compact implementation, and operational flexibility has established reconfigurable antennas as a key technology for contemporary wireless communication systems. Their ability to improve signal quality, suppress interference, reduce hardware complexity, and utilize the available spectrum more efficiently makes them well suited for cognitive radio systems, emerging wireless network generations, and portable devices designed to support multiple communication standards [4].

1.4 Fundamentals of Reconfigurable Antennas

Reconfigurable antennas are developed to provide adaptive electromagnetic performance in response to varying wireless communication demands. Unlike conventional antennas, whose characteristics are fixed once fabricated, these antennas employ electronic tuning techniques to selectively vary their operating frequency, radiation characteristics, polarization, or a combination of these properties. Such dynamic control enables a single antenna to serve multiple wireless standards, thereby improving spectrum efficiency while increasing the operational flexibility of modern communication systems [10].

1.4.1 Core Principle and Definition

A reconfigurable antenna is an antenna whose electromagnetic characteristics can be modified in a controlled manner without altering its physical geometry. This functionality is achieved by integrating switching or tuning elements into the antenna structure, allowing the effective electrical characteristics of the radiating element to be adjusted. As a result, parameters such as current distribution, electrical length, and reactive loading can be modified to obtain the desired operating characteristics [10].

The mode of electronic control applied to an antenna determines its reconfiguration category, which may involve frequency, radiation pattern, polarization, or a combination of these characteristics. Among these categories, frequency reconfigurable antennas have attracted the greatest research interest because they enable a single compact radiating structure to operate over multiple communication bands, thereby improving spectrum utilization and reducing hardware complexity [4].

1.4.2 Surface Current Distribution Modification

The performance of an antenna is governed largely by the distribution of surface current over its radiating element. In conventional antenna structures, this current distribution remains unchanged after fabrication, producing fixed resonant characteristics. Reconfigurable antennas, however, modify the surface current distribution through electronically controlled switching devices or tunable components, enabling the antenna characteristics to be adjusted according to system requirements [4], [5].

The operation of PIN diode-based reconfiguration illustrates this principle. When a PIN diode is in conduction, separate sections of radiating structure become electrically connected, creating a longer path for current flow. Conversely, when the diode is switched OFF, the current follows an alternative path with a different electrical length. Since the resonant frequency is directly related to the effective current path, changing the switching state produces different resonant frequencies and enables multi-band operation [5].

A similar principle applies to varactor-based reconfiguration, although the tuning mechanism differs. Instead of creating discrete switching states, a varactor diode alters the reactive loading of the antenna by varying its capacitance through an externally applied bias voltage. The resulting change in current distribution and stored electromagnetic energy provides continuous tuning of the operating frequency over a specified range.

1.4.3 Resonant Frequency Relationship

The dominant-mode resonance of a rectangular microstrip patch antenna may be evaluated using the following analytical expression:

$$f_r = c / (2L_{\text{eff}}\sqrt{\epsilon_{\text{eff}}})$$

Where:

- f_r = Resonant frequency (Hz)
- c = Speed of light in free space (3×10^8 m/s)
- L_{eff} = Effective electrical length of the antenna (m)
- ϵ_{eff} = Effective relative permittivity of the substrate

This relationship indicates that the resonant frequency varies inversely with the electrical length traversed by the antenna. An increase in the effective current path extends this traversed length, causing the resonant frequency to correspondingly shift toward a lower value. Conversely, reducing the effective electrical length shortens the current path and results in resonance at higher frequencies [5].

Most frequency reconfigurable antennas operate by dynamically controlling the effective electrical length (L_{eff}) of the radiating structure. This is accomplished by activating or deactivating switching elements that selectively connect or isolate different sections of the antenna. By modifying the current path in this manner, multiple resonant states can be realized using a single radiating structure [5].

1.4.4 Switching Mechanism Overview

The reconfiguration capability of an antenna is achieved by incorporating electronically controllable switching or tuning elements into the radiating structure. These components modify the electrical characteristics of the antenna, enabling changes in its operating behavior without altering the physical geometry. To achieve dynamic antenna operation, researchers have explored multiple switching and tuning techniques based on PIN diodes, varactor diodes, RF micro-electromechanical system (RF-MEMS) switches, optical switches, and tunable material technologies [6], [10].

Among the available switching technologies, PIN diodes have become the most widely adopted because of their simple biasing requirements, compact size, low cost, and fast switching speed. In most implementations, PIN diodes provide discrete frequency reconfiguration by establishing or interrupting conductive current paths within the antenna structure, thereby creating multiple operating states [4].

Continuous frequency tuning is commonly achieved using varactor diodes, whose capacitance varies with the applied bias voltage. This variable capacitance changes the reactive loading of the antenna, allowing smooth adjustment of the resonant frequency over a specified tuning range. RF-MEMS switches represent another important reconfiguration technology, offering excellent RF performance and low insertion loss. However, their practical implementation is often limited by higher fabrication complexity and increased manufacturing cost [5], [10].

The selection of a suitable switching mechanism depends on several design considerations, including the required tuning range, switching speed, power consumption, linearity, fabrication complexity, and overall implementation cost. Although the switching technologies differ in their operating principles, they ultimately achieve reconfiguration by modifying the effective current distribution and electrical characteristics of the radiating structure. This enables the antenna to adapt its electromagnetic behavior to varying communication requirements encountered in modern wireless systems [10].

In essence, the operating principle of reconfigurable antennas relies on the controlled modification of current distribution, effective electrical length, and reactive loading within the antenna structure. By altering these parameters, a single antenna can realize frequency, radiation pattern, polarization, or hybrid reconfiguration, making reconfigurable antenna technology well suited for future multi-standard and spectrum-efficient wireless communication systems.

1.5 Classification of Reconfigurable Antennas

Adaptive control of antenna characteristics enables a single radiating structure to satisfy diverse wireless communication requirements without physical modification. By electronically varying specific electromagnetic properties, reconfigurable antennas improve spectral efficiency, reduce RF hardware complexity, and support multiple communication standards. Based on the parameter selected for electronic reconfiguration, these antennas are organized into four principal classes: frequency, radiation pattern, polarization, and hybrid reconfigurable antennas [6], [10].

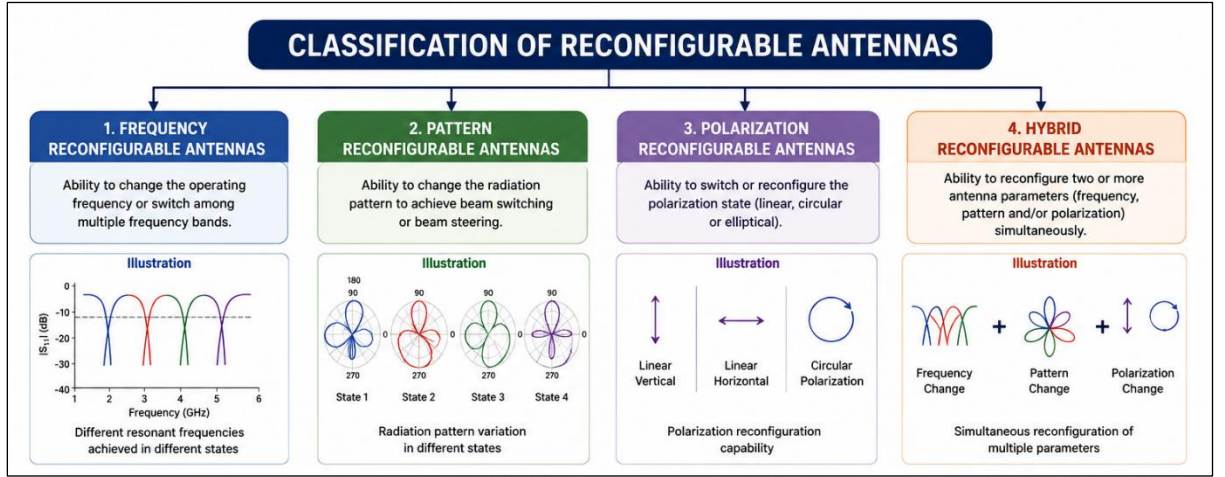


Figure 1.2 Scope of the Thesis

1.5.1 Frequency Reconfigurable Antennas

These antennas provide operation over different resonant frequencies without requiring any modification to the physical geometry of the antenna. This capability is acquired by electronical alteration of the effective electrical length, surface current flow, or reactive loading of the radiating structure through suitable switching or tuning elements. Consequently, one antenna structure can function across several communication bands, rendering it highly suitable for multi-standard wireless communication systems and cognitive radio applications [4], [5].

1.5.2 Radiation Pattern Reconfigurable Antennas

These antennas are engineered to reshape the spatial profile of radiated electromagnetic energy while preserving a nearly constant operating frequency. By electronically controlling the beam direction, radiation pattern, or coverage region, these antennas can improve signal reception, suppress interference, and enhance the reliability of wireless communication links. Owing to these capabilities, radiation pattern reconfigurable antennas have found extensive application in smart antenna systems, wireless sensing architecture, and other advanced wireless communication systems [8].

1.5.3 Polarization Reconfigurable Antennas

Polarization reconfigurable antennas provide the capability to alter the polarization state of the radiated electromagnetic wave without altering the physical geometry of the antenna.

Depending on the communication requirements, these antennas can operate between different modes of polarization, such as linear and circular polarization. This polarization adaptability reduces losses caused by polarization mismatch, improves communication reliability, and maintains stable performance under varying propagation conditions. Consequently, polarization reconfigurable antennas support a broad range of applications, including satellite communications, radar technologies, and wireless sensing systems [11].

1.5.4 Hybrid Reconfigurable Antennas

These antennas integrate more than one reconfiguration capabilities within a single radiating structure, allowing multiple antenna characteristics to be controlled simultaneously. Depending on the design requirements, these antennas can independently or concurrently modify frequency of operation, radiation behavior, polarization, or a combination of these parameters, thereby providing greater operational flexibility than single-parameter reconfigurable antennas. Although this multifunctional capability broadens their application potential, the associated antenna design, biasing network, and implementation are generally more complex than those of conventional reconfigurable antenna configurations [12].

1.5.5 Challenges in Reconfigurable Antenna Design

Reconfigurable antennas provide several important advantages for modern wireless communication systems, including frequency agility, efficient spectrum utilization, reduced hardware complexity, and the ability to support multiple communication standards using a single radiating structure. Despite these benefits, designing a high-performance reconfigurable antenna presents several technical challenges that must be carefully addressed during the design process.

- Maintaining stable gain, bandwidth, impedance matching, and radiation characteristics under different switching states.
- Minimizing the losses and parasitic effects introduced by switching or tuning elements.
- Integrating biasing networks without adversely affecting antenna performance.
- Achieving compact antenna dimensions while supporting multiple operating frequency bands.

- Balancing frequency agility, radiation efficiency, fabrication complexity, and overall implementation cost.

Addressing these challenges requires careful optimization of both the antenna structure and the reconfiguration mechanism. Consequently, the development of compact reconfigurable antennas capable of providing wide tuning ranges, stable electromagnetic performance, and low implementation complexity continues to be an important research focus in modern wireless communication systems [12].

1.6 Switching Technologies

The reconfiguration capability of an antenna is realized by integrating controllable switching or tuning elements into the radiating structure. These elements modify the electromagnetic characteristics of the antenna by altering the effective current path, electrical length, reactive loading, or material properties. Through such modifications, the operating frequency, radiation pattern, or polarization of the antenna can be adjusted to satisfy different communication requirements [6].

Among the most widely investigated are diode-based switches as well as radiofrequency micro-electromechanical systems (RF-MEMS)], and emerging materials like graphene and liquid crystals. Each of these technologies provides distinct advantages, while their suitability for a particular application depends on factors including switching speed, tuning capability, RF performance, fabrication complexity, and implementation cost [10].

1.6.1 PIN diode switches

PIN diodes are widely employed in reconfigurable antenna systems because they offer an effective combination of compact size, low cost, high switching speed, and simple biasing requirements. A PIN diode's construction features p-type and n-type semiconductor layers with an intrinsic region interposed between them. Its behavior is bias-dependent: applying forward voltage yields a low-resistance conducting path, whereas reverse bias produces a high-impedance, effectively open state [1].

Within a reconfigurable antenna, PIN diodes are used to establish or interrupt conductive paths in the radiating geometry. By selectively bridging or separating various portions of the antenna, the effective current path is modified, allowing multiple resonant frequencies or radiation states to be achieved using a common antenna aperture [13].

The widespread use of PIN diodes is primarily attributed to their fast switching capability, ease of integration, mature fabrication technology, reliable operation, and low implementation cost. These characteristics have made PIN diode-based reconfigurable antennas well suited for a broad range of wireless communication systems, comprising WLAN, LTE, WiMAX, IoT, cognitive radio, and 5G applications [13].

Considering the design objectives of compact size, low implementation cost, high switching speed, and ease of practical realization, PIN diodes have been adopted as the reconfiguration mechanism in the present work.

1.6.2 RF-MEMS switches

RF-MEMS switches achieve reconfiguration by using miniature mechanical structures that establish or interrupt electrical connections through electrostatic actuation. Their excellent RF characteristics, spanning low insertion loss, high isolation, and superior linearity, make them attractive for high-frequency microwave and millimeter-wave applications.

Despite these advantages, the practical implementation of RF-MEMS technology remains challenging because of its complex fabrication process, higher manufacturing cost, specialized packaging requirements, and relatively high actuation voltage. These factors have limited its widespread adoption in cost-sensitive commercial wireless communication systems [10].

1.6.3 Functional Materials: Graphene and Liquid Crystals

Advances in material science have introduced functional materials such as graphene and liquid crystals as alternative approaches for antenna reconfiguration. Graphene possesses electrically tunable conductivity, enabling dynamic modification of antenna characteristics and making it particularly attractive for millimeter-wave and terahertz communication systems [10].

Liquid crystals achieve reconfiguration by varying their dielectric properties under an applied electric field. This electrically controlled change in dielectric constant modifies the electromagnetic environment surrounding the antenna, enabling continuous tuning of both the resonant frequency and radiation characteristics [6].

Although graphene- and liquid crystal-based reconfigurable antennas have demonstrated significant research potential, their practical implementation is still constrained by challenges related to fabrication complexity, material stability, response time, and overall cost [6], [10].

1.6.4 Comparative Analysis of Switching Technologies

The selection of an appropriate switching technology has a direct influence on the performance, complexity, and practical implementation of a reconfigurable antenna system. Among the available approaches, PIN diodes provide a balanced combination of switching speed, implementation simplicity, reliability, and low cost, making them the preferred choice for most wireless communication applications. RF-MEMS switches offer superior RF performance but require more complex fabrication and higher manufacturing costs. Functional materials, including graphene and liquid crystals, represent promising alternatives for future adaptive antenna systems; however, their practical use remains limited by current technological and manufacturing constraints [6], [10].

Table 1.1 Comparative Analysis of Switching Technologies Used in Reconfigurable Antenna Systems

Parameter	PIN Diode	RF-MEMS	Graphene	Liquid Crystal
Switching Speed	Very High	Moderate	High	Moderate
Insertion Loss	Moderate	Low	Low	Low
Cost	Low	High	High	High
Biasing Complexity	Low	Moderate	High	High
Maturity	High	Medium	Low	Low
Suitability for This Work	Excellent	Moderate	Limited	Limited

Consequently, PIN diode-based reconfiguration continues to be the most widely adopted and practical solution for contemporary frequency and pattern reconfigurable antenna systems [8], [13].

1.7 Frequency Bands and Target Applications

The rapid proliferation of modern wireless communication systems has necessitated the allocation of multiple frequency bands for cellular networks, short-range data transmission, satellite-based communication infrastructure, and Internet of Things (IoT)-enabled applications. As a result, modern wireless devices are expected to support multiple communication standards within a single compact platform while maintaining high communication performance and efficient utilization of the available spectrum. These evolving requirements have made frequency-reconfigurable and frequency-agile antenna systems an essential component of contemporary wireless communication devices.

The antenna configurations developed in this thesis are primarily designed for operation within the sub-6 GHz spectrum, which remains one of the most important frequency ranges for present-day wireless communication. This frequency spectrum supports a diverse range of services, encompassing Long-Term Evolution (LTE), WiMAX, Wireless Local Area Networks (WLAN), fifth-generation (5G) communication systems, Bluetooth, and a wide range of Internet of Things (IoT) applications. In addition to the sub-6 GHz region, selected operating bands extend beyond 6 GHz, allowing the proposed antenna designs to support emerging wireless services as well as selected satellite communication applications. Table 1.2 summarizes the principal frequency bands considered in this research and their associated applications.

Table 1.2 Frequency Bands and Target Applications Relevant to the Proposed Antenna Systems

Frequency Band	Standard/Application	Typical Use
2.4 GHz	Bluetooth, ZigBee, WLAN	IoT and short-range communication
3.0–4.0 GHz	LTE, WiMAX, 5G Sub-6 GHz	Mobile broadband communication
5.0–5.8 GHz	WLAN (IEEE 802.11a/ac/ax)	High-speed wireless networking
5.9–7.1 GHz	Wi-Fi 6E / Wi-Fi 7	Next-generation wireless access
6.7–8.4 GHz	C-Band and X-Band Applications	Satellite communication and radar systems

Figure 1.6 provides an overview of the frequency bands considered in this research together with their corresponding wireless communication applications and the operating frequencies achieved by the proposed antenna designs. It summarizes the major wireless communication

bands extending from the 2.4 GHz Industrial, Scientific, and Medical (ISM) band to the C-band and X-band regions, while also indicating the resonant frequencies obtained from the antenna configurations presented in Chapters 3, 4, and 5.

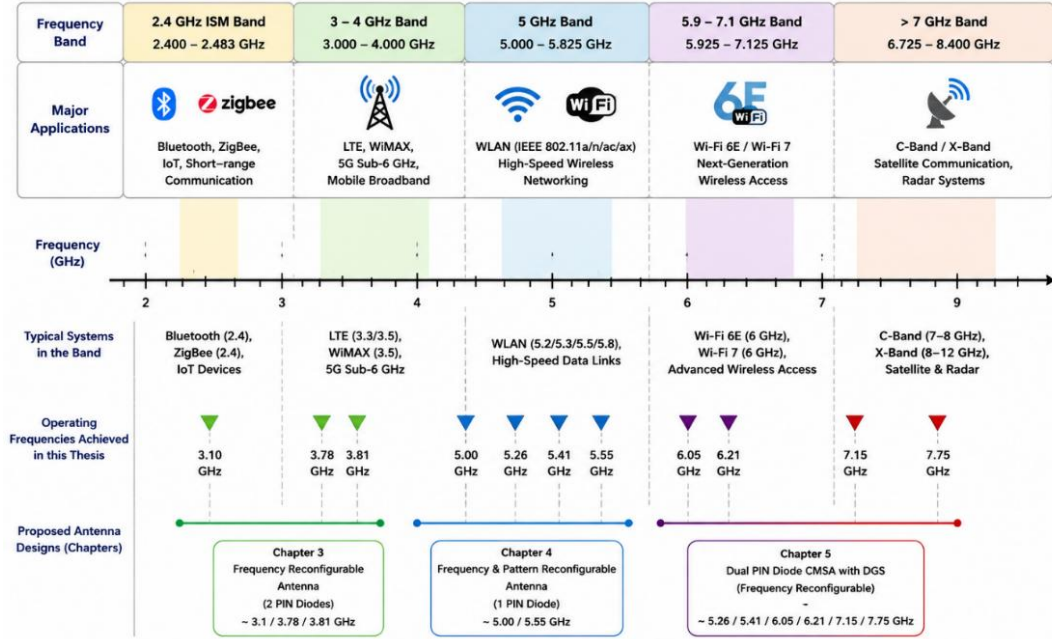


Figure 1.3 Frequency Bands and Target Applications

Figure 1.3 presents an overview of the wireless communication bands addressed in this research together with the operating frequencies achieved by the proposed reconfigurable antenna designs. The developed antennas cover important wireless frequency regions, including the sub-6 GHz spectrum, WLAN bands, emerging 6 GHz wireless access bands, and selected higher-frequency bands associated with advanced wireless and satellite communication. This wide operating range demonstrates the capability of the proposed antenna architectures to support multiple wireless standards through frequency reconfiguration.

The sub-6 GHz spectrum remains fundamental to modern wireless communication, supporting technologies such as LTE, WiMAX, 5G, WLAN, Bluetooth, and numerous Internet of Things (IoT) applications. Recent wireless standards, including Wi-Fi 6E and Wi-Fi 7, have further extended operation into the 6 GHz band to satisfy increasing bandwidth and network capacity requirements.

The proposed antenna designs achieve multi-band operation through PIN diode-based reconfiguration, enabling a single radiating structure to operate across different frequency bands. This approach reduces hardware complexity while improving spectrum utilization and maintaining compact antenna dimensions, making the developed antennas suitable for modern multi-standard wireless communication systems.

1.8 Scope & Objectives of Thesis

1.8.1 Scope of the thesis

The present research is aimed at the design, development, and performance evaluation of compact reconfigurable microstrip antenna systems capable of supporting multiple wireless communication standards through dynamic modification of antenna characteristics. The work covers theoretical investigation, electromagnetic simulation, design optimization, fabrication, and experimental validation of frequency and radiation pattern reconfigurable antennas employing PIN diode-based switching techniques.

The scope of this research includes:

- Investigation of reconfigurable antenna technologies and switching mechanisms applicable to modern wireless communication systems.
- Design and development of compact frequency reconfigurable microstrip antennas capable of supporting multiple communication bands through PIN diode switching.
- Development of frequency and radiation pattern reconfigurable antenna configurations with reduced switching complexity and improved operational flexibility.
- Design and analysis of advanced reconfigurable antenna structures incorporating multiple switching elements and defected ground structures (DGS) to enhance frequency agility and multi-band performance.
- Performance evaluation of the proposed antennas through electromagnetic simulation and measurement of reflection coefficient (S_{11}), impedance bandwidth, gain, radiation pattern, and surface current distribution.
- Fabrication and experimental validation of selected antenna prototypes using a Vector Network Analyzer (VNA) and anechoic chamber measurement facilities.

- Comparative evaluation of the proposed antenna designs with existing reconfigurable antennas reported in the literature.

1.8.2 Objectives of the Thesis

The research presented in this thesis has the following objectives:

1. To investigate the operating principles, classification, switching mechanisms, and recent developments in reconfigurable antenna technology for modern wireless communication systems.
2. To design and develop compact frequency reconfigurable microstrip antennas capable of supporting multiple wireless communication bands using PIN diode-based switching.
3. To investigate frequency and radiation pattern reconfiguration techniques and implement them in compact antenna structures with reduced switching complexity.
4. To develop advanced reconfigurable antenna configurations incorporating multiple switching elements and defected ground structures (DGS) for enhanced frequency agility and multi-band operation.
5. To analyze and optimize the proposed antenna designs in terms of return loss (S_{11}), operating bandwidth, gain, and radiation pattern characteristics, along with current density distribution across the surface under different switching conditions.
6. To fabricate, experimentally validate, and compare the proposed antenna configurations with existing reconfigurable antennas reported in the literature in order to evaluate their suitability for LTE, WLAN, WiMAX, 5G Sub-6 GHz, IoT, and related wireless communication applications.

1.9 Summary of contributions

This research advances the ongoing development of reconfigurable antenna technology through the design, analysis, fabrication, and experimental validation of compact microstrip antennas capable of supporting multiple wireless communication bands. The proposed antenna configurations employ PIN diode-based switching to achieve frequency and radiation pattern reconfiguration while maintaining compact size and low implementation complexity. The major outcomes of this proposed research are outlined below.

1. **Development of a Compact Frequency Reconfigurable Antenna:** A compact microstrip antenna employing PIN diode switching has been designed to achieve multi-band operation by modifying the effective current path within a common radiating structure.
2. **Design of a Frequency and Pattern Reconfigurable Antenna with Reduced Switching Complexity:** A compact antenna utilizing a single SMP1345-079LF PIN diode has been developed to achieve both frequency and radiation pattern reconfiguration, providing multiple operating states with reduced switching complexity.
3. **Development of a Dual PIN Diode Circular Microstrip Reconfigurable Antenna:** A circular microstrip antenna incorporating two PIN diodes and a defected ground structure (DGS) has been proposed to enhance frequency reconfiguration capability and support multiple wireless communication bands.
4. **Comprehensive Electromagnetic Performance Analysis:** The proposed antenna configurations have been evaluated through detailed analysis of reflection coefficient (S_{11}), impedance bandwidth, gain, radiation characteristics, and current density distribution across the surface under different switching conditions.
5. **Fabrication and Experimental Validation:** Representative antenna prototypes were fabricated and experimentally evaluated through Vector Network Analyzer (VNA) testing and anechoic chamber measurements. The obtained results exhibit close correlation with simulated data, thereby validating the practical viability of the proposed designs.
6. **Performance Comparison with Existing Reconfigurable Antennas:** The antenna configurations are benchmarked against existing state-of-the-art reconfigurable antennas in terms of antenna size, operating bands, switching complexity, gain, and reconfiguration capability. The comparison demonstrates that the proposed antennas provide a balanced combination of compactness, multifunctionality, and implementation simplicity for modern wireless communication systems.

1.10 Organization of Thesis

The thesis is structured into six chapters that together outline the theoretical foundation, design approach, implementation, and experimental validation of the proposed reconfigurable microstrip antenna systems.

Chapter 1 introduces reconfigurable antenna technology and presents the research background, motivation, classification, switching mechanisms, target frequency bands, scope, objectives, research contributions, and the overall organization of the thesis.

Chapter 2 reviews frequency-, pattern-, polarization-, and hybrid-reconfigurable antennas, along with switching mechanisms such as PIN diodes, varactor diodes, RF-MEMS, and tunable materials, culminating in the identification of research gaps motivating this work.

Chapter 3 presents the structural design and performance analysis of a miniaturized frequency reconfigurable patch antenna, including the antenna configuration, switching mechanism, simulated performance, surface current analysis, and comparison with reported designs.

Chapter 4 details the structural development, fabrication process, and experimental verification of a miniaturized antenna offering both frequency and radiation pattern reconfigurability through a single PIN diode. Simulated and measured outcomes are examined to substantiate the proposed configuration.

Chapter 5 discusses the development of a dual PIN diode circular microstrip antenna incorporating a defected ground structure (DGS). The chapter presents the antenna evolution, operating mechanism, fabricated prototype, experimental validation, and comparative performance evaluation.

Chapter 6 presents the conclusions of the research and summarizes the major contributions of the developed reconfigurable antenna designs. The chapter discusses the significance of the research outcomes, highlights the applicability of the developed antennas for modern wireless communication systems, and outlines potential directions for future research in reconfigurable antenna technology.

The organization of the thesis provides a logical progression from the theoretical concepts of reconfigurable antennas to the design, implementation, experimental validation, and performance evaluation of the proposed antenna systems.

CHAPTER-2

Literature Review

The rapid evolution of wireless communication systems has stimulated extensive research in reconfigurable antenna technologies capable of supporting multiple communication standards using a single radiating structure. Numerous antenna configurations employing different switching mechanisms, tuning approaches, and reconfiguration techniques have been reported to achieve frequency agility, radiation pattern control, polarization diversity, and multifunction operation. This chapter offers a structured survey of the pertinent literature, focusing particularly on frequency, pattern, and hybrid reconfigurable antenna configurations. The reported works are critically analyzed based on antenna size, switching technology, number of switching elements, frequency reconfiguration capability, radiation characteristics, and implementation complexity. Comparative studies are carried out to identify prevailing design trends and limitations in existing antenna architectures. The observations derived from this review provide the technical motivation for the compact PIN-diode-based reconfigurable antennas developed in Chapters 3, 4, and 5 of this thesis.

2.1 Overview of Reconfigurable Antenna Research

The increasing demand for high-speed wireless connectivity and seamless integration of multiple communication standards has significantly influenced the design requirements of modern antenna systems. Contemporary wireless devices are expected to support a wide range of services including LTE, WLAN, WiMAX, Bluetooth, IoT, satellite communications, and emerging 5G networks while maintaining compact dimensions and low hardware complexity [2]. Conventional fixed-frequency antennas often require multiple radiating elements to accommodate different operating bands, resulting in increased antenna aperture requirements, higher fabrication costs, and inefficient utilization of available space within portable wireless terminals [[14].

To address these challenges, reconfigurable antennas electronically regulate selected electromagnetic properties, allowing a single antenna to seamlessly adapt to diverse wireless communication needs. By incorporating controllable switching elements or tunable components, a single antenna structure can operate over multiple frequency bands, alter its

radiation pattern, or modify its polarization characteristics without requiring physical replacement of the radiating element [2]. Such adaptability enhances spectrum utilization, improves system flexibility, and reduces the need for multiple dedicated antennas in modern communication platforms [15].

Over the preceding decade, considerable research initiatives have been undertaken toward the development of reconfigurable antennas employing various switching technologies such as PIN diodes, varactor diodes, RF-MEMS devices, and optical switching mechanisms [2]. Among these technologies, PIN diodes have gained widespread acceptance owing to their rapid switching response, cost-effectiveness, compact size, and ease of integration within planar antenna structures [16]. Accordingly, continuous advances in antenna reconfiguration have resulted in diverse frequency reconfigurable antenna designs supporting LTE, WLAN, WiMAX, cognitive radio, and 5G communication technologies [17].

A review of the published literature reveals that frequency reconfiguration remains the most extensively investigated category due to the growing requirement for multi-band wireless operation [9], [20]. Researchers have proposed numerous approaches involving slot loading, current path modification, parasitic elements, and reactive loading techniques to achieve frequency agility with varying levels of complexity and performance [21]. In parallel, radiation pattern reconfigurable antennas have also attracted attention for applications requiring adaptive coverage, beam steering, interference mitigation, and improved link reliability [22]. More recently, hybrid reconfigurable antennas capable of simultaneously modifying both operating frequency and radiation characteristics have emerged as an active area of research due to their enhanced functionality and adaptability [23], [24].

Despite substantial advancements, several challenges remain evident in the existing literature. Many reported designs achieve enhanced reconfigurability at the expense of increased switching complexity, larger antenna dimensions, or complicated biasing networks [16], [25]. Furthermore, antennas capable of providing multiple frequency states often require numerous switching elements, while hybrid reconfigurable designs frequently introduce additional structural complexity [26], [24]. Therefore, a systematic comparative review of reported antenna configurations is necessary to evaluate their performance, identify common design limitations, and establish the motivation for compact reconfigurable antenna structures employing a minimum number of switching elements.

Accordingly, this chapter presents a comprehensive review and critical analysis of reported reconfigurable antenna designs. To facilitate systematic discussion, the published research is arranged based on the reconfiguration approach adopted, covering frequency-, radiation pattern-, and hybrid-reconfigurable antenna systems. Comparative assessments are subsequently performed to evaluate antenna dimensions, switching technologies, frequency agility, radiation characteristics, and implementation complexity. The insights obtained from this review form the basis for the antenna designs proposed in the subsequent chapters of this thesis.

2.2 Literature Categorization

A systematic review of the available literature reveals that reconfigurable antenna research has evolved significantly in response to the increasing demand for compact, multifunctional, and adaptive wireless communication systems. Over the preceding decade, researchers have proposed numerous antenna configurations employing different radiating structures, switching mechanisms, and tuning approaches to achieve improved frequency agility, radiation control, and operational flexibility [2]. However, the reported antenna designs differ considerably in terms of reconfiguration capability, antenna size, switching complexity, achievable frequency states, and implementation methodology [14], [15].

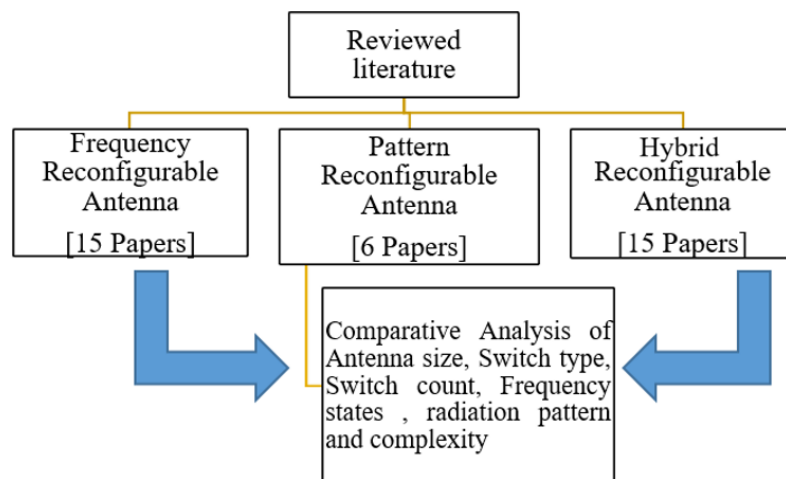


Figure 2.1 Categorization of Reconfigurable Antenna Literature Reviewed in this Thesis

As shown in Figure 2.1, the reviewed literature has been categorized into frequency reconfigurable, radiation pattern reconfigurable, and hybrid reconfigurable antenna designs.

This classification facilitates systematic comparison of reported antenna structures with respect to frequency agility, radiation characteristics, switching complexity, and practical implementation aspects. Frequency reconfigurable antennas constitute the largest category and focus on modifying the operating frequency bands through changes in the effective electrical length, current distribution, or reactive loading conditions [16], [19]. The antennas which reconfigure the radiation pattern primarily aim to alter the spatial distribution of radiated power to achieve beam switching, beam steering, or directional coverage enhancement [22]. Hybrid reconfigurable antennas combine multiple reconfiguration functionalities within a single structure, most commonly frequency and radiation pattern reconfiguration, thereby improving operational adaptability and spectrum utilization [23], [24].

An analysis of the reviewed literature further indicates that PIN diode switching remains the most widely adopted technique due to its low cost, high switching speed, ease of integration, and suitability for compact planar antenna structures [16], [17]. In contrast, varactor-based approaches provide continuous frequency tuning but often introduce additional biasing and design complexity [21], [27]. Furthermore, recent studies have shown increasing interest in compact antenna architectures capable of achieving multiple frequency states with a reduced number of switching elements while maintaining acceptable radiation performance [18], [20].

Based on these observations, the subsequent sections present a detailed review and comparative analysis of the reported frequency reconfigurable, radiation pattern reconfigurable, and hybrid antenna designs. Particular emphasis is placed on antenna compactness, number of switching elements, achievable frequency states, reconfiguration capability, and practical implementation aspects, as these parameters are directly relevant to the antenna designs developed in this research.

2.3 Antennas with Frequency Reconfiguration

Frequency reconfigurable antennas represent the most extensively investigated category of reconfigurable antenna systems due to their capability of supporting diverse communication protocols within a unified radiating structure. By dynamically modifying the effective electrical length, current distribution, or reactive loading conditions of the antenna,

frequency reconfigurable designs can operate over different frequency bands without requiring multiple dedicated antennas. Such capability is particularly attractive for modern wireless devices that are expected to simultaneously support LTE, WLAN, WiMAX, Bluetooth, IoT, cognitive radio, and 5G communication services [18], [19].

Several approaches have been proposed in the literature to achieve frequency reconfiguration, including PIN diode switching, varactor diode tuning, RF-MEMS devices, and tunable materials. Among these approaches, PIN diode switching remains the most widely adopted technique due to its cost effectiveness, rapid switching response, ease of integration, and suitability for compact planar antenna structures [16]. Alternatively, varactor-based antennas provide continuous frequency tuning by varying the effective capacitance of the radiating structure, although this often introduces additional biasing and design complexity [21], [27].

A review of the published literature indicates that researchers have primarily focused on achieving wider tuning ranges, increasing the number of frequency states, reducing antenna size, and minimizing the number of switching elements while maintaining acceptable radiation performance [9], [19]. However, these objectives often involve significant trade-offs among antenna compactness, switching complexity, gain stability, and fabrication requirements [16], [20]. Consequently, frequency reconfigurable antenna design continues to remain an active area of research for modern wireless communication systems.

To facilitate systematic analysis, the reported frequency reconfigurable antenna designs reviewed in this thesis are categorized into PIN diode based and varactor diode based configurations. The operating principles, design approaches, performance characteristics, and limitations of these antennas are discussed in the following subsections.

2.3.1 PIN Diode Based Frequency Reconfigurable Antennas

Owing to their low cost, fast switching response, and compact, planar-compatible form, PIN diodes are widely preferred for frequency reconfigurable antenna design. Acting as an RF switch, the diode modifies the effective current path of the radiating element, thereby shifting the antenna's resonant frequency. Consequently, PIN diode based reconfigurable antennas have attracted considerable attention for applications involving LTE, WLAN, WiMAX, 5G, cognitive radio, and portable wireless communication systems [16], [17].

Several researchers have employed slot modification and current path reconfiguration techniques to achieve frequency agility using a limited number of switching elements. For sub-6 GHz wireless systems, Mudda *et al.* [1] introduced a compact antenna whose operating frequency was electronically controlled through PIN diode switching that altered the current path within the radiating element. Similarly, Fertas *et al.* [28] developed a compact slot antenna capable of operating across multiple wireless communication bands through the selective activation of switching elements. Singh *et al.* [16] reported a multiband antenna for IoT applications employing three PIN diodes to achieve multiple operating states covering WLAN, WiMAX, and C-band frequencies. Bharadwaj *et al.* [9] presented a compact tri-band antenna utilizing two PIN diodes to switch among LTE, Wi-Fi, and intelligent transportation system (ITS) bands.

Compact and frequency-agile antenna designs continue to attract significant research interest. Chaouche *et al.* [11] presented a compact dual-band radiator that attained frequency reconfigurability through a single PIN diode, demonstrating efficient multi-band operation with low switching complexity. Jin *et al.* [18] introduced a differentially fed patch antenna supporting frequency reconfiguration for WLAN and sub-6 GHz 5G systems, where multiple PIN diodes were incorporated to electronically tune the resonant response. In another study, Ojaroudi Parchin *et al.* [13] developed a reconfigurable antenna array for millimeter-wave (mm-wave) 5G handsets, highlighting the effectiveness of switch-controlled frequency reconfiguration for advanced wireless communication applications.

Recent studies have increasingly focused on maximizing the number of achievable frequency states while maintaining compact antenna dimensions. Shah *et al.* [17] proposed a compact hexa-band frequency reconfigurable antenna capable of supporting multiple wireless communication services using PIN diode switching. Similarly, Awan *et al.* [19] developed a miniaturized wideband and multiband reconfigurable antenna for portable devices, demonstrating enhanced frequency agility within a compact footprint. A frequency reconfigurable antenna reported in [20] achieved triple-band operation through strategic placement of switching elements and optimization of current distribution paths. These studies indicate a growing trend toward obtaining a larger number of operating bands without substantially increasing antenna size or switching complexity.

A comparative examination of the reported designs reveals that PIN diode based reconfigurable antennas offer several practical advantages including simple biasing

requirements, low implementation cost, rapid electronic switching, and excellent compatibility with planar antenna platforms. However, the number of achievable frequency states is often closely related to the number of switching elements incorporated within the antenna structure. While increasing the number of PIN diodes generally enhances frequency agility, it may also increase biasing complexity, insertion losses, and design intricacy [16], [18], [19]. Consequently, achieving multiple operating frequency states using a minimum number of switching elements remains an important design consideration in the development of compact reconfigurable antennas.

The performance characteristics of representative PIN diode based frequency reconfigurable antennas reported in the literature are summarized in Table 2.1.

Table 2.1 Comparison of Frequency Reconfigurable Antennas Reported in Literature

Ref.	Switch Type	No. of Switches	Frequency States	Frequency Range (GHz)	Key Feature
[1]	PIN Diode	2	6	2.3–8.9	Wide tuning range
[28]	Metal Switch	3	4	2.37–8.31	Multi-band operation
[16]	PIN Diode	3	5	3.85–6.01	Compact IoT antenna
[9]	PIN Diode	2	3	3.8–5.9	Low switch count
[5]	PIN Diode	2	4 Modes	3.1–10.6	UWB reconfiguration
[11]	PIN Diode	1	2	3.2–5.8	Simple implementation
[18]	PIN Diode	4	2	2.45 / 3.50	Stable radiation characteristics
[13]	PIN Diode	2 per element	2	28 / 38	5G mmWave operation
[41]	PIN Diode	Multiple	2	28 / 38	Beam-steerable array
[17]	PIN Diode	3	6	2.1–5.2	Hexa-band operation
[19]	PIN Diode	2	8 + Wideband	2.45–6.2	High frequency agility
[21]	Varactor	2	Continuous	2.45–3.55	Continuous tuning
[20]	Lumped Switch	1	3	2.45 / 3.5 / 5.2	Portable wireless devices

The comparative analysis presented in Table 2.1 indicates that PIN diode switching remains the preferred approach for frequency reconfiguration because it combines low implementation cost, rapid electronic switching, and excellent compatibility with planar antenna platforms. It can be observed that most reported antennas achieve frequency agility by modifying the effective current path length through selective activation of switching elements. Although several designs demonstrate multiple operating frequency states, an

increase in the number of switching elements generally results in greater biasing complexity and implementation challenges [16], [18], [17]. Furthermore, while antennas reported in [1], and [19] provide a relatively large number of operating bands, most existing designs focus exclusively on frequency reconfiguration without incorporating radiation pattern adaptability. It is also evident that only a limited number of reported antennas simultaneously achieve compact dimensions, low switch count, and enhanced frequency agility. Therefore, the development of compact reconfigurable antennas capable of providing multiple operating bands using a minimum number of switching elements continues to remain an important research objective for modern wireless communication systems.

2.3.2 Varactor Diode Based Frequency Reconfigurable Antennas

Varactor diodes represent one of the most widely adopted tuning elements for achieving continuous frequency reconfiguration in modern antenna systems. Unlike PIN diodes, which operate as discrete RF switches providing predefined operating states, varactor diodes function as voltage-controlled capacitive elements whose capacitance varies with the applied reverse bias voltage. By altering the effective reactance of the radiating structure, varactor loading enables continuous adjustment of the antenna resonance frequency over a specified tuning range [21], [14]. This characteristic makes varactor-based antennas particularly attractive for cognitive radio, adaptive wireless communication, and spectrum sensing applications where continuous frequency agility is desired.

Several researchers have investigated the use of varactor-loaded antenna structures to achieve wideband frequency tuning while maintaining acceptable radiation performance. Hussain et al. [31] proposed a frequency-agile MIMO antenna system in which annular slot antennas integrated within the ground plane were tuned using varactor diodes. The reported antenna achieved continuous frequency variation from 1.73 GHz to 2.28 GHz while maintaining compact dimensions suitable for cognitive radio applications. The same authors later extended this concept by developing a quad-element frequency-tunable MIMO antenna system integrated with an ultra-wideband sensing antenna, where a single varactor diode was employed in each radiating element to realize continuous tuning from 1.77 GHz to 2.51 GHz [16]. These studies demonstrated the suitability of varactor-based tuning for adaptive wireless platforms requiring dynamic spectrum access and frequency flexibility.

Among the reported designs, the low-profile grid-slotted patch antenna presented in [21] provides an effective example of continuous frequency reconfiguration in a planar antenna structure. The antenna employs two varactor diodes integrated within a grid-slotted patch configuration, enabling continuous tuning of the operation frequency from 2.45 GHz to 3.55 GHz through variation of a single bias voltage. The reported design maintains stable broadside radiation characteristics throughout the tuning range while exhibiting gains between 4.25 dBi and 8.49 dBi, broadening its applicability to cognitive radio networks and emerging multi-service wireless communication platforms [21]. Furthermore, the use of only two tuning elements and a simple biasing network demonstrates the practicality of varactor-based frequency control in compact antenna structures.

Despite their attractive frequency-agile characteristics, varactor-based antennas introduce several design challenges. The continuous tuning capability is achieved at the expense of increased biasing complexity, nonlinear capacitance variation, and sensitivity to component tolerances [15], [21]. In addition, the tuning range is often constrained by the achievable capacitance ratio of commercially available varactor diodes, while losses associated with the tuning elements may affect antenna efficiency and gain performance. Consequently, although varactor diodes provide superior frequency agility compared to switch-based approaches, their practical implementation often requires careful optimization of the biasing circuitry and tuning network.

Overall, the reviewed literature indicates that varactor-based frequency reconfigurable antennas are well suited for applications requiring continuous tuning over a specified frequency range. However, for practical multiband wireless communication systems where discrete operating bands are sufficient, PIN diode based reconfiguration remains an attractive alternative due to its simpler biasing requirements, lower implementation complexity, and ease of integration within compact planar antenna structures [14], [15].

The literature reviewed in Sections 2.3.1 and 2.3.2 demonstrates that both PIN diode and varactor diode technologies are capable of providing effective frequency reconfiguration. While PIN diode based antennas predominantly offer discrete multiband operation, varactor-loaded structures enable continuous frequency tuning over a specified range. A comparative analysis of these approaches indicates that antenna performance is often governed by trade-offs among frequency agility, switching complexity, biasing requirements, and implementation cost. These observations motivate further investigation of other forms of

antenna reconfiguration, particularly radiation pattern control, which is discussed in the following section.

2.4 Antennas with Radiation Pattern Reconfiguration

Radiation pattern control represents an important capability of reconfigurable antenna technology for improving wireless link performance under varying propagation conditions. In contrast to frequency-reconfigurable antennas, which alter the resonant operating band, pattern-reconfigurable antennas electronically redistribute the radiated electromagnetic field while preserving operation within the same frequency range. This capability enables beam switching, beam steering, interference mitigation, spatial diversity enhancement, and improved link reliability without requiring multiple antenna elements or mechanically controlled structures [8], [14].

The operating principle of radiation pattern reconfiguration is primarily based on controlling the surface current distribution within the radiating structure or its associated parasitic elements. By selectively activating switching devices such as PIN diodes, RF-MEMS switches, or varactor diodes, the antenna can alter the phase and amplitude distribution of the radiated fields, resulting in different radiation directions and beam configurations [15]. Consequently, pattern reconfigurable antennas have found increasing applications in WLAN, WiMAX, intelligent transportation systems, wireless sensor networks, MIMO communication systems, and emerging adaptive wireless platforms.

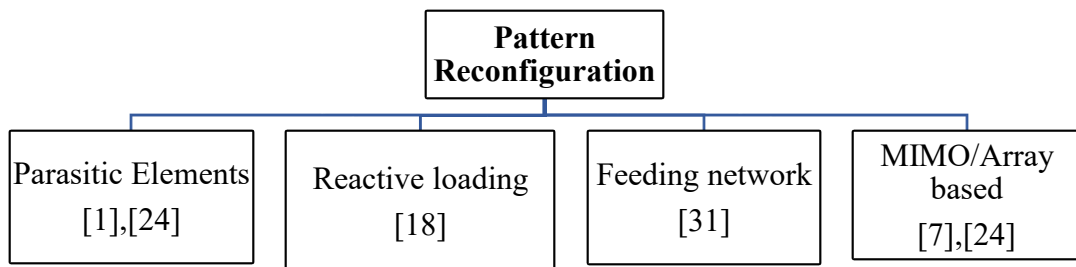


Figure 2.2 Classification of Radiation Pattern Reconfiguration Techniques Reported in Literature

One of the widely adopted approaches for pattern reconfiguration involves the use of switchable parasitic elements. Rahmani et al. [8] proposed a broadband beam-switching

microstrip antenna array employing two PIN diodes to control the radiation characteristics of parasitic radiating elements. The antenna achieved three distinct radiation states with beam tilting ranging from $\pm 30^\circ$ to $\pm 38^\circ$ while maintaining a wide operating bandwidth between 5 GHz and 6 GHz. The reported design demonstrated that simple switching arrangements can effectively steer the main radiation beam while preserving good gain and radiation efficiency.

Another important direction in pattern reconfiguration focuses on achieving multiple radiation states with enhanced directivity and front-to-back ratio. Huang and Bu [22] developed an electrically small pattern reconfigurable antenna employing six PIN diodes integrated within a dual-side printed loop structure. The proposed design generated six switchable end-fire radiation patterns spanning the full 360° azimuthal plane while maintaining a high front-to-back ratio of 35.6 dB and radiation efficiency exceeding 77%. The work demonstrated that compact antenna structures can provide extensive beam-switching capability without significantly increasing physical dimensions.

Pattern reconfiguration has also been achieved through continuously tunable reactive loading. Tian et al. [29] proposed a compact single-element beam steering antenna controlled by a single varactor diode integrated within a ground-slot structure. By varying the capacitance of the varactor, continuous beam steering from -34° to $+32^\circ$ was achieved without requiring antenna arrays or multiple switching components. The reported design highlighted the capability of reactive tuning elements to provide smooth beam control while preserving compact antenna dimensions.

In recent years, pattern reconfigurable techniques have been extended to multiple-input multiple-output systems. Han et al. [30] reported a low-profile pattern reconfigurable MIMO antenna employing parasitic strips loaded with PIN diodes. Through selective activation of the switching elements, the antenna provided nine radiation pattern configurations while maintaining adequate isolation and diversity performance. The reported design demonstrated the suitability of pattern reconfiguration for improving channel capacity and spatial diversity in compact wireless terminals.

An alternative approach was presented by Ke et al. [26], where pattern reconfiguration was achieved through a switchable feeding network rather than modification of the radiating structure itself. A compact dual-balun feeding configuration incorporating PIN diodes

enabled bidirectional and directional end-fire radiation modes while minimizing the impact on antenna geometry. The work demonstrated that feeding-network-based reconfiguration can provide effective pattern control with reduced structural complexity.

The reviewed literature indicates that radiation pattern reconfiguration can be realized through several techniques, including switchable parasitic elements, reactive loading, antenna arrays, MIMO architectures, and reconfigurable feeding networks. Although significant progress has been achieved, most reported designs focus exclusively on radiation pattern control while maintaining fixed operating frequency characteristics. Furthermore, several antennas require multiple switching elements, complex feeding structures, or large physical dimensions to achieve extensive beam-steering capability [30]. These observations suggest that integrating frequency agility and radiation pattern adaptability within a compact antenna structure remains an important research direction for future wireless communication systems.

Table 2.2 Comparison of Radiation Pattern Reconfigurable Antennas Reported in Literature

Ref.	Reconfiguration Technique	Switching Element	No. of Switching Elements	Radiation States	Key Feature
[8]	Switchable parasitic patches	PIN Diode	2	3	Beam steering from $\pm 30^\circ$ to $\pm 38^\circ$ with high gain
[22]	Dual-side printed loop with switchable dipoles	PIN Diode	6	6	360° azimuth coverage with high F/B ratio
[29]	Reactive loading of ground slot	Varactor Diode	1	Continuous beam steering	Single-element beam scanning from -34° to $+32^\circ$
[30]	Parasitic strip loading in MIMO antenna	PIN Diode	4 per element	9 configurations	Pattern diversity for MIMO systems
[26]	Reconfigurable feeding network	PIN Diode	2	3	Compact end-fire pattern reconfiguration

The comparative analysis presented in Table 2.2 reveals that PIN diode switching remains the dominant technique for radiation pattern reconfiguration owing to its simplicity, low cost, and fast switching capability. Most reported designs achieve beam switching through

the use of parasitic elements whose electrical behavior changes according to the switching state of the embedded diodes [8], [30]. Although several antennas provide multiple radiation states and wide angular coverage, these improvements are generally accompanied by an increase in the number of switching elements and biasing complexity [22]. Alternatively, reactive loading techniques employing varactor diodes can achieve continuous beam steering with a reduced number of tuning elements; however, they require more complex bias control circuitry and careful tuning optimization [29].

It is further observed that the majority of reported antennas are designed primarily for radiation pattern control while operating at a fixed frequency band. Consequently, frequency agility and radiation pattern adaptability are rarely integrated within a single compact antenna structure. These limitations have motivated recent research efforts toward hybrid reconfigurable antennas capable of simultaneously providing frequency and radiation pattern reconfiguration. Such antenna systems are reviewed in the following section.

2.5 Antennas with Hybrid Reconfiguration

Recent advances in wireless communication systems have increased the demand for antenna structures capable of simultaneously adapting multiple electromagnetic characteristics according to changing operational requirements. While frequency reconfigurable antennas provide operating band flexibility and pattern reconfigurable antennas offer spatial coverage adaptability, modern wireless platforms increasingly require both functionalities within a single compact antenna structure. This requirement has led to the development of hybrid reconfigurable antennas capable of simultaneously modifying frequency response and radiation characteristics, thereby enhancing spectrum utilization, communication reliability, and system flexibility [14], [15].

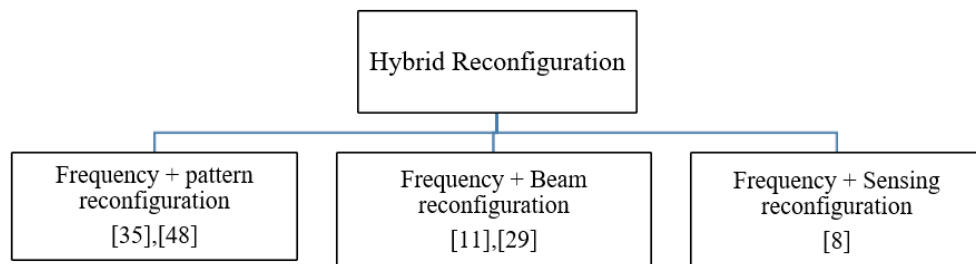


Figure 2.3 Classification of Hybrid Reconfiguration Approaches Reported in Literature

Hybrid reconfiguration is generally achieved by modifying the current density distribution over surface of the radiating structure through the use of controllable switching elements, tunable reactive components, parasitic radiators, or reconfigurable feeding networks. Depending on the switching configuration, these antennas can alter both the resonant frequency and radiation pattern while maintaining compact dimensions and low implementation complexity. Such capabilities are particularly attractive for cognitive radio systems, adaptive wireless terminals, MIMO communication platforms, and future multi-standard communication devices.

One of the notable compact hybrid antenna configurations was reported by Thanki and Raval [24], who proposed an I-shaped antenna with frequency as well as pattern reconfigurability employing a single PIN diode operating at two distinct frequency bands of 3.5 GHz and 5.2 GHz while simultaneously achieving radiation pattern switching from approximately -170° to $+160^\circ$ in the yz-plane. The design occupied only $25 \times 15 \text{ mm}^2$ and demonstrated the feasibility of achieving dual reconfiguration characteristics using minimal switching hardware.

Palsokar and Lahudkar [25] introduced a compact microstrip patch antenna that achieved both frequency and radiation pattern reconfiguration using only one PIN diode. The proposed design operated at 2.47 GHz, 3.8 GHz, and 5.36 GHz, with different switching states producing distinct radiation characteristics. By requiring only a single switching device, the antenna simplified the biasing network while reducing the influence of the control circuitry on overall antenna performance.

Hybrid reconfiguration has also been explored in advanced communication architectures. Jehangir et al. [32] proposed a frequency reconfigurable Yagi-like MIMO antenna system employing varactor diodes to achieve continuous tuning between 2.5 GHz and 4.5 GHz while maintaining directional radiation characteristics through a complementary wideband reflector. The reported design demonstrated the potential of integrating frequency agility with directional communication capabilities in compact MIMO platforms.

More sophisticated reconfiguration schemes have been investigated for next-generation communication systems. Nissanov and Singh [23] reported an ultra-wideband mmWave/THz antenna capable of simultaneous frequency, bandwidth, and beam

reconfiguration using two PIN diodes integrated within a novel microstrip structure. The proposed antenna operated over 100–302.85 GHz and illustrated the growing interest in multifunctional reconfigurable antennas for beyond-5G and future wireless networks.

In addition, Zhao et al. [12] developed a cognitive-radio-oriented reconfigurable MIMO antenna employing a hybrid arrangement of PIN and varactor diode to achieve frequency agility together with spectrum sensing capability. The antenna provided wide tuning flexibility while supporting MIMO operation within a compact planar configuration.

The reviewed literature clearly indicates that hybrid reconfigurable antennas offer superior operational flexibility compared with single-parameter reconfigurable designs. However, achieving simultaneous frequency and radiation pattern reconfiguration often requires additional switching elements, complex biasing circuits, larger antenna dimensions, or sophisticated optimization procedures. Furthermore, only a limited number of reported antennas successfully achieve compact size, multiple operating states, and low switch count simultaneously. Consequently, the development of compact hybrid reconfigurable antennas capable of providing enhanced frequency agility and radiation pattern adaptability using a minimum number of switching elements remains an active and important research area.

Table 2.3 Comparison of Hybrid Reconfigurable Antennas Reported in Literature

Ref.	Switching Technique	No. of Switching Elements	Frequency Reconfiguration	Pattern Reconfiguration	Key Feature
[12]	PIN + Varactor Diodes	6 PIN + 2 Varactor	0.9–2.6 GHz tuning with UWB sensing mode	Multiple operational modes	Cognitive radio MIMO platform
[23]	PIN Diodes	2	Frequency and bandwidth reconfiguration (100–302.85 GHz)	Beam reconfiguration	Multifunction mmWave/THz antenna
[32]	Varactor Diodes	2	Continuous tuning from 2.5–4.5 GHz	Directional radiation characteristics	Yagi-like MIMO antenna system
[25]	Single PIN Diode	1	2.47, 3.8 and 5.36 GHz	Radiation pattern switching	Low-complexity rectangular patch antenna
[24]	Single PIN Diode	1	3.5 GHz and 5.2 GHz	Bidirectional pattern reconfiguration	Compact I-shaped antenna with minimal switching hardware

The comparative analysis presented in Table 2.3 highlights the growing research interest in hybrid reconfigurable antenna systems capable of simultaneously modifying multiple radiation characteristics. It can be observed that hybrid reconfiguration generally requires a greater degree of design complexity than single-parameter reconfiguration due to the need to control both resonance behavior and radiation characteristics using the same antenna structure. Consequently, many reported designs employ multiple switching elements, tunable components, or sophisticated biasing networks to achieve the desired functionality [12], [23].

A significant observation from Table 2.3 is that only a limited number of reported antennas achieve both frequency and radiation pattern reconfiguration using a minimal number of switching elements. In particular, the antennas reported in [24] and [25] demonstrate that meaningful hybrid reconfiguration can be achieved using a single PIN diode, thereby reducing biasing complexity and implementation cost. However, these designs provide a relatively limited number of operating states and frequency bands compared with more complex architectures. Furthermore, several hybrid antennas reported in the literature are developed for specialized applications such as cognitive radio systems, MIMO communication platforms, or millimeter-wave networks, which may limit their applicability to compact multi-standard wireless terminals [12], [23], [32].

Overall, the reviewed literature indicates that achieving compact size, enhanced frequency agility, radiation pattern adaptability, and low switching complexity within a single antenna structure remains a challenging design objective. These observations provide strong motivation for the development of compact reconfigurable antennas employing a minimum number of PIN diodes while supporting multiple frequency bands and adaptive radiation characteristics, which constitute the primary focus of the work presented in the subsequent chapters of this thesis.

2.6 Switching Technologies Used in Reconfigurable Antennas

The reconfiguration capability of a reconfigurable antenna is primarily determined by the switching technology employed within the radiating structure. Switching elements are responsible for modifying the effective current path, electrical length, reactive loading, or electromagnetic properties of the antenna, thereby allowing dynamic tuning of the operating

frequency, radiation pattern, polarization, or bandwidth characteristics. The selection of an appropriate switching technology significantly influences antenna performance, tuning range, switching speed, power consumption, fabrication complexity, reliability, and overall implementation cost [14], [15].

Several switching technologies have been proposed in the literature for reconfigurable antenna applications, including semiconductor diodes like PIN and varactor, RF-MEMS switches, and functional materials such as graphene and liquid crystals. Each technology possesses distinct advantages and limitations depending on the intended application and performance requirements.

2.6.1 PIN Diodes

Owing to their less cost, high switching speed, compact form factor, and seamless compatibility with planar geometries, PIN diodes remain a preferred switching element in reconfigurable antenna design. Under forward bias, the diode presents a low-resistance state, whereas reverse bias drives it into a high-impedance state. A PIN diode behaves as a low resistance element under forward bias conditions and as a high impedance element under reverse bias conditions. Consequently, it can effectively function as an RF switch, enabling discrete changes in antenna geometry and current distribution.

The majority of frequency and pattern reconfigurable antennas reviewed in this chapter employ PIN diodes as the primary switching mechanism [1], [16], [25]. Their popularity arises from simple biasing requirements, commercial availability, and compatibility with standard printed circuit fabrication techniques. Furthermore, PIN diodes provide rapid switching capability, making them suitable for adaptive wireless communication systems requiring real-time reconfiguration.

Despite these advantages, PIN diode based designs generally provide discrete operating states rather than continuous tuning. In addition, the incorporation of multiple switching elements may increase biasing complexity and introduce insertion losses, particularly in highly reconfigurable antenna structures.

2.6.2 Varactor Diodes

Varactor diodes provide frequency reconfiguration through continuous variation of junction capacitance under reverse bias operation. Unlike PIN diodes, which operate as ON/OFF switches, varactor diodes function as voltage-controlled capacitors, allowing smooth adjustment of the antenna resonance frequency over a specified tuning range.

Several researchers have successfully employed varactor loading to achieve continuous frequency agility in cognitive radio and adaptive communication systems [16]. The grid-slotted patch antenna reported in [21] demonstrated continuous frequency tuning between 2.45 GHz and 3.55 GHz using only two varactor diodes, while maintaining stable radiation characteristics. Similarly, frequency-agile MIMO antenna systems reported in [31] utilized varactor-based tuning to achieve wide frequency coverage for cognitive radio applications.

Although varactor diodes provide superior tuning flexibility, they often require more sophisticated biasing circuits and careful optimization of the tuning network. Furthermore, nonlinear capacitance variation and component losses may influence antenna efficiency and gain stability across the tuning range.

2.6.3 RF-MEMS Switches

Radio-frequency microelectromechanical system (RF-MEMS) switches have gained significant interest owing to their superior RF characteristics, including low insertion loss, high isolation, high linearity, and negligible power consumption. RF-MEMS devices are capable of providing superior performance compared to conventional semiconductor switches, particularly in high-frequency and millimeter-wave applications [14].

Despite their attractive electrical characteristics, RF-MEMS switches are associated with relatively complex fabrication procedures, higher manufacturing costs, packaging challenges, and reduced switching speeds compared to PIN diodes. These factors have limited their widespread adoption in low-cost commercial wireless devices despite their excellent RF performance.

2.6.4 Functional Materials and Emerging Technologies

Recent advances in smart materials have introduced alternative approaches to antenna reconfiguration using graphene, liquid crystals, ferroelectric materials, and other tunable electromagnetic structures. These materials enable reconfiguration through changes in electrical conductivity, dielectric properties, or electromagnetic response under external stimuli [15].

Graphene-based reconfigurable antennas have demonstrated promising characteristics at millimeter-wave and terahertz frequencies due to their exceptional electrical properties and tunable conductivity. Similarly, liquid crystal based antennas provide electrically controlled dielectric tuning suitable for beam steering and frequency agility applications. However, these technologies are still emerging and often require specialized fabrication processes, material characterization, and complex control mechanisms. Consequently, their practical implementation remains limited when compared with established switching technologies such as PIN and varactor diodes.

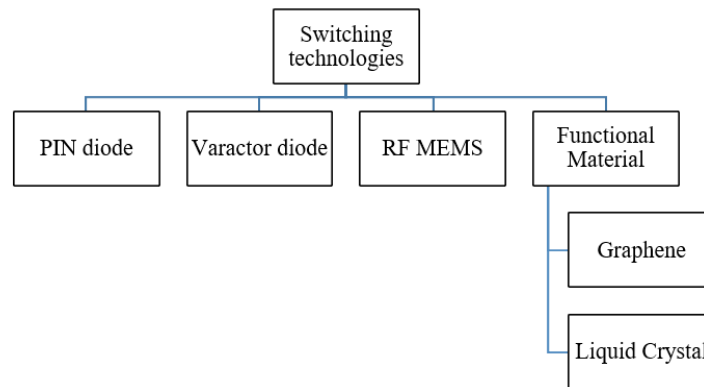


Figure 2.4 Classification of Switching Technologies Used in Reconfigurable Antennas

Overall, the literature indicates that the selection of switching technology involves a trade-off between tuning flexibility, implementation complexity, switching speed, fabrication cost, and reliability. Among the available technologies, PIN diodes continue to represent the most practical and widely adopted solution for compact reconfigurable antennas due to their simplicity, cost effectiveness, and ease of integration. These characteristics make PIN diodes particularly suitable for the antenna configurations developed in this research.

The comparison presented in Table 2.4 indicates that each switching technology offers unique advantages depending on the intended antenna application. PIN diodes remain the

most widely employed switching elements in practical reconfigurable antenna systems due to their low cost, high speed response, compact size, and seamless compatibility with planar antenna geometries [14], [15]. Varactor diodes provide continuous frequency tuning and are particularly attractive for cognitive radio systems; however, their implementation requires more sophisticated biasing and tuning networks [21], [31]. RF-MEMS switches offer excellent RF performance but suffer from fabrication complexity and higher production costs, limiting their adoption in low-cost wireless devices.

Table 2.4 Comparison of Switching Technologies Used in Reconfigurable Antennas

Technology	Switching Speed	Reconfiguration Type	Advantages	Limitations	Typical Applications
PIN Diode	High (ns range)	Discrete switching	Low cost, compact size, simple biasing, easy integration	Discrete states only, insertion loss	Frequency, pattern and hybrid reconfigurable antennas
Varactor Diode	Moderate	Continuous tuning	Smooth frequency tuning, compact implementation	Complex biasing, nonlinear behavior, tuning losses	Cognitive radio, adaptive wireless systems
RF-MEMS	Moderate to Low	Discrete switching	Very low insertion loss, high isolation, excellent linearity	High fabrication cost, packaging complexity	High-frequency and mmWave systems
Graphene-Based Switches	High	Continuous tuning	Suitable for mmWave and THz applications, tunable conductivity	Immature fabrication technology, implementation challenges	Future 6G and THz communication systems
Liquid Crystal Devices	Moderate	Continuous tuning	Electrically controllable dielectric properties, beam steering capability	Slow response, complex material control	Beam steering and adaptive antenna systems

Emerging technologies such as graphene and liquid crystal based reconfigurable structures have demonstrated promising characteristics, particularly for millimeter-wave and terahertz applications. Nevertheless, these technologies remain relatively immature when compared to semiconductor-based switching approaches and often require specialized fabrication techniques [15]. Consequently, PIN diodes continue to represent the most practical solution for compact frequency and hybrid reconfigurable antenna designs. This observation is further supported by the literature reviewed in Sections 2.3, 2.4, and 2.5, where the majority

of reported antennas employ PIN diode switching to achieve reliable and cost-effective reconfiguration.

2.7 Critical Analysis of Existing Literature

The literature reviewed in the preceding sections demonstrates significant advancements in the field of reconfigurable antennas for modern wireless communication systems. Researchers have successfully developed antenna architectures with frequency radiation pattern, and hybrid reconfigurability architectures capable of supporting multiple communication standards and adaptive operating environments. Various switching technologies including PIN diodes, varactor diodes, RF-MEMS switches, and tunable materials have been employed to achieve enhanced antenna functionality and operational flexibility [14], [15]. However, despite these developments, several technical challenges continue to limit the practical implementation of reconfigurable antennas in compact wireless devices.

A detailed examination of the reported frequency reconfigurable antennas reveals that enhanced frequency agility is often achieved at the expense of increased switching complexity. Several designs employ multiple PIN diodes or tunable elements to realize a larger number of operating bands and frequency states [16], [17], [18]. Although such approaches provide greater flexibility, the additional switching elements increase biasing network complexity, insertion losses, and fabrication challenges. Furthermore, many reported antennas focus primarily on increasing the number of operating bands without adequately addressing antenna miniaturization and practical implementation requirements [19]. Consequently, achieving multiple operating frequency states using a minimal number of switching elements remains an important design objective.

The review of radiation pattern reconfigurable antennas indicates that effective beam switching and directional radiation control can be achieved through parasitic elements, reconfigurable feeding networks, and reactive loading techniques [22], [26]. Nevertheless, most of these designs operate within fixed frequency bands and do not provide frequency agility. In addition, antennas offering extensive beam steering capability frequently require multiple switching elements or complex structural modifications, which increase overall system complexity and implementation cost [30]. Therefore, the simultaneous realization of

compactness, low switching complexity, and adaptive radiation characteristics remains a challenging task.

The hybrid reconfigurable antennas reviewed in Section 2.5 demonstrate the potential of integrating frequency and radiation pattern reconfiguration within a single radiating structure [24], [25]. However, only a limited number of reported antennas successfully achieve both functionalities while maintaining compact dimensions and low switch count. Several hybrid designs rely on multiple switching elements, sophisticated biasing arrangements, or specialized antenna configurations, thereby increasing design complexity and limiting their suitability for compact portable wireless devices [23], [29]. Although the antennas reported in [24] and [25] demonstrate hybrid reconfiguration using a single PIN diode, the number of achievable operating states and supported communication bands remains relatively limited.

Another significant observation emerging from the literature review is that PIN diode switching continues to dominate practical reconfigurable antenna implementations. While varactor diodes provide continuous frequency tuning and RF-MEMS switches offer superior RF characteristics, PIN diodes remain the preferred solution due to their low cost, fast switching response, ease of integration, and compatibility with conventional printed circuit fabrication techniques [24],[25]. Consequently, most practical reconfigurable antenna designs intended for commercial wireless applications employ PIN diode switching.

Based on the comparative analysis presented in Tables 2.1–2.4, it can be concluded that an ideal reconfigurable antenna should simultaneously satisfy several design requirements, including compact physical dimensions, low switching complexity, multiple operating frequency bands, stable radiation performance, ease of fabrication, and practical implementation. However, very few antennas reported in the literature satisfy all these requirements simultaneously. Most designs achieve improvements in one performance aspect while compromising another, resulting in trade-offs between frequency agility, radiation adaptability, compactness, and implementation complexity.

Therefore, there exists a continuing need for compact reconfigurable antenna structures capable of providing enhanced frequency agility and adaptive radiation characteristics using a minimum number of switching elements. Motivated by these observations, the present research aims at the design and optimization of compact PIN diode based reconfigurable patch antennas capable of achieving multiple frequency states and hybrid frequency–pattern

reconfiguration while maintaining low structural complexity and practical fabrication feasibility for modern wireless communication applications.

Table 2.5 Literature Analysis Matrix

Ref.	Compact Design	≤ 2 Switching Elements	Multi-Band Operation	Pattern Reconfiguration	Fabricated
[1]	X	✓	X	✓	✓
[2]	✓	✓	✓	X	✓
[7]	✓	X	X	✓	✓
[14]	✓	X	✓	X	✓
[15]	✓	✓	✓	X	✓
[20]	✓	✓	X	X	✓
[21]	X	X	X	X	✓
[24]	X	X	X	✓	✓
[31]	✓	✓	X	✓	✓
[35]	✓	✓	✓	✓	✓
[36]	✓	X	✓	X	✓
[37]	✓	✓	✓	X	✓
[48]	✓	✓	✓	✓	✓

Table 2.5 further confirms that only a limited number of reported antennas simultaneously satisfy the key design requirements of compact size, low switch count, multiband operation, and radiation pattern adaptability. While several antennas achieve frequency reconfiguration or pattern reconfiguration individually, relatively few designs integrate both functionalities within a compact and practically realizable structure. These observations establish the motivation for the antenna designs proposed in this thesis, which focus on achieving enhanced frequency agility and frequency–pattern reconfiguration using a minimal number of PIN diodes while maintaining compact dimensions and fabrication simplicity.

2.8 Summary

This chapter surveyed reconfigurable antenna technologies reported in the literature, classifying the reviewed works into frequency-, pattern-, and hybrid-reconfigurable

categories. Reconfiguration techniques based on PIN diodes, varactor diodes, RF-MEMS switches, and emerging tunable materials were examined and compared.

The survey established that PIN diode based antennas remain the most practical choice for wireless communication systems, owing to their low cost, simple biasing, and ease of implementation. Although numerous antennas achieve frequency agility or radiation pattern adaptability, only a limited number of reported designs simultaneously provide compact size, low switch count, and multifunction reconfiguration. The comparative analysis further highlighted the trade-offs among frequency agility, switching complexity, antenna size, and implementation feasibility.

These observations underscored the need for compact antennas capable of enhanced frequency and hybrid frequency–pattern reconfiguration using a minimal number of PIN diodes. The following chapter presents the design and simulation of frequency reconfigurable configurations addressing this requirement.

CHAPTER-3

Development and Simulation of Frequency-Reconfigurable Microstrip Antennas

This chapter describes the design and electromagnetic simulation of two antennas with frequency reconfigurations developed to satisfy contemporary wireless communication requirements. Both designs employ PIN diode switching to realize frequency reconfiguration while preserving compact dimensions and simple structural implementation. The first configuration is a dual L-slot microstrip patch antenna intended for WLAN and Wi-Fi operation, whereas The second configuration is a multimode printed monopole radiator intended to support sub-6 GHz 5G services together with WLAN-based wireless applications. Comprehensive descriptions covering the antenna development methodology, switching strategy, and simulated operational characteristics are discussed throughout this chapter.

3.1 Introduction

Ongoing advances in wireless networking technologies have driven the development of space-efficient antenna architectures designed to integrate multiple communication capabilities into a single radiating platform. Contemporary wireless devices are expected to provide seamless operation across WLAN, Wi-Fi, WiMAX, sub-6 GHz 5G, IoT, and related wireless technologies while maintaining compact size, low implementation cost, and dependable performance. Conventional single-band antennas often require multiple radiating elements to cover different operating frequencies, resulting in increased hardware complexity and inefficient utilization of the available installation space.

Reconfigurable antennas overcome these limitations by allowing controlled alteration of antenna parameters through switching or tuning mechanisms. Among various reconfiguration approaches, frequency reconfiguration has emerged as an attractive solution because it allows a single antenna to operate at multiple frequency bands. This capability improves spectral efficiency while reducing the need for multiple dedicated antennas.

As discussed in Chapter 2, PIN diodes are extensively utilized in practical reconfigurable antenna systems because they offer fast switching capability, compact dimensions, low power consumption, and straightforward integration. By altering the switching states of PIN diodes, the effective current path of an antenna can be altered, resulting in different resonant frequencies and operating modes.

This chapter presents two frequency reconfigurable antenna designs developed using PIN diode switching. The first design is a compact dual L-slot patch antenna intended for WLAN and Wi-Fi applications, whereas the second is a multi-mode printed monopole antenna targeting sub-6 GHz 5G and WLAN operation. The antenna structures, switching mechanisms, and simulated performance are investigated in terms of reflection coefficient, resonant frequencies, gain, and radiation characteristics. The chapter further presents a comparative analysis to examine the relative performance of the two proposed antenna configurations.

3.2 Antenna-I: Dual L-Slot Frequency Reconfigurable Patch Antenna

The work presented in this section focuses on the realization of a space-efficient microstrip radiator with frequency-switching capability achieved by integrating two PIN diodes into a dual L-slot topology, followed by its electromagnetic performance assessment. The antenna configuration is designed to provide multiple operating frequency states while preserving a simple geometry, compact dimensions, and low switching complexity. The design procedure, frequency reconfiguration strategy, and simulated performance of the antenna are discussed in the following subsections.

3.2.1 Antenna configuration and Design Evolution

The objective of the first antenna design is to develop a compact frequency reconfigurable microstrip antenna having ability to operate at multiple frequency bands while employing a minimum number of switching elements. As identified in Chapter 2, many reported frequency reconfigurable antennas achieve enhanced frequency agility by incorporating multiple PIN diodes, resulting in increased biasing complexity and implementation challenges. Therefore, the present design aims to realize frequency reconfiguration using only two PIN diodes while maintaining a simple radiating structure and compact physical dimensions.

To achieve this objective, a rectangular microstrip patch antenna is chosen as the initial radiating element due to its thin profile, ease of fabrication, and compatibility with planar wireless communication systems. Frequency reconfiguration is introduced by incorporating two symmetrical L-shaped slots within the patch structure. The slots modify the surface current distribution and create alternative current paths whose electrical lengths can be controlled through PIN diode switching.

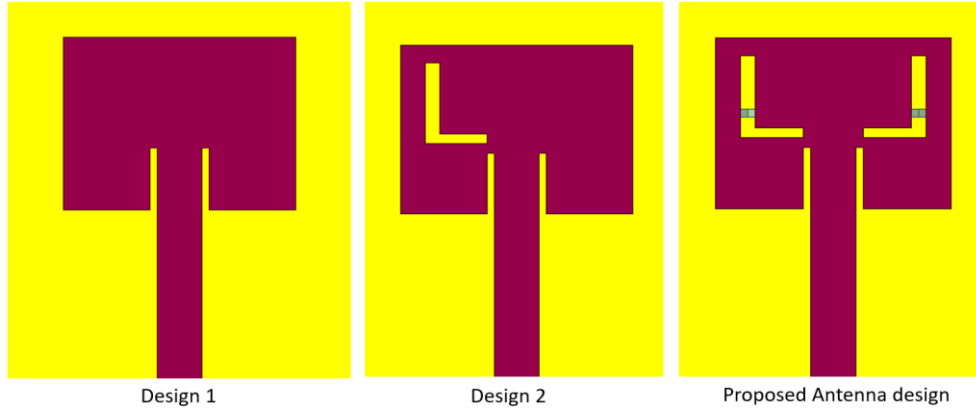


Figure 3.1 Design evolution of developed antenna

Fabrication is carried out using an FR-4 dielectric laminate ($\epsilon_r = 4.4$) having a substrate depth of 1.6 mm. An inset-fed microstrip configuration is adopted to achieve adequate impedance matching, ensuring proper interfacing with a standard 50Ω feed line. Two PIN diodes incorporated within the slot structure provide four distinct switching states, thereby generating multiple resonant frequencies suitable for WLAN, Wi-Fi, and sub-6 GHz wireless communication applications. The design process involves progressive modification of the conventional patch geometry through slot loading and switching integration. The detailed evolution of the antenna structure and the optimization procedure adopted to achieve the desired frequency reconfiguration characteristics are presented in the following subsection.

The initial antenna configuration developed in the present investigation employs a compact microstrip radiator capable of discrete frequency switching through two electronically controlled switching elements. Reconfiguration is accomplished by embedding a pair of PIN diodes within a dual L-slot topology, thereby enabling multiple resonant states without increasing structural complexity. Construction utilizes an FR-4 dielectric laminate

characterized by $\epsilon_r = 4.4$ and a laminate depth of 1.6 mm, resulting in a compact physical footprint of 35 mm $\times$ 40 mm.

The design approach implemented adopted for the developed antenna follows a progressive evolution approach. The evolution process comprises of three major stages, as depicted in Figure 3.1. In the first stage, a conventional inset-fed rectangular microstrip patch antenna is designed to establish the fundamental resonant behavior. Although the basic antenna exhibits satisfactory impedance matching, its operating frequency remains fixed and does not provide reconfiguration capability.

In the following stage, an L-slot is incorporated into the radiating patch to modify the current flow across the antenna surface, thereby extending the effective current path. As a result, additional resonant modes are generated, highlighting the contribution of slot loading to the antenna characteristics. This configuration forms the basis of the frequency reconfiguration mechanism by introducing alternative paths for surface current propagation.

During the final stage, a second L- slot is symmetrically incorporated on the opposite side of the patch, and two PIN diodes are embedded within the slot regions. Frequency reconfiguration is accomplished by selectively controlling the switching states of the PIN diodes, which changes the effective electrical path of the antenna and enables multiple resonant frequencies and operating modes. Furthermore, the symmetrical slot arrangement preserves stable radiation characteristics while providing efficient frequency agility.

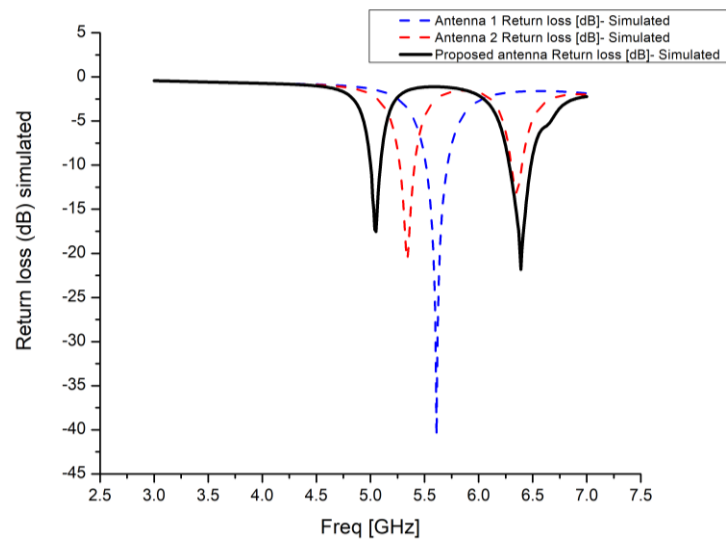


Figure 3.2 Simulated Reflection Coefficient Characteristics during Antenna Evolution

To evaluate the influence of each structural modification, the reflection coefficient responses obtained during the antenna evolution process are compared in Figure 3.2. The incorporation of the first L-slot alters the resonant characteristics of the conventional patch antenna by surface altering the surface current flow across the radiating element. The inclusion of the second slot and PIN-diode locations further modifies the electromagnetic behavior, resulting in the final antenna configuration capable of frequency reconfiguration. The evolution study establishes that the proposed slot arrangement provides the structural basis for the antenna's desired electromagnetic response.

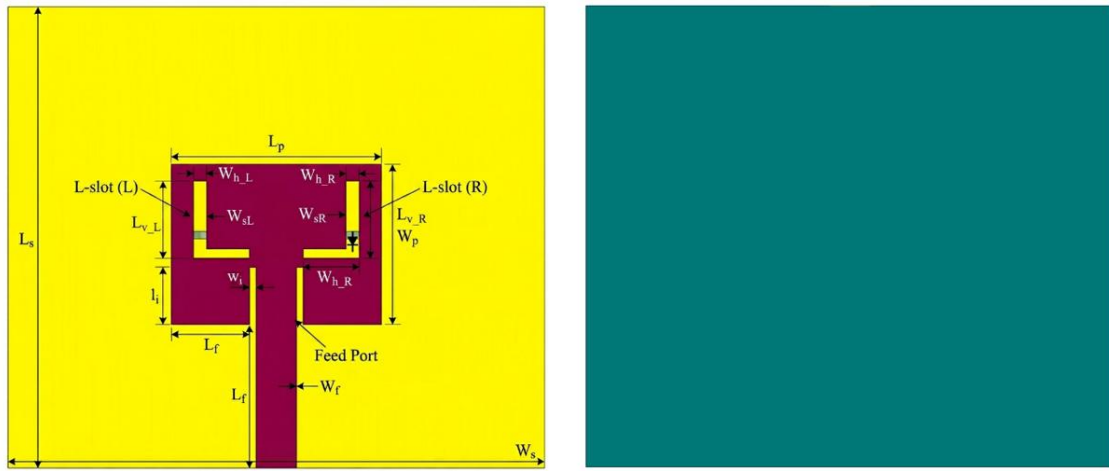


Figure 3.3 Optimized geometry of the proposed antenna (a) Top view (b) Bottom view

The developed antenna configuration incorporates an inset microstrip feed arrangement for effective impedance transformation through a conventional 50Ω feeding network. An inset-feed arrangement was adopted because it offers structural simplicity, straightforward manufacturing, and efficient impedance transformation without the need for separate matching components. Following extensive parametric optimization in Ansys HFSS, the feed location together with the slot geometry was refined to obtain the required resonant bands while preserving acceptable return-loss performance under every switching condition.

The optimized antenna layout is illustrated in Figure 3.3. The overall structure comprises a rectangular patch radiator, an inset microstrip feedline, two symmetrically positioned L-shaped slots, and two PIN diode locations identified as D1 and D2. The optimized geometric parameters are provided in Table 3.1.

Table 3.1 Optimized Geometrical Dimensions of the Proposed Frequency Reconfigurable Antenna

Parameter	Description	Value (mm)
Ls	Length of substrate	35
Ws	Width of substrate	40
H	Thickness of substrate	1.6
Lp	Length of patch	11.75
Wp	Width of patch	15.7
Lf	Length of feed line	15.82
Wf	Width of feed line	3
Li	Inset feed depth	4.2
Wi	Inset feed gap	0.5
L _{vL}	Left slot vertical arm length	5.7
L _{vR}	Right slot vertical arm length	5.7
L _{hL}	Left slot horizontal arm length	4.2
L _{hR}	Right slot horizontal arm length	4.2
W _{sL}	Width of left slot	0.7
W _{sR}	Width of right slot	0.7

The incorporation of dual L-shaped slots together with two controllable PIN diodes enables the antenna to operate in four distinct switching states. Each switching state modifies the current path within the radiating patch, thereby altering the current propagation path and producing different resonant frequencies. The detailed PIN diode modelling approach, switching mechanism, and antenna operation modes are presented in the following section.

3.2.2 PIN Diode Modelling and Switching States

Frequency reconfiguration in the developed antenna is attained through the integration of two PIN diodes, denoted as D1 and D2, across the L-shaped slot sections. The switching action of these diodes modifies the electrical continuity of the slot structure, thereby altering the effective current path and resonant characteristics of the antenna. By selectively controlling the diode states, multiple operating frequencies can be realized using a single radiating element.

To accurately represent the RF behavior of the PIN diodes during simulation, equivalent lumped-element models were implemented in Ansys HFSS. This modelling approach

provides a practical representation of the diode characteristics while maintaining computational efficiency. In the forward-biased condition, the diode behaves as a conductive path with low resistance and is represented by a series RL network. In the reverse-biased condition, the diode presents a high impedance and is modelled using a parallel RC network in series with an inductance.

The equivalent circuit models used in the simulation are illustrated in Figure 3.4.

ON-State Parameters

- $R = 1.5 \Omega$
- $L = 0.7 \text{ nH}$

OFF-State Parameters

- $R = 5 \text{ k}\Omega$
- $C = 0.15 \text{ pF}$
- $L = 0.7 \text{ nH}$

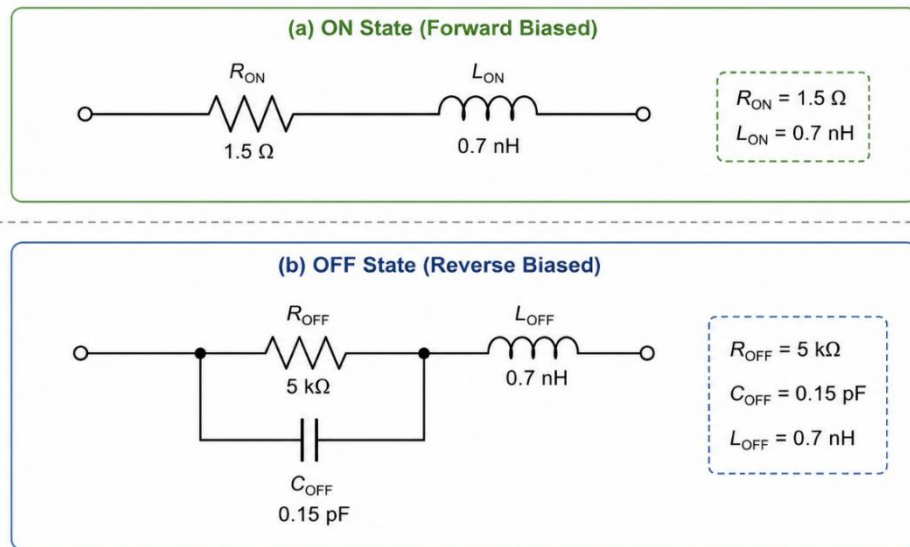


Figure 3.4 Equivalent circuit representation of PIN diode in ON and OFF state

The use of two PIN diodes results in four possible switching configurations. Each configuration produces a distinct current distribution and consequently different resonant frequencies. The switching states considered for the developed antenna are summarized in Table 3.2.

Table 3.2 Switching States of the Developed Frequency Reconfigurable Antenna

Mode	PIN Diode D1	PIN Diode D2
Mode 0	OFF	OFF
Mode 1	OFF	ON
Mode 2	ON	OFF
Mode 3	ON	ON

The OFF–OFF state corresponds to the condition where both slot sections remain electrically disconnected, whereas the ON–ON state establishes conductive paths through both diode locations. The remaining switching combinations provide intermediate electrical configurations, resulting in different effective current paths and frequency responses. The influence of these switching states on the distribution of surface currents and resonant behavior of the antenna is discussed in the following sections.

3.2.3 Surface Current Distribution Analysis

Surface current distributions of the proposed antenna were investigated to assess the influence of PIN diode switching on the resonant behavior of the radiating structure. The corresponding current distributions for the four switching states are illustrated in Figure 3.5. It can be observed that the switching conditions alter the current concentration around the L-shaped slot regions, thereby modifying the electromagnetic behavior of the antenna and producing different resonant frequencies.

a. Mode 0 (D1 = OFF, D2 = OFF)

Both PIN diodes remain turned off state and the slot discontinuities are electrically isolated. The current distribution on the surface is mostly concentrated near the feed region and the inner corners of L slots. A relatively symmetrical current distribution is observed on both sides of the patch, indicating balanced excitation of the radiating structure. The resulting current path supports resonant frequencies at 5.05 GHz and 6.40 GHz.

b. Mode 1 (D1 = OFF, D2 = ON)

When diode D2 is switched ON while D1 remains OFF, the current distribution becomes asymmetrical. Increased current concentration is observed around the slot section associated

with the activated switching path, indicating that the local current flow is influenced by the electrical connection introduced by the diode. This redistribution of current modifies the resonant characteristics of the antenna and results in operating frequencies of 5.25 GHz and 6.40 GHz.

c. Mode 2 (D1 = ON, D2 = OFF)

Mode 2 represents the complementary switching condition of Mode 1. In this state, the current concentration shifts toward the opposite slot region due to the activation of diode D1 and deactivation of diode D2. The altered current distribution changes the effective electromagnetic characteristics of the radiating patch and produces resonances at 5.25 GHz and 6.14 GHz. The observed current pattern confirms that independent control of the two PIN diodes enables selective modification of the resonant behavior.

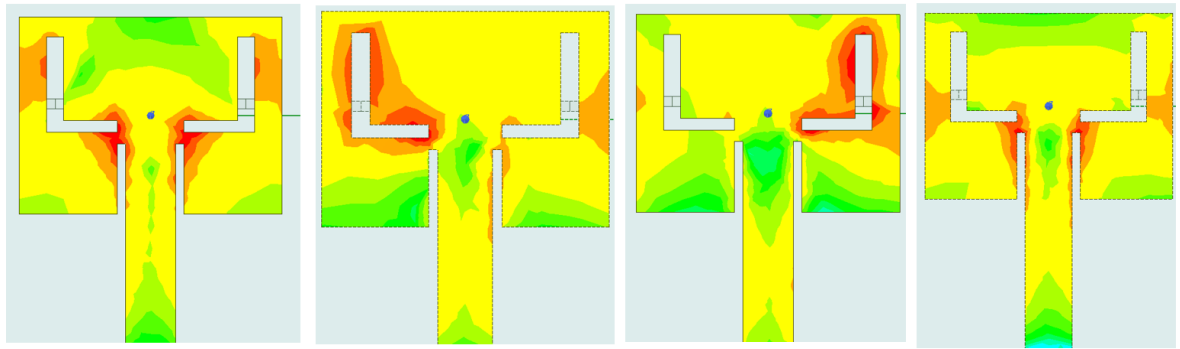


Figure 3.5 Surface Current Distribution for Modes 0-3

d. Mode 3 (D1 = ON, D2 = ON)

In Mode 3, both PIN diodes are activated, establishing conductive paths across both slot discontinuities. The current distribution becomes more uniformly distributed around the feed region and slot sections, restoring structural symmetry. The simultaneous activation of both switching elements produces a different resonant response compared to the remaining modes, resulting in antenna operation at 5.40 GHz.

As illustrated in Figure 3.5, different PIN diode switching configurations modify the surface current profile around the slotted regions. The resulting redistribution of current flow changes the antenna's equivalent electrical behavior, giving rise to separate resonant modes under each switching configuration. These observations verify that the proposed frequency

reconfiguration technique is successfully realized using only two PIN diodes while preserving a compact antenna geometry.

3.2.4 Reflection Coefficient Characteristics

Impedance-matching performance was examined through the simulated S_{11} response of the developed frequency-reconfigurable antenna configuration under different PIN diode switching conditions. The S_{11} characteristics corresponding to the four operating modes are illustrated in Figure 3.6(a–d), while the associated resonant frequencies are summarized in Table 3.3.

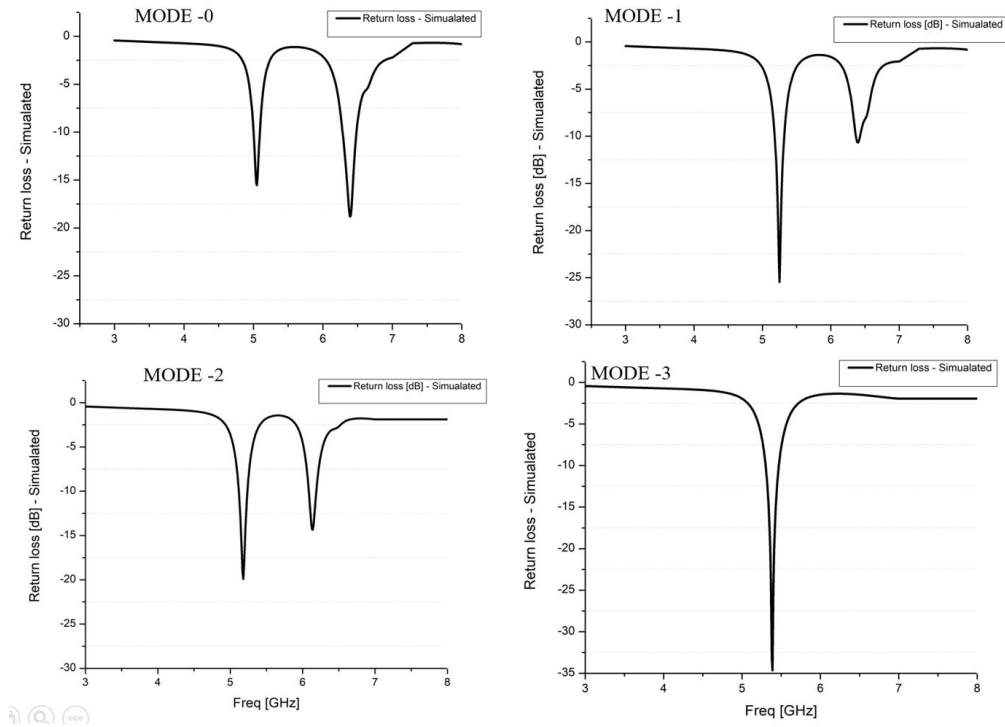


Figure 3.6 Simulated S_{11} Responses for the Reconfigurable States in modes 0-3

Figure 3.5(a) presents the simulated S_{11} response corresponding to Operating State 0, in which each PIN diode remains non-conducting (OFF). Under this switching configuration, dual-band behavior is observed with resonance occurring at 5.05 GHz and 6.40 GHz. Both operating bands satisfy the conventional impedance-matching criterion of $S_{11} < -10$ dB, indicating efficient radiation and satisfactory matching performance.

The reflection coefficient response corresponding to Mode 1 is shown in Figure 3.6(b). In this switching configuration, diode D2 is activated while diode D1 remains OFF. The lower

resonant frequency shifts to 5.25 GHz, whereas the higher resonance remains around 6.40 GHz. The observed frequency variation demonstrates the influence of the activated switching path on the electromagnetic behavior of the slot-loaded patch structure.

Figure 3.6(c) presents the simulated reflection coefficient for Mode 2, where diode D1 is conducting and diode D2 remains OFF. In this state, the antenna resonates at 5.25 GHz and 6.14 GHz. Compared with Mode 1, a noticeable shift is observed in the upper resonant frequency, confirming that the two PIN diodes independently affect the resonant characteristics of the antenna.

The reflection coefficient characteristic obtained for Mode 3 is shown in Figure 3.6(d). When both PIN diodes are switched ON simultaneously, the antenna exhibits a single dominant resonance at 5.40 GHz. The establishment of conductive paths across both slot sections alters the electromagnetic response of the antenna and results in a different resonant behavior compared with the remaining operating modes.

A comparison of the four switching states reveals that the resonant frequencies can be effectively controlled through electronic switching. The observed frequency shifts are associated with changes in the electrical continuity of the slot regions, which modify the current distribution and electromagnetic coupling within the radiating patch. Consequently, multiple operating frequencies are achieved without altering the antenna footprint.

Table 3.3 Resonant Frequencies of the Proposed Antenna under Different Switching States

Mode	D1	D2	Resonant Frequencies (GHz)
Mode 0	OFF	OFF	5.05, 6.40
Mode 1	OFF	ON	5.25, 6.40
Mode 2	ON	OFF	5.25, 6.14
Mode 3	ON	ON	5.4

The proposed antenna provides frequency agility within the 5–6.5 GHz frequency range using only two PIN diodes. The ability to realize multiple resonant states with a limited number of switching elements reduces circuit complexity and simplifies practical implementation. Furthermore, satisfactory impedance matching is maintained in all operating modes, demonstrating the effectiveness of the proposed reconfiguration approach.

The resonant frequencies corresponding to different switching configurations are summarized in Table 3.3.

3.2.5 Gain Characteristics

The radiation gain of the developed frequency-reconfigurable antenna configuration was analyzed to determine how PIN diode switching influences the antenna's radiating performance. The simulated maximum gain corresponding to each operating state is illustrated in Figure 3.7, while the numerical values are compiled in Table 3.4.

The simulated results demonstrate that the developed antenna configuration maintains stable radiation performance throughout the frequency reconfiguration process. Depending on the selected switching configuration, the maximum realized gain ranges from 2.95 dBi to 4.28 dBi. These gain variations primarily arise from changes in the surface current profile and resonant behavior produced by different PIN diode switching combinations.

Table 3.4 Simulated Peak Gain of the Proposed Antenna

Mode	D1	D2	Peak Gain (dBi)
Mode 0	OFF	OFF	2.95
Mode 1	OFF	ON	3.8
Mode 2	ON	OFF	3.43
Mode 3	ON	ON	4.28

Under Mode 0 (D1 = OFF, D2 = OFF), the developed antenna configuration delivers a maximum realized gain of 2.95 dBi. Activating D2 while maintaining D1 in the OFF condition (Mode 1) increases the realized gain to 3.80 dBi. For Mode 2 (D1 = ON, D2 = OFF), the corresponding maximum realized gain reaches 3.43 dBi. The optimum gain performance is observed in Mode 3, where simultaneous activation of both PIN diodes produces a maximum realized gain of 4.28 dBi. This improvement is primarily associated with the redistribution of surface current paths, resulting in more efficient utilization of the radiating structure.

The gain values obtained in all switching states demonstrate that the proposed antenna preserves acceptable radiation performance while providing frequency agility. The findings validate that the integration of two PIN diodes facilitates frequency reconfiguration without introducing significant degradation in antenna gain. Consequently, the proposed design is

suitable for WLAN, Wi-Fi, and related wireless communication applications operating within the considered frequency range.

3.2.6 Far-Field Radiation Pattern Evaluation

The far-field response of the developed frequency-reconfigurable antenna configuration was analyzed to examine the effect of PIN diode switching on its directional radiation behavior. Simulated radiation plots corresponding to the representative resonant frequencies for each operating state are illustrated in Figure 3.7.

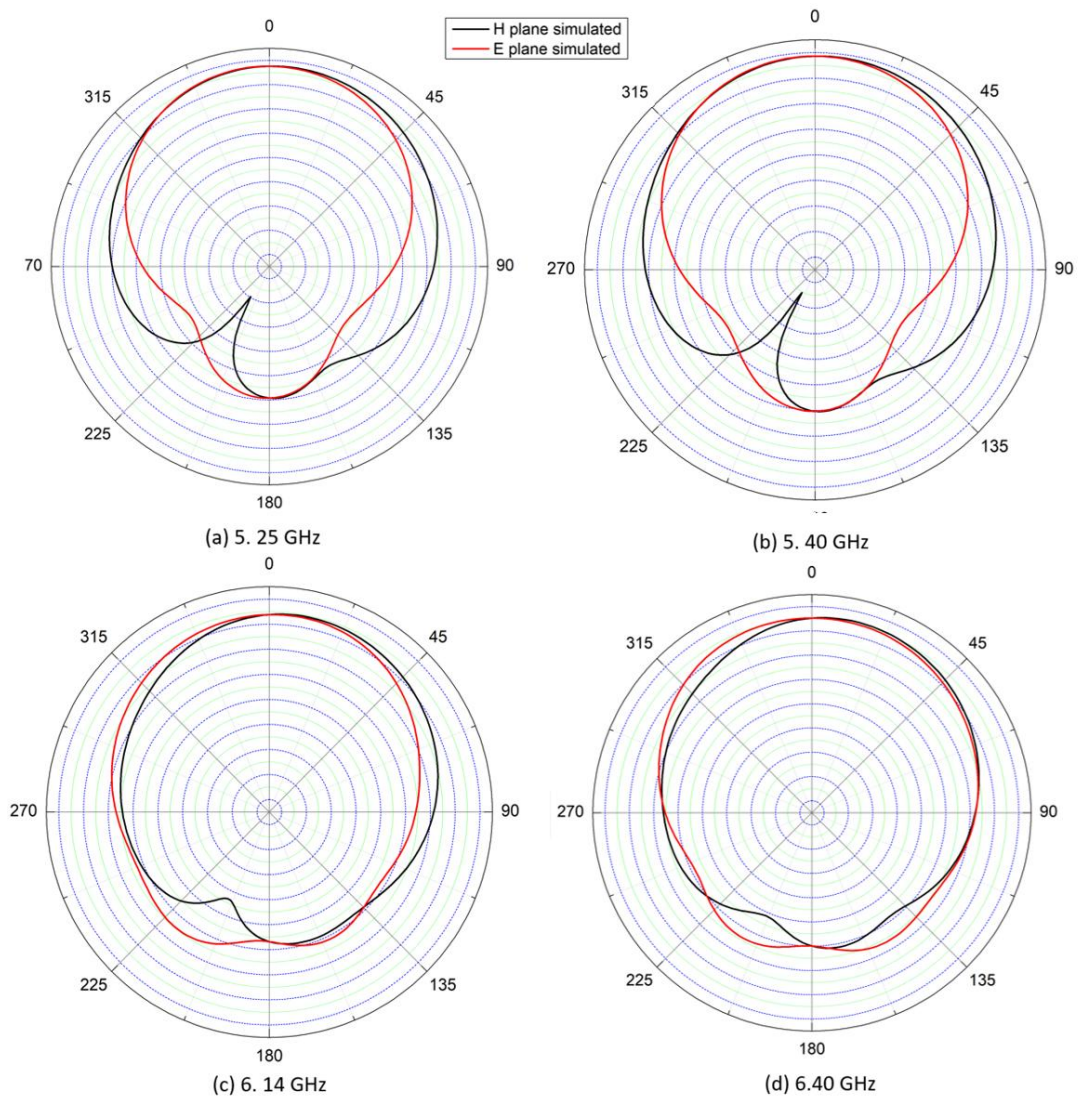


Figure 3.7 Simulated Radiation Patterns at Representative Frequencies

The simulated far-field responses demonstrate consistent directional characteristics throughout all frequency reconfiguration states. Although the resonant frequencies shift

according to different PIN diode switching configurations, the overall radiation profile remains nearly unchanged. Such behavior is advantageous for practical wireless systems because frequency tuning is accomplished without causing noticeable deterioration in the directional radiation characteristics.

Under Mode 0, the developed antenna configuration produces a broadside directional response, which is commonly associated with rectangular microstrip patch radiators. Comparable directional characteristics are retained in Modes 1 and 2, where activating a single PIN diode changes the resonant frequency while preserving the overall radiation profile. During Mode 3, simultaneous activation of both PIN diodes continues to provide stable far-field performance without significant degradation of the principal radiation direction.

The simulation results demonstrate that the slot-loading strategy together with the PIN diode switching arrangement predominantly influences the resonant behavior of the antenna while producing only minor changes in its far-field characteristics. These observations confirm that frequency reconfiguration is achieved without degrading the antenna's inherent radiation properties.

Overall, the analysis of Radiation Characteristics demonstrates that the proposed antenna is capable of providing multiple frequency states while maintaining acceptable radiation characteristics across all operating modes. The stable radiation behavior, combined with compact dimensions and low switching complexity, makes the antenna apt for WLAN, Wi-Fi, and related wireless communication applications.

3.2.7 Discussion

The simulation results presented in the preceding sections demonstrate the effectiveness of the proposed dual L-slot microstrip antenna in achieving frequency reconfiguration using a simple switching arrangement. By incorporating two PIN diodes within the slot structure, four distinct operating modes were realized, producing multiple resonant frequencies within the 5–6.5 GHz region. The achieved frequency agility confirms that the proposed slot configuration effectively modifies the electromagnetic behavior of the antenna through electronic switching.

A distinguishing feature of the proposed design is its compact overall footprint of 35 mm × 40 mm while employing only two switching elements. Compared with many reported frequency reconfigurable antennas that utilize multiple switching devices and complex biasing arrangements, the present design provides a comparatively simple implementation without sacrificing reconfiguration capability. The use of a limited number of PIN diodes also contributes to reduced circuit complexity and facilitates practical realization.

The developed antenna configuration provides satisfactory impedance characteristics throughout every switching configuration, with resonance occurring at 5.05 GHz, 5.25 GHz, 5.40 GHz, 6.14 GHz, and 6.40 GHz. Furthermore, the simulated maximum realized gain varies between 2.95 dBi and 4.28 dBi, demonstrating reliable radiation performance during the entire frequency reconfiguration process. The far-field radiation study additionally verifies that the directional characteristics remain essentially unchanged despite changes in the PIN diode switching configurations.

Overall, the developed antenna configuration effectively realizes multiple operating frequency states using a compact radiating structure with only two PIN diodes. The simulation outcomes confirm the effectiveness of the adopted design approach and demonstrate the practicality of implementing frequency reconfiguration while maintaining low structural complexity and a simplified switching arrangement. The following section introduces another frequency-reconfigurable antenna design developed to further investigate multi-band operating characteristics for contemporary wireless communication systems.

3.3 Antenna-II: Multi-Mode Frequency Reconfigurable Monopole Antenna

The second antenna investigated in this work is a compact monopole antenna with frequency reconfigurability that supports multiple wireless communication standards within a single radiating structure. Unlike the first antenna, which primarily targets frequency reconfiguration within the WLAN spectrum, this design is intended to provide wider frequency coverage suitable for sub-6 GHz 5G, WLAN, WiMAX, satellite communication, and Internet of Things (IoT) applications.

The antenna employs a printed monopole configuration incorporating multiple radiating strips and two PIN diodes to achieve frequency agility. Through regulation of the switching

states of the PIN diodes, different current paths are established within the radiating structure, resulting in multiple operating bands and distinct frequency responses. The proposed design provides four operating modes and supports a total of nine resonant bands while maintaining compact footprint of 30 mm x 20 mm x 1.6 mm.

The antenna is realized using an FR-4 substrate and utilizes a partial ground plane to enhance impedance bandwidth and radiation performance. The compact size, simple geometry, and limited number of switching elements make the design suitable for integration into modern portable wireless devices where space and hardware complexity are critical design constraints.

The design methodology, switching mechanism, and simulated performance parameters of the developed antenna are detailed in the sections that follow. Detailed analyses of the antenna geometry, PIN diode operation, reflection coefficient characteristics, radiation behavior, and frequency reconfiguration performance are subsequently discussed.

3.3.1 Antenna Geometry and Design Evolution

The developed antenna configuration is based on a compact printed monopole topology intended to provide multi-band frequency reconfiguration for contemporary wireless communication applications. Fabrication employs an FR-4 dielectric substrate having overall size of 30 mm x 20 mm x 1.6 mm. The substrate material has a dielectric constant of 4.3 and a loss tangent of 0.025. A partial ground conductor is incorporated on the opposite surface of the substrate to improve impedance bandwidth together with radiation efficiency. Excitation of the radiating element is accomplished using a 50 Ω microstrip feedline directly connected to the monopole radiator.

The completed antenna structure comprises multiple radiating strips of different lengths interconnected through two PIN diode locations. Their arrangement establishes several equivalent current paths, allowing the radiator to generate multiple resonant modes under different switching configurations. Selective switching of the PIN diodes reconfigures the electrical current paths, enabling operation across multiple frequency bands while preserving a compact physical footprint. The development of the antenna was carried out through a systematic design evolution process. The various stages involved in the evolution of the proposed structure are illustrated in Figure 3.8. The initial configuration consisted of a

simple monopole radiator designed to provide fundamental resonance within the desired operating range. Additional strip elements were subsequently incorporated to introduce new resonant modes and improve impedance matching characteristics. Further optimization of strip dimensions and switching locations resulted in the final antenna geometry capable of supporting multiple operating bands.

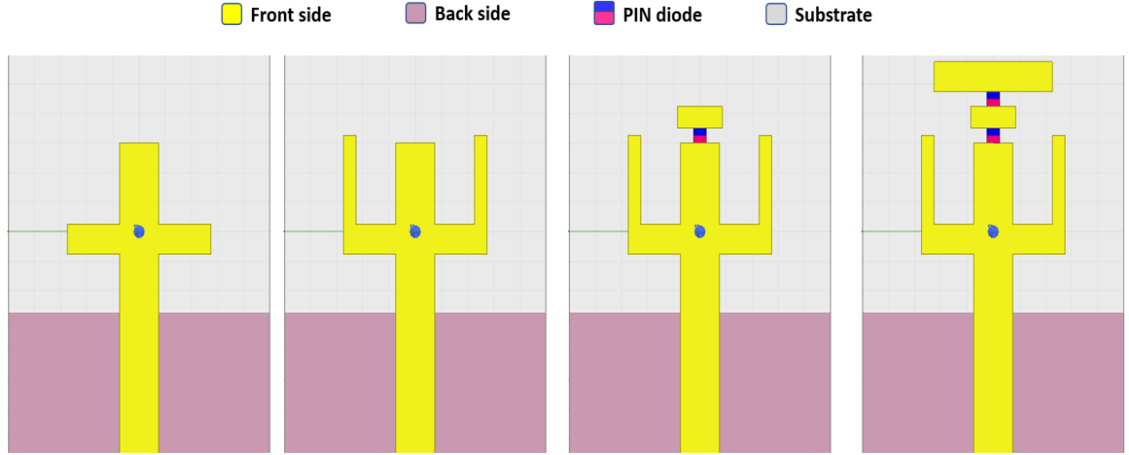


Figure 3.8 Evolution of the proposed reconfigurable monopole antenna

To evaluate each structural modification, the simulated S_{11} responses corresponding to various stages of antenna development are compared in Figure 3.9.

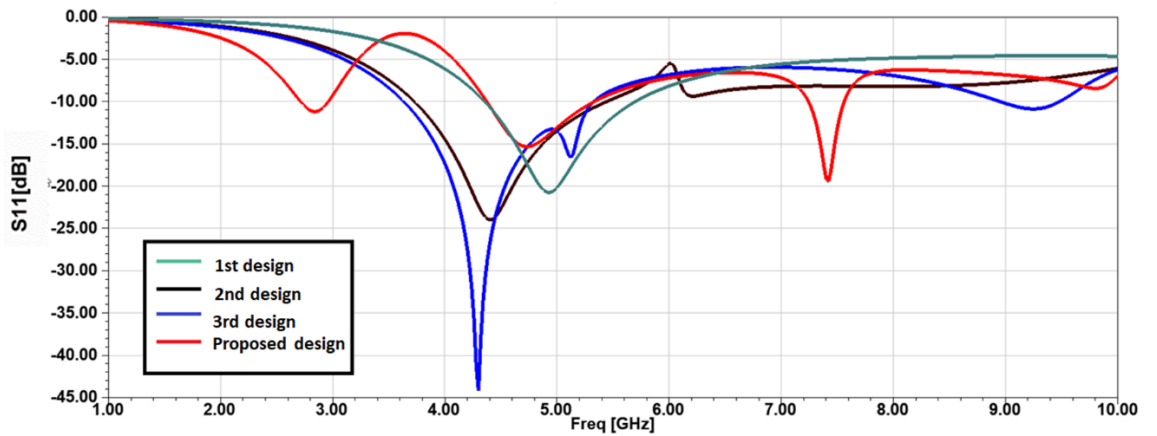


Figure 3.9 Simulated S_{11} during antenna evolution

It can be observed that the introduction of additional radiating strips significantly improves the impedance matching characteristics and generates additional resonant bands. Progressive modifications to the geometry lead to wider frequency coverage and enhanced multi-band

behavior. The final antenna configuration exhibits the desired resonant characteristics required for frequency reconfiguration.

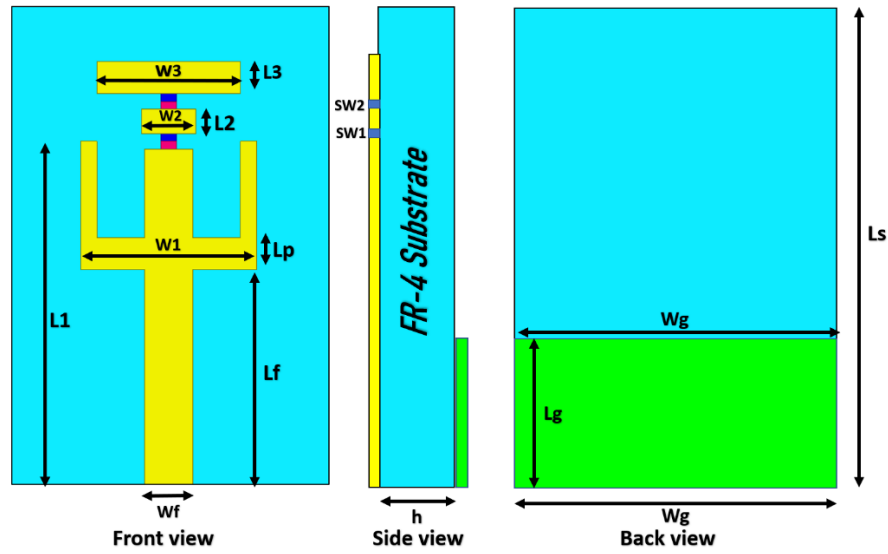


Figure 3.10 Geometry of the proposed antenna

Figure 3.11 illustrates the finalized geometric configuration of the proposed antenna, and the associated dimensional values are compiled in Table 3.5. The compact dimensions, simple planar structure, and limited number of switching elements make the antenna suitable for integration into portable wireless devices requiring multi-standard communication capability.

Table 3.5 Optimized Dimensions of the Proposed Multi-Mode Frequency Reconfigurable Antenna

Parameter	Description	Value (mm)
W_s	Width of substrate	30
L_s	Length of substrate	20
W_g	Width of ground plane	30
L_g	Length of ground plane	9.5
W_f	Width of microstrip feed line	3
L_f	Length of microstrip feed line	13.5
L_p	Length of central radiating strip extension	2
L_1	Total length of radiating monopole structure	21
L_2	PIN diode mounting gap length	1.5
L_3	Length of upper connecting strip	2

W_1	Width of lower horizontal radiating strip	11
W_2	Width of upper horizontal strip	3.4
W_3	Length of top radiating strip	9
H	Substrate thickness	1.6

As observed from Table 3.5, the proposed antenna occupies an overall area of only 30 mm x 20 mm. The compact dimensions are achieved through the use of multiple radiating strips integrated within a printed monopole configuration. The optimized geometrical parameters were obtained through extensive parametric analysis to achieve the desired multi-band frequency reconfiguration characteristics while maintaining satisfactory impedance matching and radiation performance.

3.3.2 Operating Modes of the Developed Antenna

The frequency reconfigurability of the developed monopole antenna is attained using two PIN diodes, denoted as SW_1 and SW_2 . The switching states of these diodes determine the electrical connectivity between the radiating strips and consequently modify the effective radiating structure. Depending on the ON and OFF combinations of the switching elements, the antenna operates in four distinct modes, each providing a different frequency response.

The operating principle is based on the selective activation of radiating sections through electronic switching. When the switching states are altered, the effective current path within the antenna changes, resulting in different resonant frequencies and impedance bandwidths. This mechanism enables a single compact antenna structure to support multiple wireless communication bands without requiring additional radiating elements.

The available operating modes and their corresponding frequency bands are tabulated in Table 3.6. It can be observed that the antenna is capable of operating either as a wideband radiator or as a multi-band radiator depending on the selected switching configuration. The achieved frequency coverage includes several sub-6 GHz 5G bands, WLAN bands, and other wireless communication frequencies, demonstrating the versatility of the proposed design.

Table 3.6 Operating Modes of the Proposed Multi-Mode Frequency Reconfigurable Antenna

Mode	SW1	SW2	Operating Frequency Bands (GHz)
Mode 1	OFF	OFF	3.69–5.61

Mode 2	ON	OFF	3.45–4.27, 4.80–5.55, 8.00–8.94
Mode 3	OFF	ON	3.56–5.38, 7.57–7.88
Mode 4	ON	ON	2.71–2.96, 4.37–5.33, 7.24–7.56

The reflection coefficient characteristics corresponding to these operating modes are presented and discussed in the following section.

3.3.3 Simulated S_{11} Performance Evaluation

The simulated S_{11} response of the developed antenna configuration was examined to assess its frequency-switching behavior under different PIN diode operating conditions. The corresponding S_{11} curves for the four switching modes are illustrated in Figure 3.11. The simulation findings confirm that, by appropriately controlling the two PIN diodes, the developed design supports both wideband and multi-band operating characteristics.

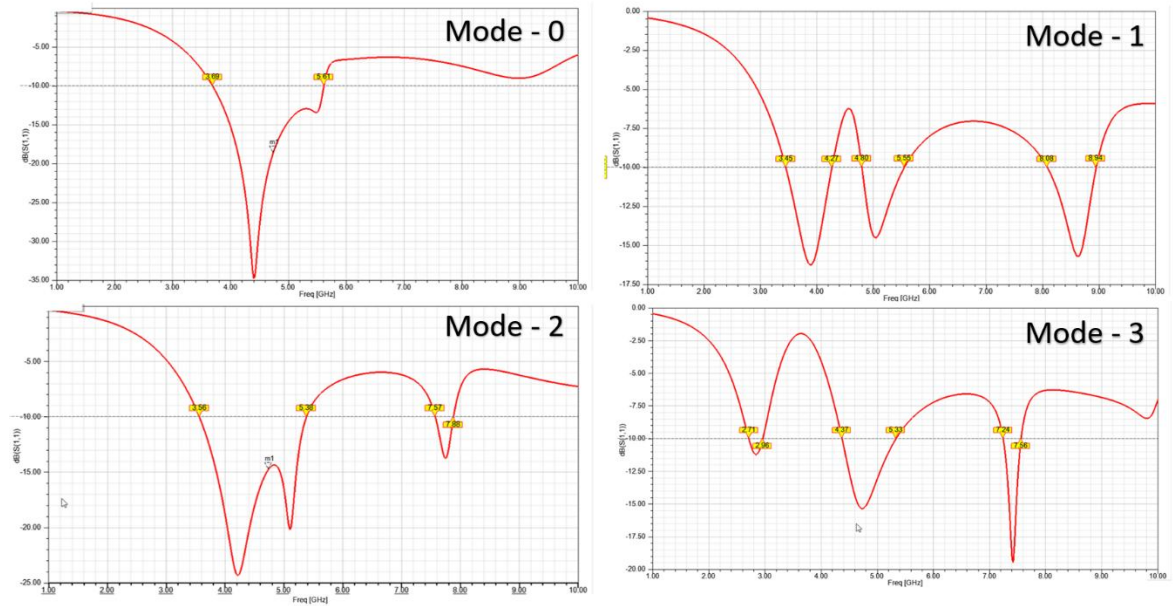


Figure 3.11 Simulated S_{11} characteristics for Different Switching Modes

In Mode 1 (SW1 = OFF, SW2 = OFF), the antenna operates over a wide frequency range extending from 3.69 GHz to 5.61 GHz. This operating mode provides continuous bandwidth coverage across a significant portion of the sub-6 GHz spectrum and is suitable for wideband wireless communication applications.

When SW1 is switched ON while SW2 remains OFF (Mode 2), the antenna exhibits three distinct operating bands covering 3.45–4.27 GHz, 4.80–5.55 GHz, and 8.00–8.94 GHz. The

introduction of an additional conductive path modifies the resonant characteristics of the radiator and results in a tri-band response. These frequency bands provide coverage for several wireless communication services including sub-6 GHz 5G and WLAN applications.

In Mode 3 (SW1 = OFF, SW2 = ON), the antenna operates as a dual-band radiator covering the frequency ranges of 3.56–5.38 GHz and 7.57–7.88 GHz. Compared with Mode 2, a different switching combination alters the effective current distribution and produces an alternative set of resonant bands.

When both switching elements are activated (Mode 4), the antenna exhibits tri-band operation with frequency coverage extending over 2.71–2.96 GHz, 4.37–5.33 GHz, and 7.24–7.56 GHz. The appearance of an additional lower-frequency band demonstrates the effectiveness of the proposed switching mechanism in generating multiple operating states from a single compact radiator.

A comparison of the four operating modes reveals that the proposed antenna offers considerable flexibility in frequency selection. Depending on the switching configuration, the antenna can operate either as a wideband structure or as a multi-band radiator. The achieved frequency coverage spans several important wireless communication bands, including sub-6 GHz 5G, WLAN, WiMAX, satellite communication, and IoT-related applications.

The results confirm that the proposed strip-loaded monopole configuration successfully achieves multi-mode frequency reconfiguration using only two PIN diodes. Furthermore, satisfactory impedance matching is maintained throughout the operating bands, indicating the suitability of the antenna for practical wireless communication systems.

3.3.4 Radiation Pattern Characteristics

The radiation performance of the proposed multi-mode frequency reconfigurable antenna was investigated to evaluate the effect of PIN diode switching on its far-field characteristics. The simulated radiation patterns corresponding to representative operating frequencies are presented in Figure 3.12.

The obtained results indicate that the antenna maintains stable radiation characteristics throughout the reconfiguration process, despite significant variation in operating frequency

across switching conditions. The radiation patterns, typical of printed monopole antennas, provide adequate coverage for practical wireless communication applications.

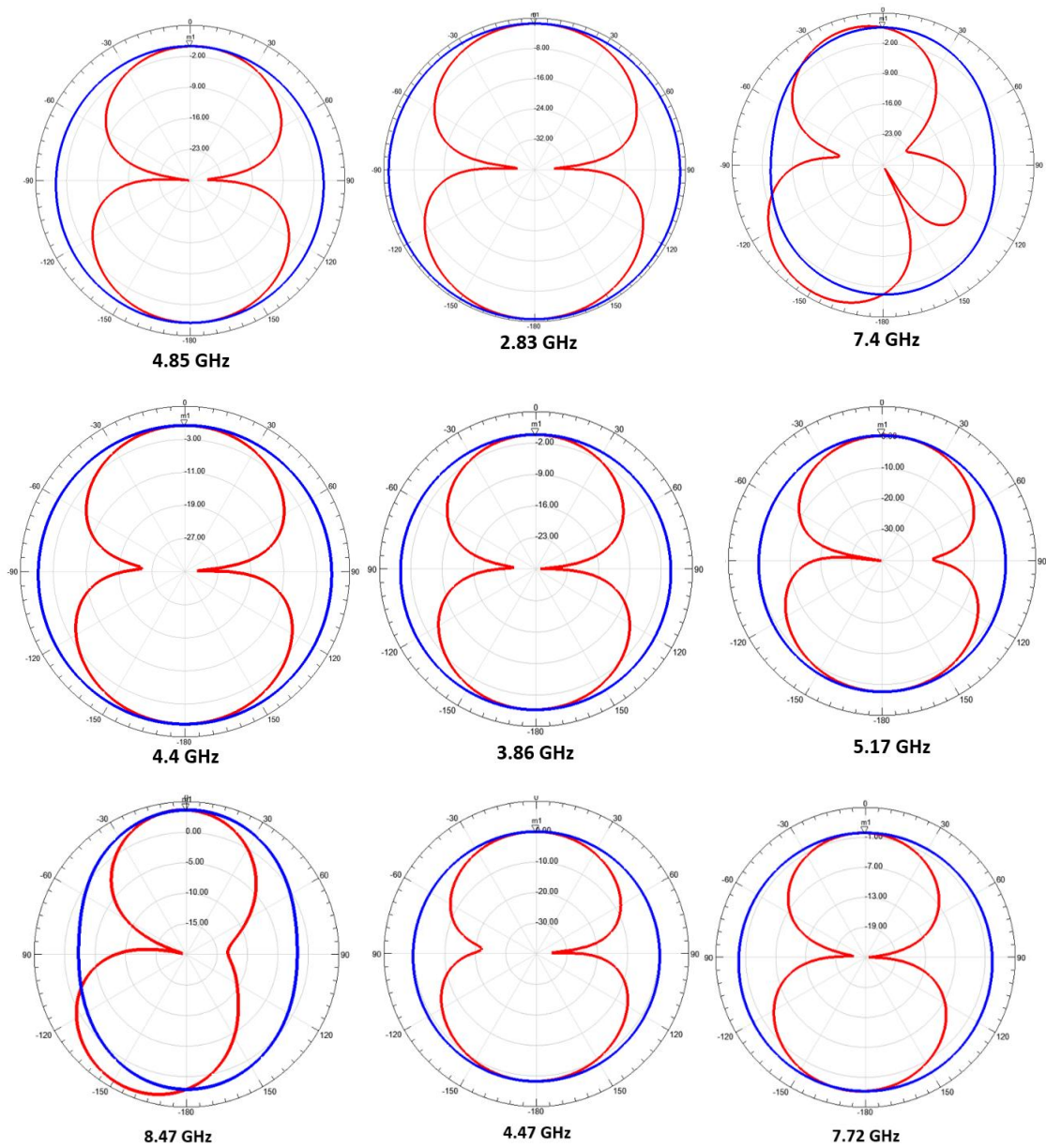


Figure 3.12 Simulated Radiation Patterns at Representative Frequencies

Across the various operating modes, the antenna demonstrates satisfactory radiation performance without exhibiting severe pattern distortion. The changes introduced by the PIN diode switching mechanism primarily influence the resonant behavior of the antenna while producing only limited variations in the far-field radiation characteristics. This observation confirms that frequency reconfiguration is achieved without significantly affecting the fundamental radiation properties of the antenna.

The simulated radiation patterns further indicate that the proposed design is capable of supporting multiple wireless communication services while maintaining acceptable radiation coverage. Such behavior is particularly desirable in reconfigurable antenna systems where frequency agility must be achieved without compromising radiation performance.

Overall, the radiation analysis validates the effectiveness of the proposed monopole structure in providing stable radiation characteristics over multiple operating bands. The combination of compact dimensions, multi-band functionality, and satisfactory radiation performance demonstrates the suitability of the proposed antenna for sub-6 GHz 5G, WLAN, WiMAX, satellite communication, and IoT applications.

3.4 Comparative Performance Evaluation

The performance characteristics of both developed frequency-reconfigurable antenna configurations are examined in this section through a detailed comparison with representative designs previously published in the literature. The evaluation considers design footprint, switching complexity, operating frequency range, supported frequency bands, and application relevance. This comparative assessment offers a detailed perspective on the strengths and practical limitations associated with the developed antenna configurations while emphasizing their contribution to advances in reconfigurable antenna technology.

3.4.1 Comparison with Existing Literature

Table 3.8 presents a comparative assessment between the developed antenna configurations and representative frequency-reconfigurable antenna designs available in previously published studies. The selected references encompass a variety of design methodologies employing PIN diodes, lumped switching devices, and tunable structures to realize frequency reconfiguration. The evaluation emphasizes practical design aspects, including physical dimensions, number of switching elements, operating frequency range, and achievable frequency reconfiguration capability.

The reviewed literature demonstrates that frequency reconfiguration is commonly achieved through the incorporation of multiple switching devices and complex radiating structures. Several reported antennas employ three or more switching elements to obtain multiple resonant bands, which increases biasing complexity and implementation cost. In contrast,

both antennas proposed in this work utilize only two PIN diodes while providing multiple operating states and wide frequency agility.

Table 3.7 Comparison of Proposed Antennas with Reported Frequency Reconfigurable Antennas

Ref.	Size (mm ²)	Switching Element	No. of Switches	Frequency Coverage (GHz)	Reconfiguration Characteristics
[14]	25 × 28	PIN Diodes	2	2.30–8.90	Six resonant bands
[17]	30 × 25	PIN Diode	1	3.2/3.5 and 5.2/5.8	Dual-band switching
[20]	25 × 25	PIN Diodes	3	3.85–6.01	Five frequency states
[21]	60 × 120	PIN Diodes	4	28/38	Dual-band mm-Wave operation
[36]	33 × 16	Varactor Diodes	2	2.45–3.55	Continuous frequency tuning
[37]	30 × 30	PIN Diodes	2	3.80–5.90	Tri-band operation
[39]	33 × 16	PIN Diodes	3	2.10–5.20	Hexa-band operation
[52]	35 × 53	Lumped Switch	1	2.45, 3.50, 5.20	Triple-band operation
Proposed Antenna-I	35 × 40	PIN Diodes	2	5.05–6.40	Four switching states
Proposed Antenna-II	30 × 20	PIN Diodes	2	2.71–8.94	Four modes with nine operating bands

Among the reported designs, compact dimensions are generally achieved at the expense of reduced frequency coverage or limited reconfiguration capability. The first proposed antenna maintains a compact size of 35 mm × 40 mm while providing four distinct switching states and multiple resonant frequencies within the WLAN and Wi-Fi frequency range. The second proposed antenna further reduces the antenna footprint to 30 mm × 20 mm and simultaneously achieves extensive frequency coverage extending from approximately 2.7 GHz to 8.9 GHz.

Another important observation from Table 3.8 is that many reported antennas are optimized for a specific wireless standard such as WLAN, LTE, WiMAX, or 5G operation. In comparison, the second proposed antenna supports multiple communication services through a single radiating structure, including sub-6 GHz 5G, WLAN, WiMAX, satellite communication, and IoT-related applications. This capability enhances system flexibility and improves spectrum utilization without requiring multiple dedicated antennas.

The comparison further indicates that the proposed designs achieve a favourable balance between compactness, switching complexity, and frequency reconfiguration capability. The use of only two PIN diodes simplifies the biasing network while maintaining effective frequency control. Consequently, the proposed antennas offer practical solutions for compact wireless devices requiring adaptable frequency characteristics and multi-standard communication capability.

3.4.2 Comparison between Proposed Antennas

Although both antennas employ PIN-diode-based frequency reconfiguration, their design objectives and operating characteristics are significantly different. The first antenna utilizes a dual L-slot microstrip patch configuration to provide frequency agility within the WLAN and Wi-Fi spectrum. The design emphasizes compact implementation, stable radiation characteristics, and relatively higher gain performance. The antenna achieves four switching states using two PIN diodes and provides resonant frequencies between 5.05 GHz and 6.40 GHz.

The second antenna adopts a printed monopole configuration incorporating multiple radiating strips and two PIN diodes. Compared with the first design, it offers significantly broader frequency coverage and supports a larger number of operating bands. Through four switching configurations, the antenna can operate over several frequency ranges extending from 2.71 GHz to 8.94 GHz, enabling support for multiple wireless communication standards.

From a radiation performance perspective, the first antenna provides higher peak gain due to its patch-based structure, making it suitable for WLAN and Wi-Fi communication systems requiring improved directional radiation characteristics. In contrast, the second antenna

prioritizes frequency versatility and application diversity, resulting in wider operating bandwidths and increased frequency coverage.

Table 3.8 Comparison between the Proposed Frequencies Reconfigurable Antennas

Parameter	Antenna-I	Antenna-II
Antenna Configuration	Dual L-slot inset-fed microstrip patch antenna	Multi-strip printed monopole antenna
Overall Size (mm ²)	35 × 40	30 × 20
Switching Elements	2 PIN diodes	2 PIN diodes
Operating Modes	4	4
Frequency Coverage (GHz)	5.05–6.40	2.71–8.94
Reconfiguration Capability	Multiple resonant frequencies within WLAN/Wi-Fi bands	Nine operating bands covering sub-6 GHz 5G, WLAN, WiMAX, satellite and IoT bands
Peak Gain (dBi)	4.28	1.92
Primary Advantage	Higher gain and stable radiation characteristics	Wider frequency coverage and greater application flexibility

The compact dimensions of the second antenna make it attractive for highly integrated wireless terminals, whereas the first antenna offers a more application-specific solution with improved gain performance. Therefore, the selection of either design depends on the intended application requirements. The first antenna is more suitable for dedicated WLAN and Wi-Fi systems, while the second antenna is better suited for multi-standard wireless platforms requiring extensive frequency agility.

Overall, both proposed antennas successfully demonstrate the effectiveness of PIN-diode-based frequency reconfiguration using a minimal number of switching elements. The obtained results validate the adopted design methodologies and confirm the suitability of the proposed antennas for modern wireless communication systems.

CHAPTER-4

Patch Antenna with Frequency and Pattern Reconfiguration

4.1 Introduction

Advances in wireless networking have increased the demand for antenna systems that can dynamically adjust their operating characteristics to satisfy diverse communication requirements. In addition to frequency agility, many applications demand dynamic control of radiation characteristics to improve coverage, reduce interference, and enhance communication reliability. As a result, antennas capable of providing both frequency and radiation pattern reconfiguration have attracted considerable research interest.

Reconfigurable antennas offer significant advantages over conventional fixed-frequency antennas by enabling multiple operating modes within a single radiating structure. Such adaptability improves spectrum utilization, reduces hardware requirements, and facilitates compact system integration. However, many reported designs employ multiple switching elements and complex biasing networks, increasing fabrication complexity and implementation cost.

To overcome these challenges, this chapter covers the development, implementation, and experimental verification of a compact microstrip radiator capable of simultaneous frequency and radiation-pattern reconfiguration using a single PIN switching device. The developed configuration incorporates nested inverted U-shaped radiating sections with strategically placed slots to generate multiple resonant modes and radiation responses. Frequency and pattern reconfiguration are realized by altering the conduction state of the PIN diode, thereby redistributing surface currents to produce different operating bands and radiation characteristics.

Unlike the antenna configurations investigated in Chapter 3 through simulation alone, the design presented in this chapter was fabricated and experimentally characterized. Numerical predictions and measurement results are correlated to confirm the effectiveness of the developed design and demonstrate its practical feasibility.

The chapter begins with the antenna design evolution, structural configuration, and switching strategy. It then examines the simulated frequency response and radiation behavior, followed by the fabrication process and experimental measurement arrangement. A correlation between computational and experimental findings is subsequently presented. Finally, the developed antenna configuration is benchmarked against representative reconfigurable antenna designs reported in the literature.

4.2 Proposed Antenna with Frequency and Pattern Reconfiguration

4.2.1 Antenna Geometry Progression

The developed dual-function frequency- and radiation-pattern-reconfigurable antenna originated from a stepwise design methodology intended to realize multiband operation, beam reconfiguration, and reduced switching complexity. The progressive modification of the antenna geometry is depicted in Figure 4.1, whereas the associated simulated S_{11} responses are presented in Figure 4.2. Every design iteration was introduced to enhance overall electromagnetic behavior while realizing the intended reconfiguration objectives.

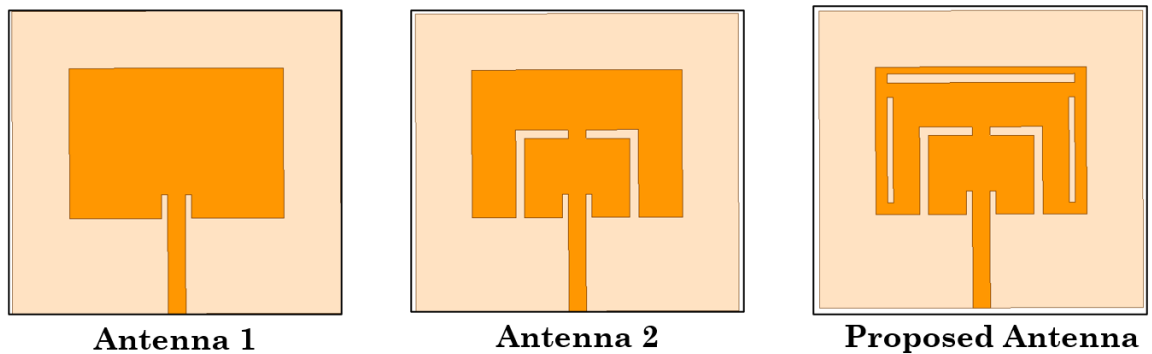


Figure 4.1 Geometry progression of developed antenna

The first stage, referred to as Antenna 1, consists of a conventional inset-fed rectangular microstrip patch. This configuration serves as the reference structure and exhibits a limited number of resonant frequencies within the operating range. Although acceptable impedance matching is obtained at selected frequencies, the antenna provides fixed radiation characteristics and limited frequency flexibility.

During the second design stage, an inverted U-slot is introduced into the patch radiator to obtain Antenna 2. This geometric modification redistributes the surface current profile, establishing an additional resonant path within the radiator. Consequently, extra resonant

modes appear, extending the operating bandwidth while improving impedance behavior. Moreover, the slot-loaded geometry lengthens the equivalent electrical path of the radiator without enlarging the overall antenna footprint.

To realize frequency and pattern reconfiguration, additional structural modifications are introduced in the final design. An outer inverted U-shaped radiating section together with strategically positioned horizontal and vertical slots are incorporated around the inner structure. Furthermore, a PIN diode is inserted across the upper section of the inner slot to enable electrical switching between different operating states. The combined effect of these modifications produces multiple current paths and allows dynamic alteration of the effective radiating structure.

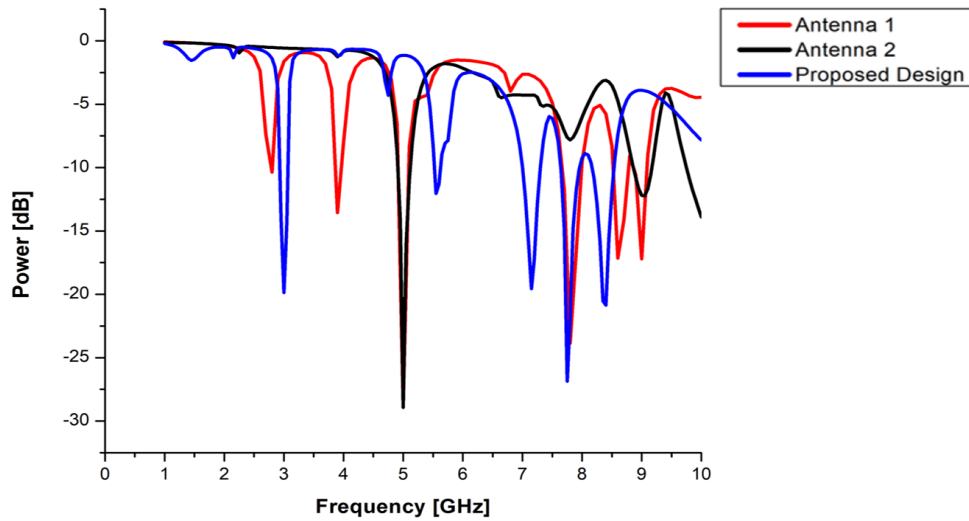


Figure 4.2 Simulated S_{11} Comparison: Antenna1, Antenna2, and Proposed

The reflection coefficient responses shown in Figure 4.2 clearly demonstrate the progressive improvement achieved during the design evolution process. Compared with Antenna 1 and Antenna 2, the proposed antenna exhibits a larger number of resonant frequencies and improved impedance matching characteristics. Additional resonances are generated in the lower and upper frequency regions, resulting in enhanced frequency coverage and improved operational flexibility. The finalized antenna configuration generates two resonant modes in one diode configuration and four resonant modes in the alternate diode configuration, successfully realizing frequency agility while requiring only a single PIN switching device.

The design evolution confirms that the introduction of nested slot structures and controlled switching effectively enhances the reconfigurable behavior of the antenna. By utilizing only one PIN diode and a compact planar configuration, the proposed design achieves multiple operating bands and radiation pattern variations while maintaining structural simplicity and ease of fabrication.

4.2.2 Structural Configuration of the Antenna

The antenna is built on 1.6 mm FR-4 laminate ($\epsilon_r = 4.4$, $\tan \delta = 0.02$), chosen to achieve the required frequency and radiation pattern reconfiguration with minimal substrate losses. The overall footprint measures 55.2 mm x 50.8 mm, and the complete geometry is presented in Figure 4.3. A continuous metallic ground conductor occupies the lower face of the dielectric substrate, whereas the radiating element is formed on the opposite face and energized through a 50 Ω microstrip feeding structure.

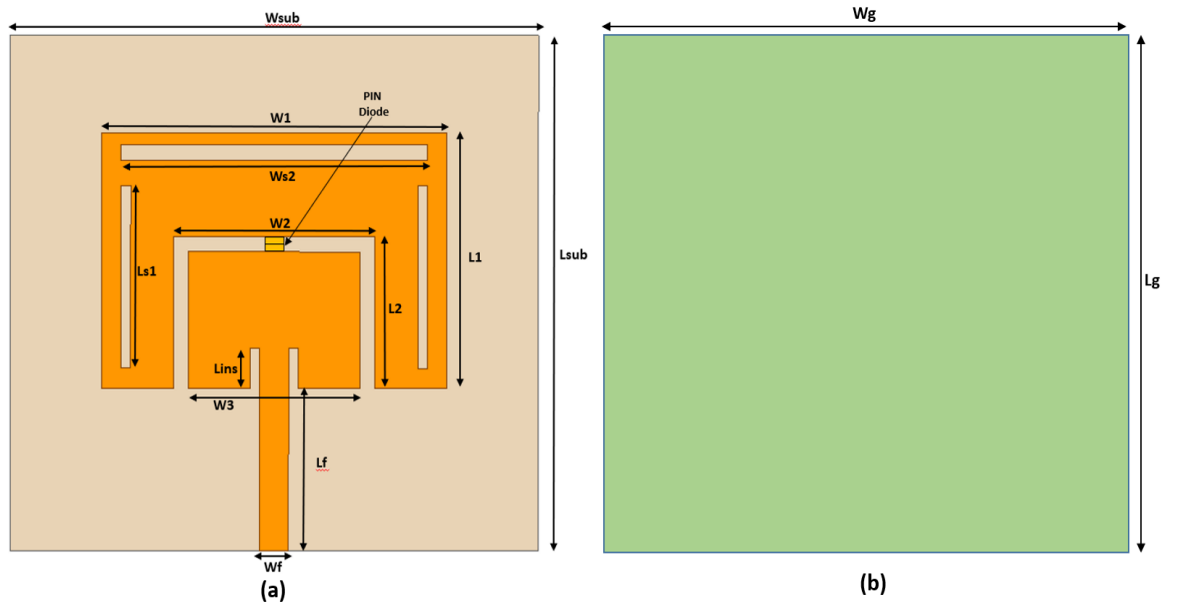


Figure 4.3 Geometry of the developed frequency and pattern reconfigurable antenna: (a) Top view (b) Bottom view

The radiating element consists of two nested inverted U-shaped conducting sections. The outer inverted U-shaped structure forms the primary radiating framework and is characterized by dimensions W_1 and L_1 . An inner inverted U-shaped structure with dimensions W_2 and L_2 is positioned concentrically within the outer radiator. The

arrangement of these two radiating sections creates multiple current paths and contributes to the compact realization of the antenna.

The upper segment of the inner inverted U-shaped radiator is electrically bridged by a single PIN diode. This switching element governs the conductive path responsible for the inner resonating structure. The diode is strategically located to control the electrical continuity of the inner radiator and to modify the resonant current path under different switching conditions. This arrangement enables dynamic alteration of the antenna characteristics while maintaining a simple biasing configuration.

Table 4.1 Optimized Dimensions of the Developed Patch with Frequency and Pattern Reconfiguration

Parameter	Description	Value (mm)
W_{sub}	Width of substrate	55.2
L_{sub}	Length of substrate	50.8
W_1	Width of outer inverted U-shaped radiator	36
L_1	Length of outer inverted U-shaped radiator	25.2
W_2	Width of inner inverted U-shaped radiator	21
L_2	Length of inner inverted U-shaped radiator	15
L_{s1}	Length of vertical side slots	18
W_{s2}	Length of horizontal slot	32
W_3	Width of inner patch	18
W_g	Ground conductor width	55.2
L_g	Ground conductor length	50.8
W_f	Feed line conductor width	3
L_f	Feed line conductor length	20
L_{ins}	Length of inner stubs	4.6

In addition to the nested radiating elements, a horizontal slot is introduced along the upper region of the outer radiator, while two vertical slots are formed on the side arms. These modifications redirect surface current flow and establish additional resonance modes within the structure. Two short metallic stubs positioned near the feed section further improve impedance behavior and strengthen the antenna's electromagnetic characteristics.

The final geometric dimensions obtained after design optimization for the developed antenna are provided in Table 4.1. These dimensions were obtained through extensive parametric optimization to achieve the desired operating bands, stable radiation characteristics, and effective reconfiguration performance while preserving compact size and structural simplicity.

The overall antenna configuration combines slot loading, nested radiating elements, and electronic switching within a single planar structure. Such an arrangement provides an effective platform for achieving both frequency and radiation pattern reconfiguration using only one switching element. The operating principle and switching mechanism of the antenna are discussed in the following section.

4.2.3 PIN Diode Switching States

The reconfigurable operation of the proposed antenna is realized using a single SMP1345-079LF PIN diode manufactured by Skyworks Solutions. The diode is positioned across the upper section of the inner inverted U-shaped radiating structure, where it controls the electrical connection between different portions of the radiator. By changing the biasing condition of the diode, the current path within the antenna can be altered, thereby modifying the resonant behavior and radiation characteristics of the antenna.

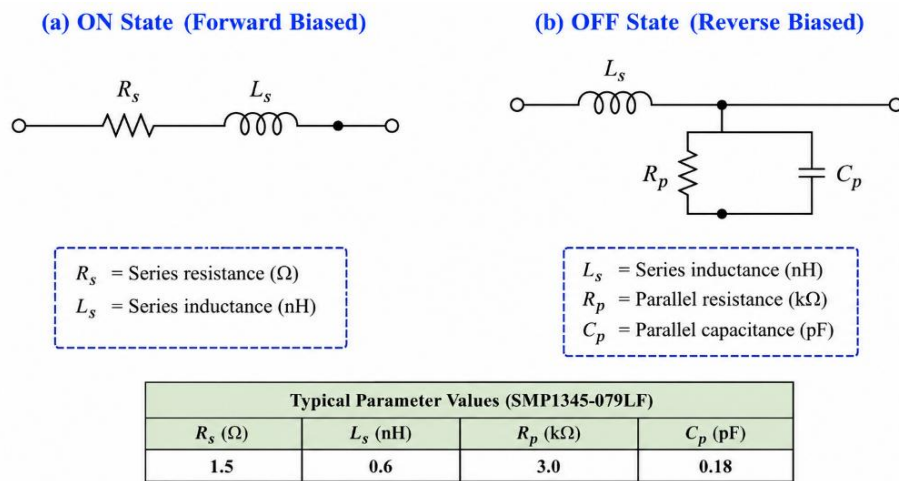


Figure 4.4 Equivalent circuit models of the SMP1345-079LF PIN diode under ON and OFF states.

For electromagnetic simulation, the SMP1345-079LF PIN diode is represented using equivalent circuit models corresponding to its conducting and non-conducting states, as

shown in Figure 4.4. In the forward-biased condition, the diode behaves as a low-resistance conductive path, allowing RF current to flow across the switching location. In the reverse-biased condition, the diode exhibits a high impedance and effectively interrupts the current flow between the connected sections of the radiating element.

The switching action directly affects the effective electrical length of the antenna. When the PIN diode remains in turned off state, the available current paths are restricted, resulting in a limited number of resonant modes. When the diode is switched ON, additional conductive paths are established, increasing the effective electrical length and generating additional resonances. Consequently, different operating bands are obtained under the two switching conditions.

Table 4.2 Operating states of the developed antenna with frequency and pattern reconfiguration

Case	PIN Diode State	Number of Frequency Bands	Operating Frequency Bands (GHz)	Center Frequency (GHz)
0	OFF	2	4.91–5.10, 7.64–7.96	5.0, 7.80
1	ON	4	3.00–3.18, 5.50–5.63, 7.00–7.30, 7.64–7.96	3.10, 5.55 7.15 7.75

The operating conditions investigated in this study are listed in Table 4.2. Under Case 0, the switching diode remains non-conducting, allowing the radiator to function in a two-band resonant mode. During Case 1, the diode is turned ON, activating additional resonant paths within the radiating topology to realize four-band operation. Employing only one switching device simplifies bias-circuit implementation while maintaining effective frequency- and pattern-reconfiguration capability.

Besides controlling the resonant frequencies, diode switching also redistributes RF surface currents across the radiator. The resulting variation in current flow modifies the radiation characteristics at selected operating frequencies, thereby enabling radiation-pattern reconfiguration together with frequency agility. The effect of surface-current redistribution across the radiator is discussed in the following subsection.

4.2.4 Surface Current Distribution Analysis

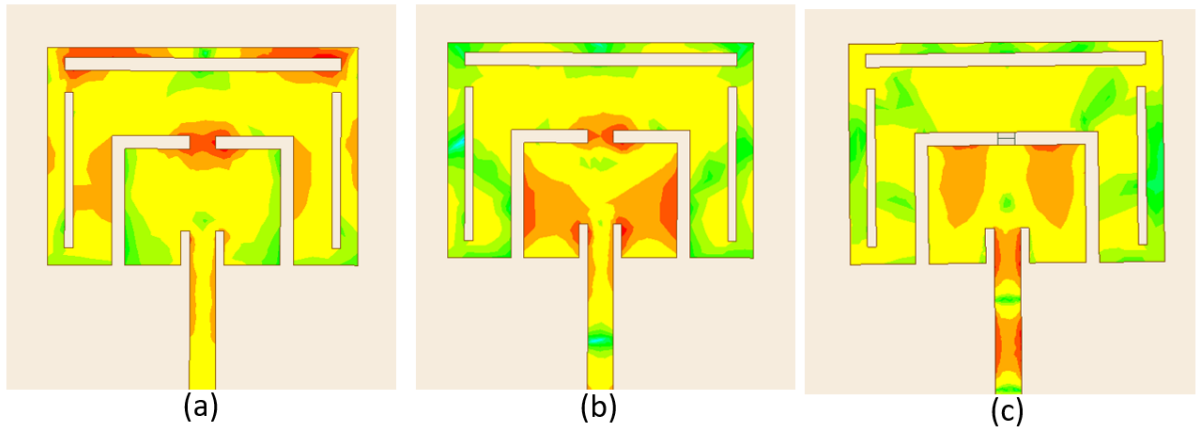


Figure 4.5 Surface current distributions at resonant frequencies: (a) 3.0 GHz (PIN diode ON), (b) 5.55 GHz (PIN diode ON), and (c) 7.80 GHz (PIN diode OFF)

To clarify the electromagnetic behavior of the developed antenna, simulated surface-current maps were examined for representative resonant modes under different diode-switching conditions. These distributions identify the principal radiating regions and demonstrate how PIN diode switching modifies the effective current path. Representative surface-current maps at 3.0 GHz, 5.55 GHz, and 7.80 GHz are provided in Figure 4.5.

When the SMP1345-079LF PIN diode is switched ON, an electrically continuous path is created across the switching junction, enabling RF current to propagate over a larger portion of the radiator. At 3.0 GHz (Figure 4.5(a)), pronounced current accumulation appears along the microstrip feed, the central radiating region, and the connected inner radiator. The resulting increase in the equivalent current path lowers the antenna resonance, producing the minimum operating frequency under the ON condition.

The current distribution at 5.55 GHz, shown in Figure 4.5(b), exhibits significant current concentration around the inner inverted U-shaped structure and the diode region. Compared with the lower-frequency resonance, the current becomes more localized within the central portion of the antenna, indicating the excitation of a different resonant mode. The interaction between the inner and outer radiating sections contributes to the generation of additional operating bands while maintaining satisfactory impedance matching.

For the diode OFF configuration, Figure 4.5(c) presents the simulated surface-current profile at 7.80 GHz. In this condition, the current flow through the switching location is interrupted, and the radiating behavior is primarily governed by the remaining conductive paths within the antenna structure. The current is concentrated near the feed region, inner radiator, and upper radiating sections, indicating excitation of a higher-order resonant mode. The reduction in effective electrical length relative to the ON state explains the disappearance of the lower-frequency resonances and the resulting dual-band response.

A comparison of the current distributions clearly demonstrates the role of diode switching in controlling the current paths within the antenna. When the diode is activated, additional conductive routes become available, increasing the effective electrical length and producing extra resonant frequencies. Conversely, when the diode is deactivated, the current path is restricted, resulting in fewer resonant modes. These observations confirm that the reconfigurable behavior of the antenna is directly associated with the modification of surface current distributions produced by the switching mechanism.

Current redistribution under different switch configurations alters the antenna's electromagnetic emission profile. As a result, the far-field beam structure exhibits reconfiguration alongside the frequency shift. The S_{11} characteristics corresponding to both switching states are presented below.

4.2.5 Simulated Reflection Coefficient Characteristics

We validated the frequency reconfiguration capability by executing electromagnetic field simulations in Ansys HFSS. Figure 4.6 presents the reflection coefficient traces across the diode's two operational states—with particular focus on the ON/OFF switching behavior of the SMP1345-079LF PIN diode. These scattering parameter measurements reveal the antenna's resonant structure and quantify how diode switching modulates the operating frequencies.

Disabling the PIN diode interrupts the electrical pathway coupling the radiating sections, effectively shortening the accessible electromagnetic path length within the antenna body. Under this configuration, the antenna enters a dual-band operational regime with primary resonances at approximately 5.0 GHz and 7.75 GHz. Both frequencies maintain impedance alignment within the -10 dB threshold, confirming adequate energy coupling from the feed network to the radiating structure. This dual-band behavior emerges from the current

patterns established along the peripheral radiating arms and the slot-loaded regions, which dominate the electromagnetic response in the absence of the central diode bridge.

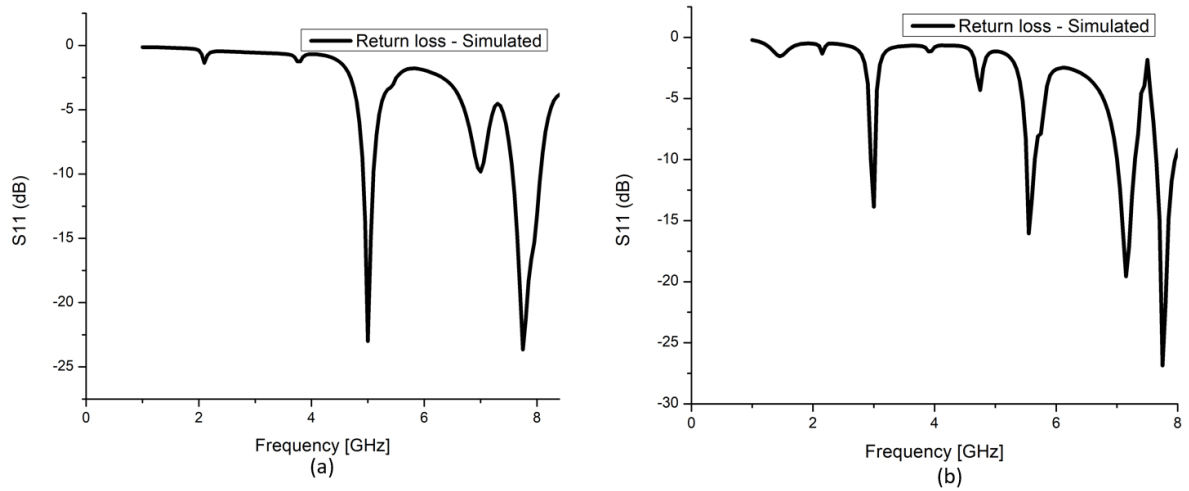


Figure 4.6 Simulated S_{11} for PIN Diode (a) ON and (b) OFF State

Activating the PIN diode establishes a conducting path across the switching junction, permitting current redistribution throughout extended regions of the radiating structure. This electrical reconfiguration lengthens the electromagnetic path traversed by the antenna's current distribution and excites additional modal responses. The result is a shift toward quad-band operation, with resonant frequencies manifesting at approximately 3.10, 5.55, 7.15, and 7.75 GHz. The appearance of these supplementary resonances validates the efficacy of single-diode switching architecture for achieving multi-band frequency reconfiguration.

A comparison of the two switching conditions clearly illustrates the reconfigurable nature of the antenna. The OFF state supports operation over two distinct frequency bands, whereas the ON state generates four operating bands covering a wider frequency range. The lower-frequency resonance observed near 3.10 GHz is achieved due to the increased current path length created when the diode is activated. Similarly, the resonances appearing near 5.55 GHz and 7.15 GHz are associated with additional resonant modes generated by the interaction between the nested radiating sections and the slot configuration.

The simulation results reveal consistent impedance alignment throughout the operating spectrum. All reflection coefficient measurements remain suppressed below -10 dB, substantiating robust energy coupling between the feed network and the radiating structure across both operational states. Particularly noteworthy is the ability to transition between dual-band and quad-band configurations through a single diode element - a feature that underscores the architectural elegance and practical efficiency of this reconfigurable design.

The resonant frequencies extracted from the S_{11} simulations, paired with their corresponding directional gain characteristics, are compiled in Table 4.3.

Table 4.3 Simulated operating frequencies and gain characteristics of the proposed antenna.

Case	PIN Diode State	Resonant Frequency (GHz)	Reflection Coefficient (dB)	Peak Gain (dBi)
0	OFF	5	-23	3.69
0	OFF	7.75	-23.65	2.75
1	ON	3.1	-18.53	3.98
1	ON	5.55	-15	5.27
1	ON	7.15	-19.56	3.66
1	ON	7.75	-26.85	5.59

Reflection coefficient measurements confirm that current path manipulation enables effective frequency tuning across multiple bands. The operating frequencies identified from the simulation results are subsequently validated through experimental measurements and discussed in Section 4.3. In addition to frequency agility, the antenna also exhibits radiation pattern variation under different operating conditions, which is experimentally investigated in the later sections of this chapter.

4.3 Fabrication and Experimental Validation

To verify the practical feasibility of the proposed frequency and pattern reconfigurable antenna, a prototype was fabricated and experimentally characterized. The validation process was carried out to confirm the frequency reconfiguration capability achieved through PIN diode switching and to evaluate the radiation characteristics under different operating conditions. Experimental validation employed a precision-calibrated VNA for S-parameter acquisition and anechoic chamber facilities to map the radiation patterns across both switching states.

Fabrication utilized commercially available FR4 substrate, chosen for its economical accessibility and suitable dielectric characteristics ($\epsilon_r = 4.4$, 1.6mm thickness). The optimized slot configuration and switching arrangement obtained through electromagnetic simulation were implemented on the fabricated prototype. A Skyworks SMP1345-079LF

PIN diode was integrated at the designated switching location, while appropriate biasing components were employed to provide effective isolation between the RF and DC paths.

Experimental measurements across both switching states were directly compared against HFSS predictions, revealing the fidelity of the design approach and quantifying deviations attributable to substrate tolerance stack-up, solder joint parasitics, connector discontinuities, and diode equivalent circuit effects.

The validation process consists of three major stages. First, the fabricated antenna prototype and measurement arrangements are presented. Subsequently, the reflection coefficient characteristics are analyzed to verify the operating frequency bands obtained under different switching conditions. Radiation measurements across both switching states were conducted to demonstrate pattern agility and quantify the fidelity between full-wave predictions and experimental far-field data.

The close correspondence observed between simulation and measurement validates the modal excitation fidelity of the slot-based reconfiguration scheme and affirms the spectral compatibility of the antenna with multi-band wireless communication applications. The detailed experimental results are presented in the following sections.

4.3.1 Fabricated Prototype and Measurement Setup

Practical validation of the frequency and pattern reconfigurable design required fabrication and experimental characterization of a working prototype. The antenna structure was realized on FR4 laminate [substrate ($\epsilon_r = 4.4$, $\tan \delta = 0.02$, $h = 1.6$ mm)], with geometry derived directly from electromagnetic optimization. Prototype implementation leveraged standard PCB fabrication processes to translate the optimized design dimensions with high fidelity. The Skyworks SMP1345-079LF PIN diode was integrated at the designated switching junction to enable dynamic frequency and radiation pattern control.

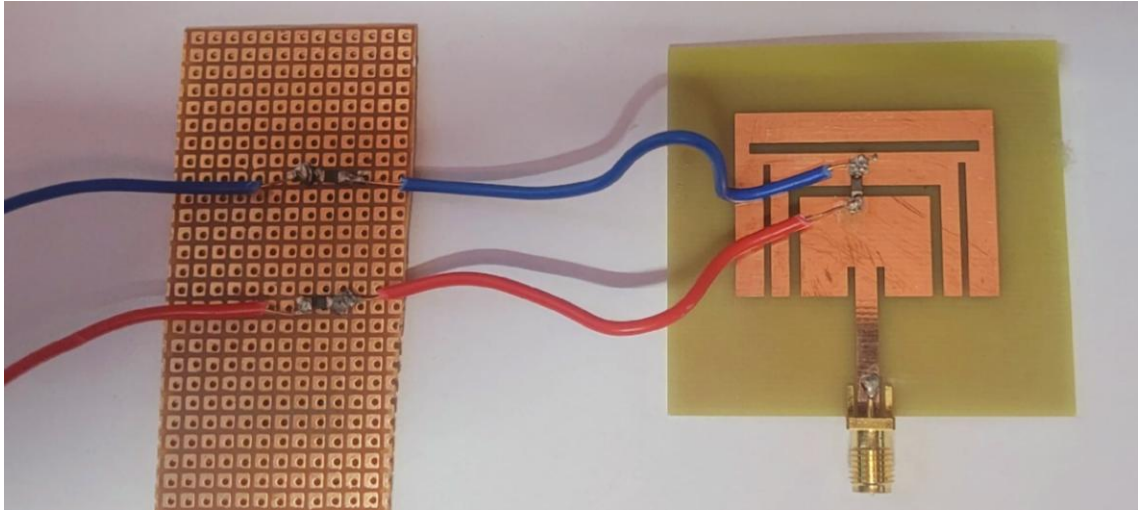


Figure 4.7 Fabricated prototype of the proposed frequency and pattern reconfigurable antenna.

The fabricated structure follows a conventional microstrip architecture: the top substrate face contains the radiating geometry and feed line, while the bottom face provides the ground reference plane. Particular attention was given to maintaining dimensional accuracy during fabrication, as small variations in slot dimensions or diode placement can influence the resonant characteristics of reconfigurable antennas. The PIN diode was carefully soldered across the switching gap, and the biasing arrangement was implemented to ensure reliable switching operation without significantly affecting the RF performance.

The antenna's S-parameter response was mapped across both switching states using calibrated vector network analysis and anechoic chamber facilities. Bias voltage modulation of the PIN diode controlled the switching transitions during measurement. Complete two-port calibration was executed beforehand to eliminate parasitic effects from the measurement chain—cables, connectors, and fixture discontinuities.

The characterization apparatus (Figure 4.8) consisted of a 50Ω SMA-connected antenna interface to precision VNA instrumentation. Reflection coefficient acquisition covered the full frequency band across both switching configurations, with experimental observations subsequently contrasted against full-wave electromagnetic predictions to establish design validation and characterize deviations attributable to real-world implementation

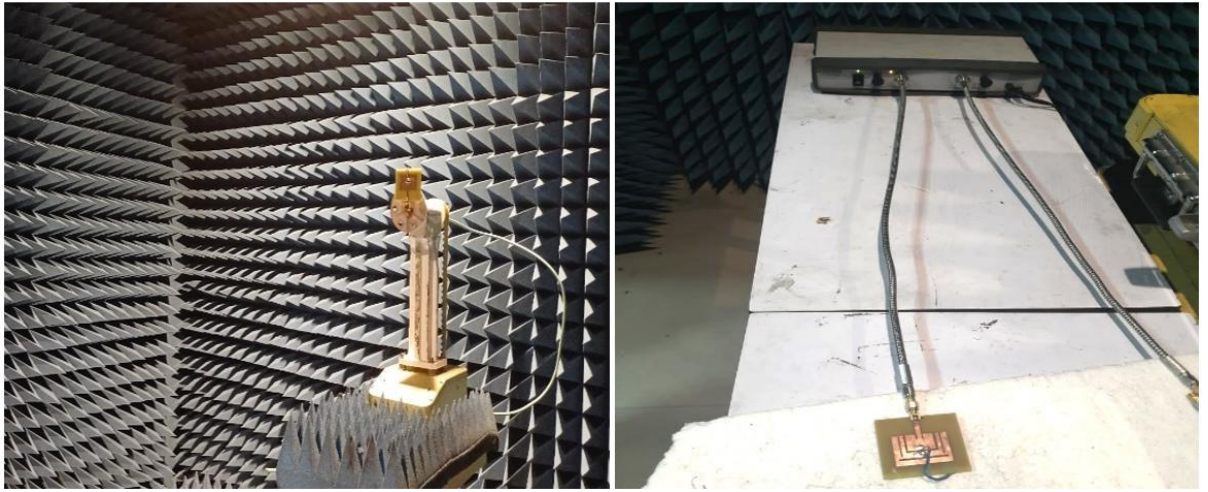


Figure 4.8 Measurement setup: (a) Radiation pattern measurement in an anechoic chamber
(b) VNA measurement of antenna reflection response

Radiation pattern acquisitions were carried out within an anechoic chamber to provide a reflection-free enclosure and ensure accurate far-field characterization. During measurement, the antenna under test was secured atop an azimuthal rotary positioner while a calibrated gain-standard horn radiator served as the transmitting antenna. The received power levels were sampled across discrete angular positions to obtain the radiation patterns corresponding to each reconfigurable resonant state of the antenna.

Collectively, the VNA-based reflection coefficient measurements and anechoic chamber radiation pattern characterization furnish a dual-domain experimental verification of the realized design. Scattering parameter and far-field data are juxtaposed against the simulated responses in the subsequent sections to evaluate the effectiveness of the frequency and pattern reconfiguration mechanism implemented using a single PIN diode.

4.3.2 Measured Reflection Coefficient Characteristics

Experimental quantification of the antenna's S_{11} response was undertaken to substantiate the numerical electromagnetic analysis presented previously. Reflection measurements spanning both conductive and reverse-biased operational modes of the integrated PIN diode were executed using calibrated network analysis with systematic source-load de-embedding. Direct comparison of measured scattering parameters against full-wave HFSS data established the computational model's predictive fidelity while simultaneously validating the

switching mechanism's capability to achieve frequency-band reconfiguration through controlled diode bias modulation

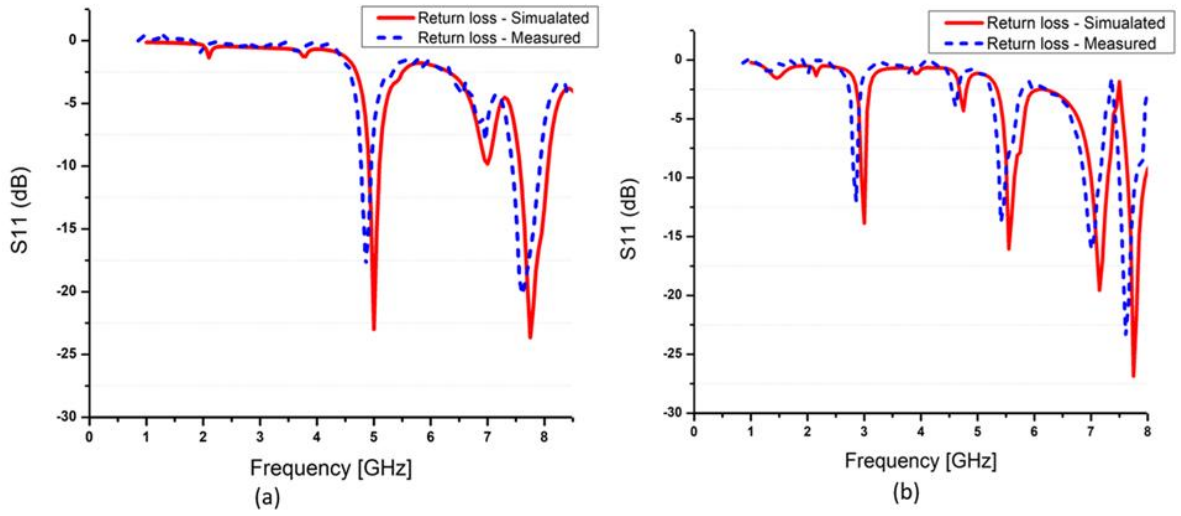


Figure 4.9 Simulated vs Measured S_{11} for PIN Diode ON/OFF States

Figure 4.9 presents the experimental validation of S_{11} magnitude response across the PIN diode's dual operational bias states. In the reverse-bias configuration, the antenna manifests dual-resonance behavior with primary modal responses centered approximately at 5.0 GHz and 7.8 GHz. The measured scattering parameter traces exhibit exceptional concordance with full-wave predictions, maintaining impedance alignment ($S_{11} < -10$ dB) throughout both resonant passbands. This quantitative agreement substantiates the predictive capability of the electromagnetic model and validates the architectural implementation of the intended dual-band operational regime.

Activation of the integrated PIN diode engenders additional electromagnetic modal excitation through redistribution of the current pathway architecture within the radiating structure. This operational state precipitates quad-band resonant behavior, with characteristic impedance minima manifesting at approximately 3.1 GHz, 5.55 GHz, 7.15 GHz, and 7.8 GHz. Experimental S_{11} measurements demonstrate excellent parametric concordance with full-wave electromagnetic predictions, substantiating the frequency-agile reconfiguration capability inherent to the diode-switching architecture.

Quantitative analysis reveals minor frequency offset between measured and simulated resonant peaks across selective operating bands. Such discrepancies are intrinsic to real-world microstrip antenna implementations and stem from cumulative effects of fabrication

dimensional tolerances, substrate permittivity variance ($\epsilon_r = 4.4 \pm \delta$), solder-joint parasitic inductance associated with diode integration, coaxial feed-line discontinuities at the SMA interface, and bias network component reactance. Furthermore, deviations between the idealized electromagnetic model (zero-loss materials, perfect geometry) and the as-fabricated prototype architecture contribute to measurable frequency perturbations in the experimental response.

Notwithstanding the fabrication-induced frequency perturbations enumerated above, quantitative analysis demonstrates adequate parametric concordance between measured and simulated S_{11} response across the entire operational bandwidth. Experimental measurements faithfully reproduce both the dual-modal and quad-modal resonant architectures predicted through full-wave electromagnetic simulation, thereby substantiating the efficacy of the diode-mediated frequency reconfiguration mechanism. The exceptional measurement-to-simulation agreement validates the design methodology's predictive accuracy and establishes the prototype's practical implementability for multi-band RF communication systems.

Experimental impedance characterization furnishes empirical confirmation of the adopted design framework's electromagnetic modelling fidelity, establishing confidence in the optimization approach. Comprehensive architectural validation is further accomplished through far-field radiation pattern characterization, presented in the subsequent section.

4.3.3 Radiation Pattern Characteristics

The radiation characteristics of the proposed frequency and pattern reconfigurable antenna were experimentally evaluated to validate the simulated performance and investigate the influence of PIN diode switching on the far-field behavior of the antenna. Radiation pattern measurements were carried out inside an anechoic chamber at the operating frequencies corresponding to the ON and OFF states of the SMP1345-079LF PIN diode. The measured E-plane and H-plane radiation patterns were subsequently compared with the simulated results obtained through full-wave electromagnetic analysis.

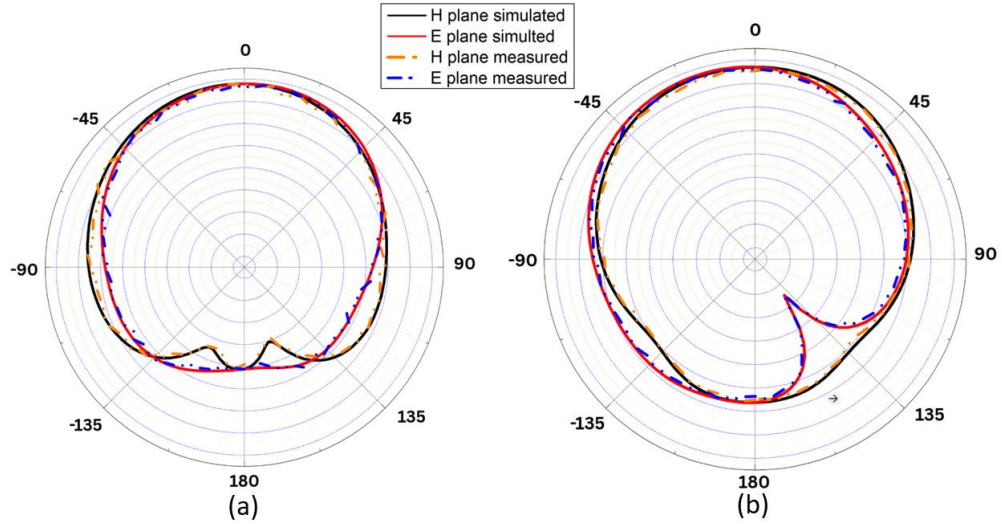


Figure 4.10 Simulated and measured E-plane and H-plane radiation patterns of the proposed antenna at (a) 3.10 GHz and (b) 5.00 GHz.

Figure 4.10 juxtaposes the full-wave simulated and experimentally acquired far-field radiation patterns at 3.10 GHz and 5.00 GHz. At 3.10 GHz, which corresponds to the lowest resonant frequency in the PIN diode ON state, the antenna demonstrates stable radiation characteristics with strong agreement between the co-polarized E-plane and H-plane pattern envelopes extracted from simulation and measurement. The experimental radiation profiles accurately reproduce the predicted main lobe direction and beam shape from the simulation. Similarly, at 5.00 GHz, the measured far-field patterns exhibit strong spatial correlation with the full-wave predictions, substantiating that the fabricated antenna successfully maintains the intended radiation performance across both operating bands.

Figure 4.11 illustrates the radiation characteristics at 3.10 GHz, 5.55 GHz, 7.15 GHz, and 7.75 GHz. At these higher operating frequencies, the E-plane and H-plane response variations become more evident due to excitation of higher-order resonant modes and the corresponding redistribution of surface currents across the antenna structure. The measured patterns demonstrate strong agreement with simulated responses, confirming the electromagnetic behavior anticipated through full-wave analysis.

The observed differences in radiation characteristics directly correlate with the current path reconfiguration induced by the switching mechanism. When the PIN diode transitions between states, the antenna's electromagnetic path length is modulated, producing both frequency shifts and modifications to the current distribution that governs radiation performance. Consequently, the antenna exhibits distinct directional responses at each

operating frequency, with characteristic E-plane and H-plane patterns that reflect the active resonant mode configuration.

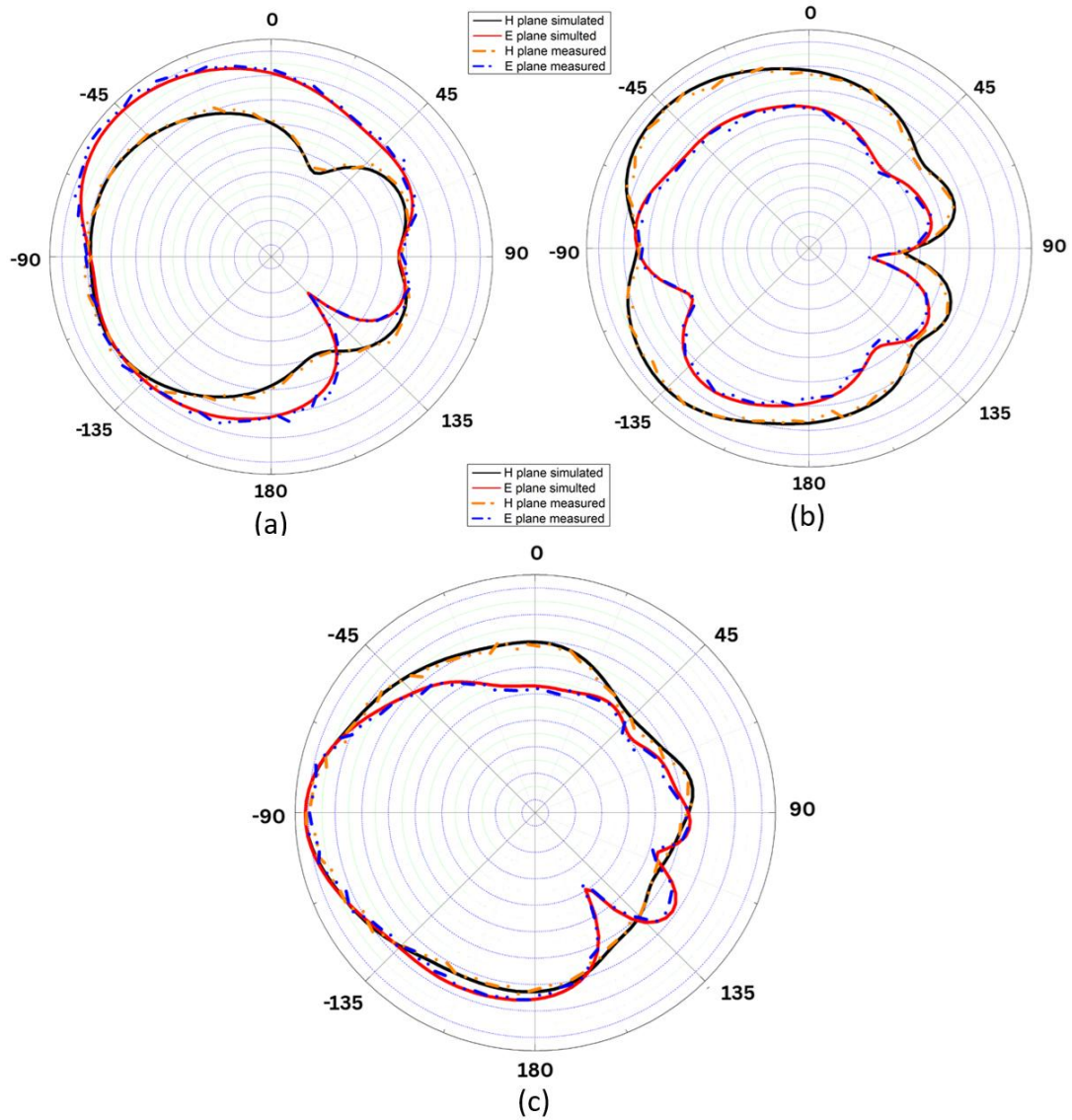


Figure 4.11 Figure 4.11 Simulated and measured E-plane and H-plane radiation patterns of the proposed antenna at (a) 5.55 GHz, (b) 7.15 GHz and (c) 7.75 GHz.

While minor deviations are observed between measured and simulated results—particularly in sidelobe magnitude levels and radiation pattern nulls—the overall pattern characteristics remain consistent across the operating bandwidth. Such discrepancies are inherent to practical antenna characterization and originate from fabrication tolerances, measurement alignment uncertainties, feed network discontinuities, and parasitic effects from the integrated biasing components in the prototype.

Comparative analysis of radiation patterns across all operating frequencies demonstrates that the antenna maintains stable radiation performance while supporting multiple operational modes. Importantly, the observed variations in E-plane and H-plane characteristics confirm the antenna's pattern reconfiguration capability alongside its frequency-agility function. The strong measurement-to-simulation agreement validates the adopted design methodology and establishes the antenna's applicability for modern multi-band wireless systems requiring dynamic and adaptable operating characteristics.

4.4 Comparison with Existing Literature

To evaluate the effectiveness of the developed antenna, its performance is compared with previously reported reconfigurable antenna designs available in the literature. The comparison includes antenna dimensions, number of switching elements, operating frequency bands, pattern reconfiguration capability, and maximum gain. The comparative results are presented in Table 4.4.

Table 4.4 Performance comparison of the proposed antenna with reported reconfigurable antenna designs.

Ref	Size(mm ³)	No. of switches	Reconfigurable frequency (GHz)	Pattern reconfigurable	Maximum gain (dBi)
[20]	50 x 50 x 1.6	4	4.5, 4.8/5.2, 5.8	Yes	3.8
[33]	61 x 38 x 1.5	3	2.0 to 10.0 (8 bands)	NA	NA
[34]	80 x 30 x 1.6	4	2.4 to 6.5 (4 bands)	No	4.5
[35]	60 x 50 x 1.6	3	5.2 and 5.8	Yes	3
[36]	30 x 49 x 1.6	8	1.98 to 2.76 (Multiband)	No	1.8
[37]	60 x 40 x 1.6	12	2.3 to 5.87 (4 bands)	Yes	12.87
[38]	60 x 66 x 1.6	4	2.96 and 3.26	Yes	3.29
[39]	50 x 45 x 1.52	5	2, 3.5 and 5.3	Yes	1.8
[40]	40 x 50 x 0.254	2	1.64 to 2.54 (3 bands)	Yes	NA
Prop.	50.8 x 55.2 x 1.6	1	3.10, 5, 5.55, 7.15, 7.75	Yes	5.59

Table 4.4 demonstrates that reported frequency-reconfigurable antennas typically employ multiple switching elements and intricate radiating architectures to achieve multiband operation. In most implementations, three to twelve active switches are required to realize the specified operating bands and directional characteristics. While such approaches provide

substantial reconfiguration capability, they incur significant penalties in biasing network complexity, fabrication challenges, DC power consumption, and manufacturing cost.

The proposed antenna achieves simultaneous frequency and pattern reconfiguration through integration of a single SMP1345-079LF PIN diode. Relative to reported designs, this configuration substantially reduces switching complexity while preserving multi-mode operation. The minimized number of active switching elements significantly simplifies the bias distribution network and enhances practical implementation feasibility for deployment in wireless communication systems.

A distinctive feature of the proposed design is the generation of five discrete operating frequencies—3.10 GHz, 5.00 GHz, 5.55 GHz, 7.15 GHz, and 7.75 GHz—across two diode bias states. This multi-band performance is realized without augmenting the antenna's structural complexity or incorporating supplementary switching components. Furthermore, the proposed antenna preserves radiation pattern reconfiguration across all operating frequencies, a capability absent from many frequency-reconfigurable architectures documented in prior research.

The measured peak gain of 5.59 dBi demonstrates adequate directional performance while maintaining a compact planar architecture. While certain reported antennas achieve higher gain magnitudes, they typically necessitate substantially more switching elements or significantly more complex antenna topologies. Therefore, the proposed design establishes an effective trade-off among gain performance, switching element count, antenna footprint, and reconfiguration capability.

Overall, comparative analysis substantiates that the proposed antenna integrates compact substrate dimensions, minimal switching complexity, multi-frequency band operation, and radiation pattern reconfiguration into a unified structure. The achievement of these combined functionalities through a single PIN diode underscores the design's operational efficiency and establishes its applicability for modern multiband wireless communication systems demanding adaptive operating characteristics.

4.5 Summary

This chapter has delineated the design, electromagnetic simulation, prototype fabrication, and experimental characterization of a compact frequency and pattern reconfigurable microstrip antenna utilizing a single SMP1345-079LF PIN diode through slot-loaded radiating elements and a simplified switching mechanism.

The design methodology encompassed systematic parametric investigation via antenna topology evolution, diode bias state analysis, and reflection coefficient profiling. Full-wave electromagnetic simulations established multifrequency operation through PIN diode state modulation, with frequency reconfiguration realized via electrical path redistribution within the radiating structure.

Prototype validation was conducted through FR4 substrate fabrication and experimental measurement using calibrated network analysis and anechoic chamber characterization. Measured S_{11} response exhibited strong agreement with simulated predictions, substantiating the reconfiguration mechanism's operational effectiveness. Experimental E-plane and H-plane measurements confirmed the predicted radiation characteristics and validated pattern reconfiguration capability.

Comparative analysis demonstrates that this architecture integrates compact dimensions, multiband capability, reduced switching complexity, and experimentally established performance—features achieved through a single PIN diode while maintaining operation across five discrete frequencies. Unlike designs requiring multiple switching elements, this approach provides simultaneous frequency and pattern reconfiguration.

The analysis substantiates the antenna's efficacy for contemporary wireless systems demanding adaptive frequency and radiation behavior, confirming practical implementation feasibility and establishing its potential for integration into compact multifunction wireless platforms.

CHAPTER-5

Compact Circular Microstrip Antenna with Frequency Reconfiguration

5.1 Introduction

The escalating demand for miniaturized wireless transceivers capable of sustaining concurrent multi-standard operation has intensified the need for antenna architectures with dynamically tunable spectral characteristics. Conventional microstrip radiators are fundamentally constrained to single or narrowly defined frequency bands, rendering them inadequate for modern multifunctional RF front-end platforms. Reconfigurable antennas circumvent this limitation by dynamically reconfiguring their electromagnetic operating state through controllable switching elements, enabling a single radiating aperture to address multiple spectral allocations while preserving compactness.

Among established reconfiguration methodologies, PIN diode switching remains among the most practically viable, attributed to its low forward-bias voltage requirements, sub-microsecond switching speed, minimal insertion loss, and straightforward monolithic integration with planar microstrip topologies. Selective modulation of electrical continuity across the radiating element or ground plane perturbs the surface current density distribution and effective electrical path length, thereby inducing multiple resonant conditions without necessitating supplementary radiating elements.

Extending the parametric investigations from Chapters 3 and 4, this chapter presents a frequency reconfigurable circular microstrip antenna incorporating two PIN diodes embedded within the radiating patch and a defected ground structure (DGS). The circular patch geometry is adopted for its inherent symmetry, azimuthally uniform current distribution, and multimodal resonance excitation capability through controlled structural perturbations. To extend spectral agility, a combination of T-shaped and U-shaped slot perturbations is etched into the radiating patch, complemented by an inverted U-shaped DGS to regulate the near-field electromagnetic behavior. Coordinated PIN diode switching across four binary states yields multiple distinct operating frequencies, addressing several contemporary wireless communication bands.

The antenna geometry is developed and refined through full-wave electromagnetic simulation. Systematic characterization of the $|S_{11}|$ spectral response, surface current density maps, far-field radiation patterns, and realized gain is conducted to elucidate the excitation mechanism across all switching configurations. Experimental validation is performed on an FR-4 substrate prototype, characterized via a Vector Network Analyzer (VNA) and far-field anechoic chamber facility, with measured data cross-referenced against simulated predictions to substantiate the reconfiguration mechanism.

The chapter is structured as follows: Section 5.2 delineates the antenna topology, design rationale, geometrical parameters, and switching principle. Section 5.3 analyses the simulated $|S_{11}|$ response, current density distributions, and far-field behavior. Section 5.4 details the fabrication procedure, measurement methodology, and experimental validation. Section 5.5 juxtaposes the design against previously reported reconfigurable architectures, and Section 5.6 consolidates the principal findings.

5.2 Proposed Antenna Design

The antenna architecture is developed to achieve compact frequency reconfiguration through a planar topology employing dual PIN diode switching. The architecture integrates a circular microstrip radiating aperture with strategically engineered slot discontinuities and an inverted U-shaped defected ground structure (DGS) to stimulate multiple discrete resonant modes while sustaining a compact physical footprint. In contrast to fixed-frequency circular microstrip radiators, this architecture dynamically perturbs the effective electrical path length of both the radiating aperture and ground plane through binary switching of two PIN diodes, enabling spectral agility without any increase in overall aperture area.

The antenna is realized on an FR-4 dielectric substrate ($\epsilon_r = 4.4$, $\tan \delta = 0.02$) and comprises a slotted circular radiating patch on the top metallization layer and a complimentary U-shaped slot pattern milled into the bottom ground metallization. The cumulative electromagnetic interaction of the T-shaped slot, U-shaped slot, edge slot perturbations, and DGS systematically redistributes the surface current density under each switching state, thereby inducing distinct resonant conditions addressable to multiple wireless communication bands. The subsequent subsections delineate the design rationale, aperture geometry, optimized dimensional parameters, and the electrodynamic operating principle governing frequency reconfiguration across all four PIN diode switching combinations.

5.2.1 Design Concept

The antenna architecture is developed to realize compact frequency reconfiguration while sustaining a planar topology with minimized switching complexity. To this end, a circular microstrip patch antenna (CMSA) is selected as the primary radiating aperture, owing to its azimuthal geometric symmetry, reduced physical footprint, and inherent capacity to support multiple resonant modes through controlled structural perturbations. Unlike fixed-frequency circular patch radiators that are electromagnetically constrained to a single dominant resonance, the present configuration integrates deliberately positioned slot discontinuities and binary-controlled switching elements to systematically perturb the surface current density distribution, thereby enabling multi-band spectral operation across switching states.

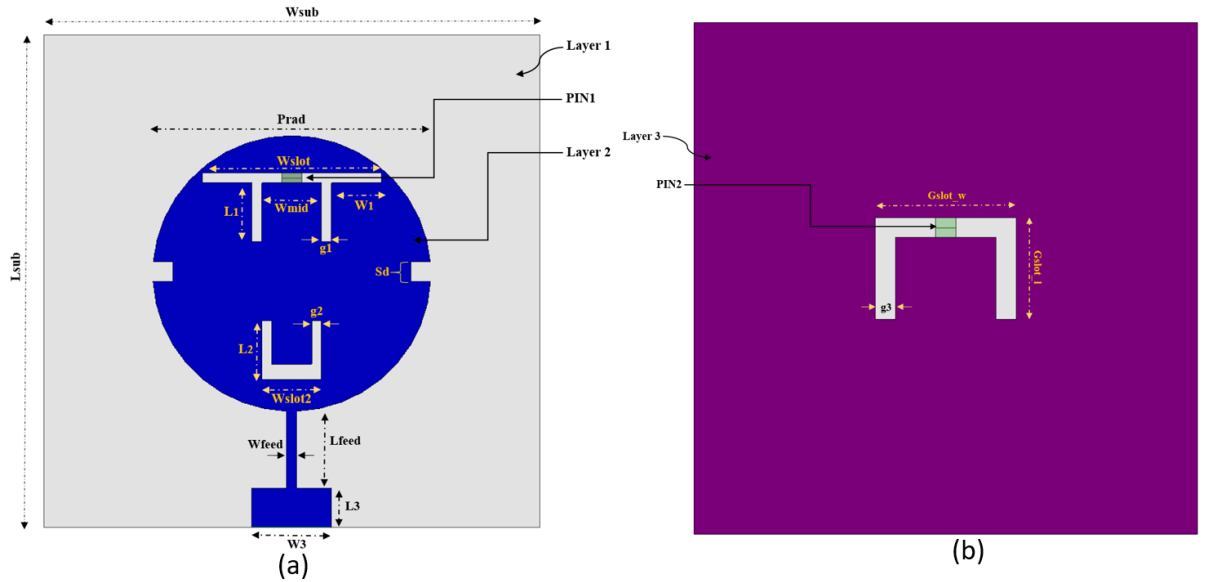


Figure 5.1 Geometry of the developed compact CMSA Antenna: (a) Top and (b) Bottom View

As depicted in Figure 5.1, the radiating aperture is modified by introducing a T-shaped slot and a U-shaped slot, supplemented by two square slot cut-outs positioned near the outer periphery of the circular patch. These geometric discontinuities partition the surface current into multiple conductive paths, effectively elongating the electrical path length without proportionally increasing the physical aperture dimensions. Consequently, several higher-order resonant modes are excited within a single radiating structure while preserving the inherently compact geometry of the circular patch.

Dual PIN diodes are precisely positioned at electromagnetically critical junctions spanning

the slotted aperture and ground-plane perturbation network. The first PIN diode is integrated within the slotted radiating element, where its binary switching action modulates the continuity of surface current traversing the circular aperture. The second PIN diode is embedded within the DGS to regulate ground-plane current redistribution and introduce supplementary resonant behavior through controlled ground-side perturbation. The coordinated binary actuation of these two switching elements generates four distinct current topologies, each yielding a differentiated resonant frequency response across the operating spectrum.

Beyond the slotted radiating aperture, an inverted U-shaped DGS is etched into the bottom ground metallization to refine impedance matching and extend frequency reconfiguration range. The DGS perturbs the electromagnetic coupling between the radiating patch and ground plane by introducing distributed inductive-capacitive loading effects, facilitating the excitation of additional resonant conditions while sustaining stable far-field radiation characteristics across switching states.

The antenna thus achieves frequency reconfiguration through the synergistic interplay of slot-induced current redistribution, dual PIN diode switching, and defected ground engineering. Rather than employing multiple discrete radiating elements, the architecture dynamically modulates the effective electrical length and current density topology of a single compact aperture, yielding a low-profile, monolithically realizable structure with reduced circuit complexity — well-suited for contemporary multi-band RF communication front-ends.

5.2.2 Antenna Geometry and Design Parameters

Figure 5.1 renders the complete antenna topology alongside the dimensional annotations, while Table 5.1 consolidates the full set of electromagnetically optimized parameters. The antenna is constructed upon a commercially available FR-4 dielectric substrate, with material properties $\epsilon_r = 4.4$, $\tan \delta = 0.02$, and $h = 1.6$ mm governing the electromagnetic propagation environment within the substrate layer. The total aperture occupies a lateral footprint of $25 \text{ mm} \times 25 \text{ mm}$, constituting an electrically compact form factor conducive to integration within contemporary miniaturized wireless front-end modules. All geometrical parameters were systematically refined through iterative full-wave electromagnetic

simulation to satisfy the target multi-band $|S_{11}|$ response across all four PIN diode switching states.

Table 5.1 Optimized geometrical parameters of the proposed antenna.

Parameter	Description	Value (mm)
W_{sub}	Lateral extent of the FR-4 dielectric substrate	25
L_{sub}	Longitudinal dimension of the FR-4 dielectric substrate	25
P_{rad}	Diameter of the circular radiating patch	14
W_{slot}	Transverse span of the horizontal section of the T-shaped slot discontinuity	9
L_1	Axial extent of the vertical stem of the T-shaped slot discontinuity	3
W_1	Width of each horizontal segment of the T-shaped slot	2.5
W_{mid}	Transverse dimension of the central stem of the T-shaped slot	3
W_{slot2}	Transverse span of the bridging segment of the U-shaped slot discontinuity	3
L_2	Axial extent of the parallel vertical branches of the U-shaped slot	2.2
S_d	Side length of the square slot cut-outs	1
g_1	Slot gap of the T-shaped slot	0.5
g_2	Slot gap of the U-shaped slot	0.5
L_{feed}	Longitudinal extent of the $50\ \Omega$ microstrip transmission feed conductor	3.9
W_{feed}	Transverse dimension of the $50\ \Omega$ microstrip feed conductor	0.5
L_3	Length of the rectangular impedance matching stub	2
W_3	Width of the rectangular impedance matching stub	4
G_{slot_w}	Transverse span of the bridging arm of the complementary inverted U-shaped ground-plane slot	7
G_{slot_l}	Axial extent of the parallel vertical branches of the inverted U-shaped ground metallization slot	5
g_3	Kerf width of the inverted U-shaped ground-plane slot discontinuity	1

The radiating element comprises a circular microstrip patch of diameter (P_{rad}), driven through a $50\ \Omega$ microstrip feed line engineered to sustain efficient power transfer across the target operating bands. A rectangular impedance-matching stub is incorporated at the feed junction to refine the input admittance transition between the feed network and the radiating aperture, minimizing reflection losses across multiple spectral allocations.

To activate frequency reconfiguration, the circular aperture is electromagnetically perturbed through the introduction of a T-shaped slot, a U-shaped slot, and two square slot cut-outs. The T-shaped slot primarily elongates the surface current trajectory across the upper patch

region, augmenting the effective electrical path length associated with lower-order resonant modes. The U-shaped slot, positioned proximal to the feed region, introduces supplementary current detour paths that stimulate higher-order resonances and broaden impedance matching across concurrent operating bands. The two square slot cut-outs further redistribute the local current density along the patch periphery, facilitating precision tuning of individual resonant frequencies while sustaining the compact aperture footprint.

The bottom metallization layer features a complementary inverted U-shaped slot pattern etched into the ground plane, which serves as the primary electromagnetic boundary condition controller for the antenna's near-field behavior. This ground-plane perturbation redistributes the subsurface current density by injecting distributed reactive loading — manifested as equivalent lumped inductance and capacitance — into the transmission path, thereby precisely regulating the inter-layer electromagnetic coupling between the radiating aperture and the ground metallization. The resultant controlled impedance perturbation extends the reconfiguration bandwidth while simultaneously suppressing anomalous current accumulations and sustaining far-field pattern stability across all four binary switching states.

The two PIN diodes are embedded at electromagnetically sensitive locations within the slotted patch and DGS to maximize their perturbative influence over the current paths governing resonance excitation. This placement strategy enables efficient modulation of the effective electrical length without imposing structural complexity or compromising the planar profile. The architecture consequently sustains multiple discrete resonant conditions through controlled electromagnetic state reconfiguration while retaining fabrication simplicity.

The optimized dimensional parameters in Table 5.1 were extracted following exhaustive parametric sweeps targeting the desired resonant frequencies, acceptable $|S_{11}|$ minima, and stable radiation characteristics across all switching configurations. The finalized geometry represents a systematically derived trade-off among aperture compactness, switching efficiency, and multi-band operational coverage.

5.2.3 Operating Principle of the Developed Antenna

Frequency reconfiguration in the developed architecture is governed by the coordinated

actuation of two PIN diodes embedded within the radiating patch and defected ground structure. Unlike fixed-frequency microstrip radiators, where surface current follows a single predetermined conductive trajectory, the present configuration dynamically redistributes the current density by selectively establishing or interrupting RF conduction paths through binary PIN diode switching. Each switching state consequently perturbs the effective electrical path length, inducing a distinct resonant condition while the physical aperture geometry remains invariant.

The PIN diodes are represented in full-wave electromagnetic simulation through their high-frequency lumped-element equivalent circuit models. Under forward bias (ON state), each diode presents a low-resistance conduction path in series with a small parasitic inductance, sustaining RF current continuity with negligible insertion impedance. Under reverse bias (OFF state), the diode exhibits high RF impedance arising from the parallel resistance-capacitance combination in series with the junction inductance, effectively severing the RF current path. This equivalent circuit accurately captures the high-frequency switching behavior of the diode within the electromagnetic solver environment.

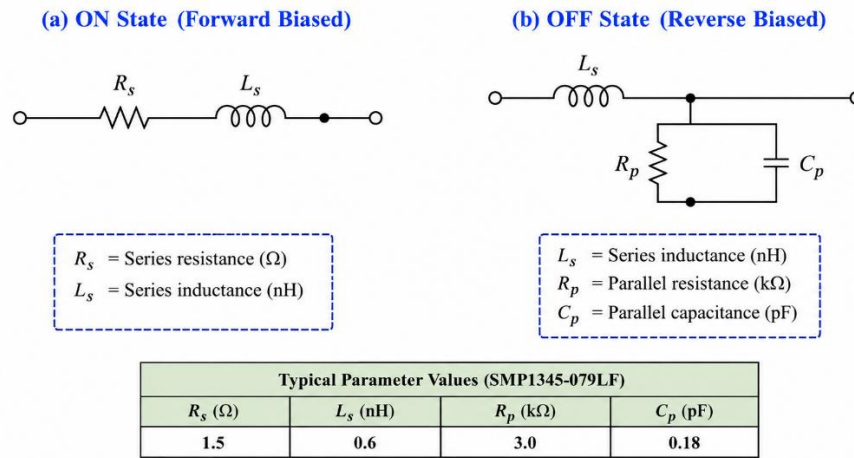


Figure 5.2 Equivalent circuit models of the SMP1345-079LF PIN diode under ON and OFF states.

The antenna employs two independently biased PIN diodes, designated D1 and D2. D1 is embedded within the slotted circular radiating patch, where its switching action directly perturbs the surface current traversing the slot-loaded aperture. D2 is integrated within the DGS, modulating ground-plane current redistribution and altering the electromagnetic coupling between the radiator and ground metallization. The binary permutation of these

two switching elements generates four discrete current topologies, each establishing a unique conductive path and a differentiated resonant frequency response.

Table 5.2 *Operating states of the proposed antenna under different PIN diode switching configurations*

State	D1	D2	Operating Mechanism	Resonant Frequency (GHz)
Mode 0	OFF	OFF	Both switching paths are open, resulting in the shortest effective current path and excitation of the fundamental resonant modes.	3.78, 6.21
Mode 1	OFF	ON	The ground current path is modified through the DGS while the radiating patch remains unchanged, producing an alternative resonant mode.	5.41
Mode 2	ON	OFF	The radiating patch current path is extended by activating the patch-mounted PIN diode, while the DGS remains inactive.	3.80, 6.05
Mode 3	ON	ON	Concurrent forward-biasing of both PIN diodes perturbs the current density across the aperture and ground metallization, establishing a reconfigured effective electrical path length.	5.26

With both diodes in the OFF state, available conduction paths are restricted, yielding one set of resonant frequencies. Independent activation of D1 or D2 modifies the electrical continuity of the radiating structure along distinct current trajectories, displacing the resonant conditions to alternative spectral allocations. With both diodes simultaneously forward-biased, the surface current traverses the longest effective conductive path established by the combined slot configuration and DGS perturbation, exciting a further distinct resonant condition. The four switching permutations thus collectively address multiple operating frequencies from a single compact aperture without recourse to supplementary radiating elements.

The electrodynamic operating principle of the antenna is therefore founded on controlled modulation of the effective electrical path length through coordinated patch-and-ground switching. The synergistic integration of slot-induced current redistribution, dual PIN diode actuation, and defected ground engineering sustains efficient frequency reconfiguration while preserving aperture compactness, simplified biasing circuitry, and practical fabrication compatibility. The influence of each switching state on the $|S_{11}|$ spectral response, surface

current density distribution, and far-field radiation behavior is systematically characterized in the subsequent sections.

5.3 Simulated performance Analysis

5.3.1 Reflection Coefficient Characteristics

The simulated $|S_{11}|$ spectral responses of the antenna across all four PIN diode switching configurations are presented in Figure 5.3. The reflection coefficient characteristic serves as the primary metric for evaluating impedance matching performance and frequency reconfiguration range. Through independent binary control of the two PIN diodes, the antenna exhibits distinct resonant conditions corresponding to differentiated surface current topologies established across the radiating aperture and defected ground structure.

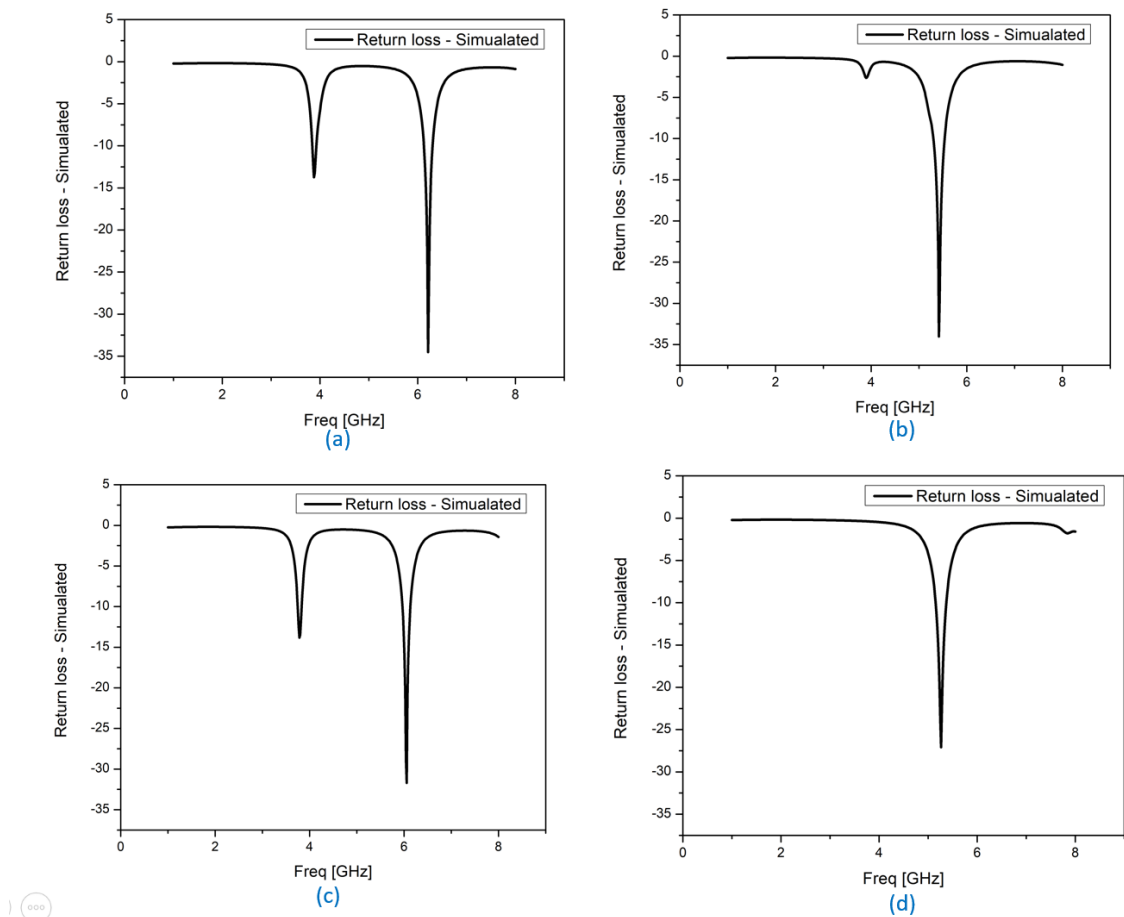


Figure 5.3 Simulated S_{11} for PIN diode Modes 0–3

Under Mode 0, with both PIN diodes reverse-biased (OFF), the antenna excites resonances at 3.78 GHz and 6.21 GHz. In this configuration, both switching paths remain electrically open, constraining the surface current to the shortest available conductive trajectory within the slot-loaded circular patch and DGS. The $|S_{11}|$ minima at both frequencies remain well below the -10 dB threshold, confirming satisfactory impedance matching across both resonant conditions.

In Mode 1, with D1 reverse-biased and D2 forward-biased, the ground-plane current distribution is perturbed while the radiating aperture retains its unmodified conduction topology. This asymmetric switching configuration excites a single dominant resonance at 5.41 GHz, substantiating that ground-side reconfiguration exerts a pronounced influence on the electromagnetic coupling mechanism and the resulting spectral response.

Under Mode 2, D1 is forward-biased while D2 remains reverse-biased. Activating the patch-mounted diode restores RF continuity across the slotted circular radiator, augmenting the effective electrical path length within the aperture. The antenna consequently excites dual resonances at 3.80 GHz and 6.05 GHz, corroborating the role of patch-side reconfiguration in stimulating multiple concurrent resonant modes.

With both diodes simultaneously forward-biased (Mode 3), surface current redistribution occurs concurrently across the radiating patch and ground metallization. This coordinated switching condition establishes a modified electromagnetic conduction topology, yielding a distinct resonant frequency at 5.26 GHz. The observed spectral displacement confirms that joint patch-and-ground actuation constitutes an effective mechanism for compact frequency reconfiguration.

The simulated $|S_{11}|$ responses collectively confirm that each switching permutation generates a unique impedance characteristic while sustaining reflection coefficient minima below -10 dB at all target resonant frequencies. These results verify that the synergistic combination of slot-induced current redistribution, dual PIN diode switching, and defected ground engineering achieves spectral agility without any expansion of the physical aperture. The electromagnetic mechanisms underpinning these frequency transitions are further substantiated through surface current density analysis in the subsequent section.

5.3.2 Surface Current Distribution

Surface current density mapping offers direct electromagnetic insight into the reconfiguration mechanism governing the proposed antenna's multi-state spectral behavior. Figure 5.4 depicts the simulated current density distributions across both the radiating aperture and the defected ground structure at representative resonant frequencies corresponding to each PIN diode switching state. These distributions substantiate that frequency reconfiguration is fundamentally driven by controlled perturbation of the effective conductive topology through the synergistic interaction of the slot-loaded circular patch geometry, binary PIN diode actuation, and the distributed electromagnetic loading introduced by the DGS.

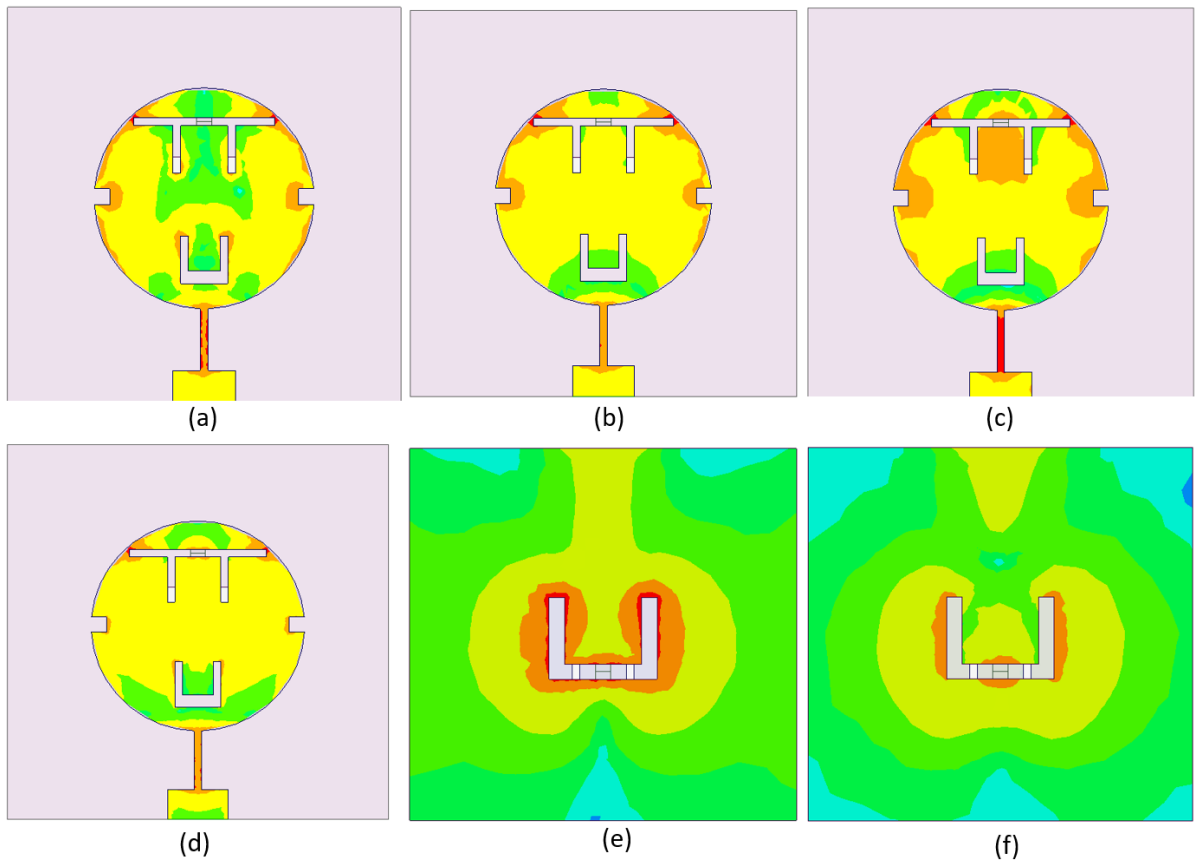


Figure 5.4 Simulated surface current density maps: (a–d) radiating aperture at 3.80, 5.25, 5.41, and 6.21 GHz; (e–f) ground metallization (DGS) at 3.80 and 5.25 GHz

Figure 5.4(a) depicts the surface current density on the radiating aperture at 3.80 GHz. High current concentration is observed along the microstrip feed line, extending into the central patch region through the U-shaped slot discontinuity. Substantial current density is additionally sustained along the lower slotted section of the radiator, indicative of an

elongated effective electrical path governing the lower resonant condition. This spatially distributed current topology confirms efficient excitation of the fundamental resonant mode through the slot-perturbed aperture.

The current density distribution at 5.25 GHz, depicted in Figure 5.4(b), exhibits a more spatially balanced redistribution across the upper and central patch regions. Relative to the lower-frequency mode, the current becomes increasingly localized around the slot-loaded sections of the aperture, corroborating that simultaneous forward-biasing of both PIN diodes establishes a differentiated conduction topology. The resulting modified current trajectory excites an intermediate resonant mode while sustaining acceptable impedance matching across the band.

Figure 5.4(c) presents the current density at 5.41 GHz, where the dominant current concentration is confined to the T-shaped slot in the upper patch region. The lower U-shaped slot contributes negligibly to this resonant condition, confirming that this operating mode is primarily governed by the upper slot geometry. The comparatively abbreviated current path produced under this switching state displaces the resonance toward a higher spectral allocation.

At 6.21 GHz, illustrated in Figure 5.4(d), the surface current is further confined to the upper patch periphery surrounding the T-shaped slot, with markedly attenuated current density across the remaining radiating surface. This spatially constrained current topology corresponds to the shortest effective electrical path among all four switching states and is consequently associated with the highest excited resonant frequency.

The electromagnetic contribution of the DGS is delineated in Figures 5.4(e) and 5.4(f). At 3.80 GHz, intense current concentration around the inverted U-shaped slot confirms active DGS participation in establishing the lower-frequency resonant condition through enhanced near-field electromagnetic coupling with the radiating aperture. At 5.25 GHz, the ground-plane current becomes more spatially confined around the slot periphery, indicating that the DGS transitions toward a reactive tuning role, modifying the coupling characteristics and contributing to the excitation of the additional resonant mode.

Collectively, the surface current density analysis substantiates that frequency reconfiguration is achieved through dynamic modulation of the effective electrical path

length across both the radiating aperture and ground metallization via dual PIN diode actuation. The observed inter-state variations in current topology are fully consistent with the $|S_{11}|$ spectral responses characterized in the preceding section, confirming the electromagnetic validity of the reconfiguration mechanism in realizing compact multi-band operation.

5.3.3 Radiation Characteristics

The far-field radiation characteristics of the antenna were systematically examined through full-wave electromagnetic simulation to quantify the influence of dual PIN diode switching on the radiative performance. Beyond spectral reconfigurability, sustaining stable far-field behavior across all switching states is a critical design constraint. Accordingly, the simulated radiation performance was characterized at representative resonant frequencies corresponding to each of the four binary switching configurations.

The simulated far-field responses confirm that the antenna sustains stable broadside radiation across all operating states. Although each switching configuration perturbs the surface current density topology across the radiating aperture and ground metallization, the dominant radiation mechanism remains governed by the fundamental excitation of the circular microstrip patch. Consequently, no appreciable deflection or distortion of the principal radiation direction is observed across switching states.

The slot-loaded circular aperture and DGS predominantly govern the resonant and impedance characteristics of the antenna, introducing only marginal perturbations to the far-field pattern envelope. The azimuthal geometric symmetry of the circular radiator assists in preserving stable radiation performance despite the localized electromagnetic discontinuities introduced by the slot perturbations and switching elements. Furthermore, the compact placement of the two PIN diodes suppresses anomalous scattering contributions that could otherwise degrade pattern integrity.

The simulated realized gain remains within an acceptable range across the target operating bands, with moderate inter-state variations attributable to surface current redistribution and the consequent modification of the effective radiating aperture, rather than any fundamental alteration of the radiation mechanism.

Experimental validation of the simulated far-field predictions was conducted using a

calibrated anechoic chamber facility. Measured far-field E- and H-plane pattern cuts, alongside their juxtaposition against simulated responses, are presented and analyzed in Section 5.4.3.

5.4 Fabrication and Experimental Validation

The fabrication procedure and experimental characterization of the dual PIN diode frequency-reconfigurable circular microstrip antenna are detailed in this section. While full-wave electromagnetic simulation yields reliable predictions of the expected antenna behavior, physical realization and experimental measurement are indispensable for substantiating design feasibility under practical operating conditions. Experimental validation further establishes the robustness of the reconfiguration mechanism by quantifying the correspondence between simulated predictions and measured antenna characteristics across all switching states.

Based on the optimized geometrical parameters established in the preceding section, the antenna was fabricated on an FR-4 dielectric substrate using standard photolithographic PCB processing techniques. The dual PIN diode configuration was implemented in accordance with the optimized layout, with dedicated DC biasing networks incorporated to independently actuate the four switching permutations required for frequency reconfiguration. A 50 Ω SMA coaxial connector was mounted at the feed port to interface the fabricated prototype with the measurement instrumentation.

The fabricated prototype was experimentally characterized through $|S_{11}|$ acquisition via a calibrated VNA and far-field evaluation within an RF-absorber-lined anechoic chamber under controlled electromagnetic boundary conditions. The measured responses were subsequently juxtaposed against the corresponding simulated results to assess design fidelity and to identify any discrepancies attributable to fabrication tolerances, substrate parameter uncertainties, connector transition losses, solder joint parasitics, and ambient measurement conditions.

The subsequent subsections delineate the fabricated prototype, experimental measurement configuration, measured $|S_{11}|$ characteristics, and far-field radiation patterns across switching states. The measured performance is ultimately benchmarked against simulated predictions

to validate the dual PIN diode reconfiguration technique and substantiate its suitability for compact multi-band RF communication applications.

5.4.1 Fabricated Prototype and Measurement Setup

Following full-wave electromagnetic simulation-based refinement, a physical prototype was realized to experimentally substantiate the frequency reconfiguration performance of the antenna. The structure was fabricated on a commercially procured FR-4 dielectric substrate characterized by a relative permittivity of $\epsilon_r = 4.4$, loss tangent of $\tan \delta = 0.02$, and substrate thickness of $h = 1.6$ mm. The optimized dimensional parameters tabulated in Table 5.1 were strictly adhered to during fabrication to maximize geometric fidelity between the simulation model and the physical prototype. The radiating aperture, defected ground metallization, microstrip feed network, and PIN diode mounting locations were accurately transferred to the substrate using standard photolithographic PCB processing techniques.

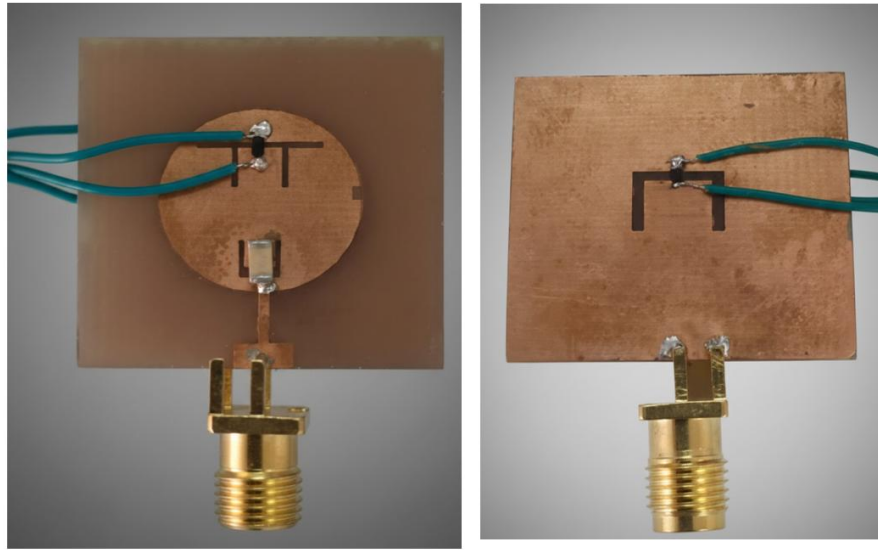


Figure 5.5 Fabricated Prototype of developed compact CMSA antenna: Top and Bottom Views

The realized prototype integrates two Skyworks SMP1345-079LF PIN diodes mounted at electromagnetically critical junctions spanning the slotted aperture and ground-plane perturbation network, respectively. An SMA coaxial port terminating at 50Ω is soldered onto the microstrip feed conductor to establish RF excitation and instrumentation interfacing. Meticulous attention was directed during the soldering process toward minimizing parasitic inductance and capacitance contributions arising from the connector

transition, PIN diode mounting pads, and interconnecting conductors, thereby preserving the designed impedance characteristics of the feed network and radiating aperture.

Experimental characterization of the fabricated prototype was conducted across two independent measurement facilities. The $|S_{11}|$ spectral response was acquired using a calibrated Vector Network Analyzer (VNA), while far-field radiation characteristics were evaluated within an RF-absorber-lined anechoic chamber under controlled free-space electromagnetic conditions. Prior to data acquisition, full two-port SOLT calibration of the VNA was performed across the target frequency range to systematically eliminate systematic measurement errors introduced by coaxial cable losses, connector mismatches, and port impedance deviations.

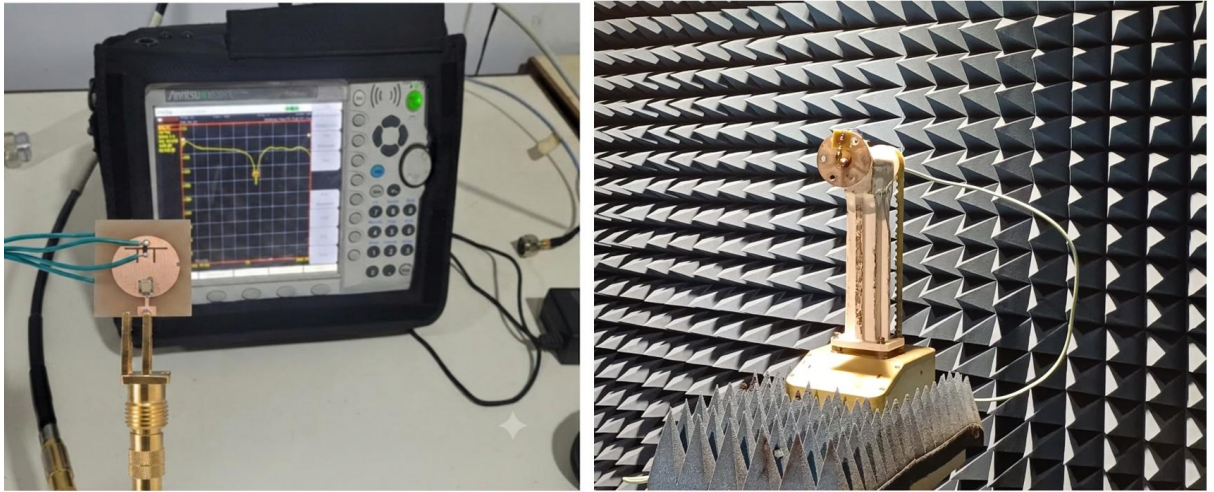


Figure 5.6 Experimental Setup: S_{11} and Radiation Pattern Measurement

During far-field characterization, the fabricated prototype was secured on a low-scattering azimuthal positioner within the anechoic chamber and driven through the SMA coaxial feed port. A calibrated reference transmitting antenna was employed to establish a controlled plane-wave illumination, while the received signal amplitude was recorded across the requisite angular range to reconstruct the E-plane and H-plane radiation pattern cuts. Measurements were conducted across the representative switching states corresponding to the resonant frequencies examined in the full-wave simulation study.

The fabricated prototype and associated measurement infrastructure collectively constitute the experimental platform for substantiating the dual PIN diode frequency reconfiguration mechanism. The measured $|S_{11}|$ spectral responses and far-field radiation characteristics

obtained from these experimental investigations are juxtaposed against the corresponding simulated predictions in the subsequent sections to evaluate the practical RF performance of the antenna across all operative switching configurations.

5.4.2 Measured Reflection Coefficient Characteristics

The $|S_{11}|$ spectral characteristics of the fabricated prototype were acquired using a calibrated VNA and juxtaposed against the corresponding simulated responses to substantiate the proposed frequency reconfiguration mechanism. Figure 5.7 presents the simulated and measured $|S_{11}|$ characteristics across all four PIN diode switching configurations. The comparison reveals strong correspondence between simulated predictions and experimental measurements, corroborating the electromagnetic validity of the antenna design under practical operating conditions.

Under Mode 0 ($D1 = \text{OFF}$, $D2 = \text{OFF}$), the fabricated prototype exhibits dual-band operation at the lower and upper resonant frequencies identified during simulation. The measured resonances closely track the simulated spectral responses, with only marginal frequency displacements observed. These minor deviations are primarily attributable to photolithographic fabrication tolerances, FR-4 substrate parameter uncertainties, solder joint parasitics associated with the PIN diode pads and SMA connector transition, and practical biasing network implementation.

In Mode 1 ($D1 = \text{OFF}$, $D2 = \text{ON}$), the antenna sustains a single resonant condition generated through ground-plane current redistribution via DGS-side diode actuation. The measured $|S_{11}|$ response exhibits satisfactory impedance matching and closely tracks the simulated characteristic, confirming that the ground-side reconfiguration mechanism is faithfully reproduced in the fabricated prototype.

Under Mode 2 ($D1 = \text{ON}$, $D2 = \text{OFF}$), two distinct resonant frequencies are experimentally substantiated, corresponding to the modified conduction topology established across the slotted circular radiating aperture. The measured response accurately reproduces the simulated dual-band behavior, corroborating that forward-biasing the patch-mounted diode effectively augments the electrical path length of the radiator while sustaining acceptable impedance matching across both spectral allocations.

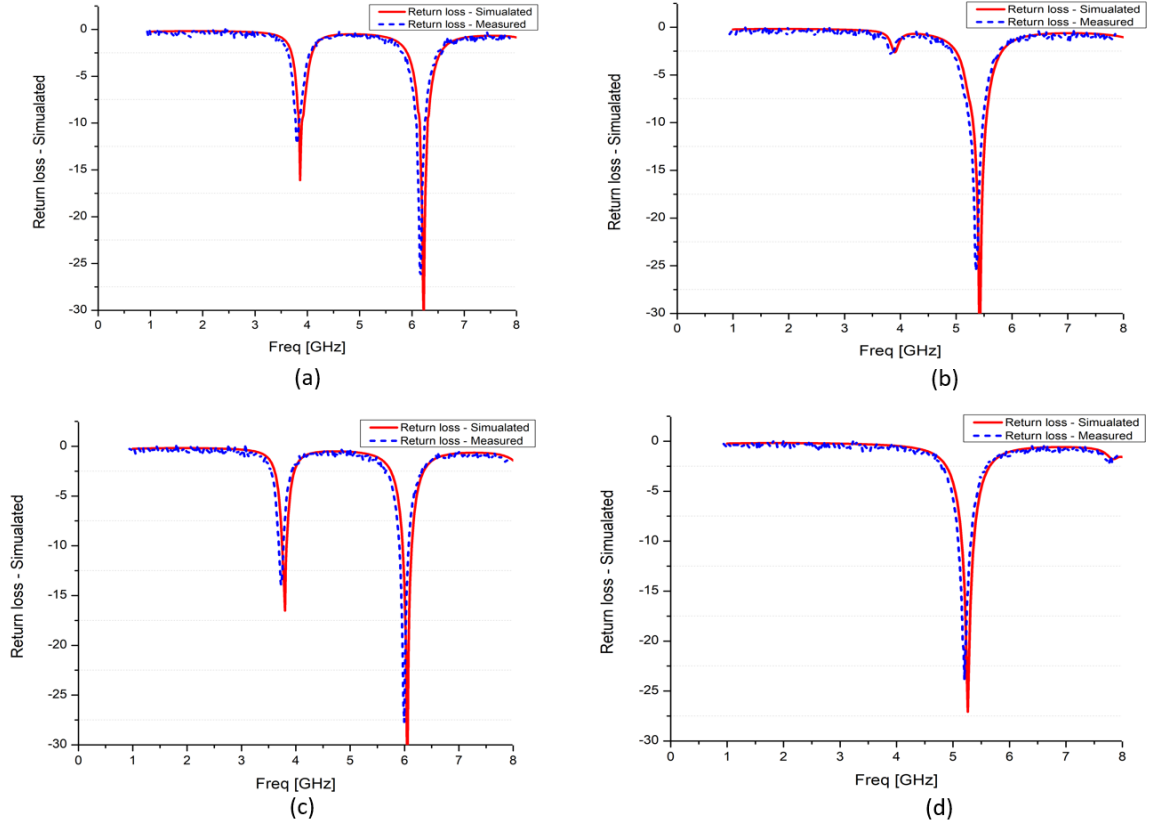


Figure 5.7 Simulated vs Measured S response for Modes 0–3

With both diodes simultaneously forward-biased (Mode 3), the antenna exhibits a distinct resonant frequency arising from the concurrent perturbation of both the radiating aperture and ground metallization. The measured response retains close agreement with the simulated characteristic, confirming that coordinated dual-diode actuation successfully establishes the target resonant condition predicted during the design phase.

Collectively, the measured $|S_{11}|$ characteristics substantiate the dual PIN diode frequency reconfiguration technique across all switching permutations. The observed discrepancies between simulated and measured responses remain within acceptable engineering tolerances and are attributable to practical fabrication and measurement factors rather than inherent design deficiencies. The strong simulated-to-measured correspondence establishes the reliability of the proposed antenna and substantiates its suitability for practical multi-band RF communication front-end applications.

5.4.3 Far-Field Radiation Characterization

Experimental far-field assessment of the fabricated prototype was conducted to substantiate the simulated radiative behavior of the frequency-reconfigurable architecture. Measured radiation patterns were acquired within an RF-absorber-lined anechoic chamber at representative resonant frequencies corresponding to each PIN diode switching state. Figure 5.8 juxtaposes the simulated and measured E-plane and H-plane pattern cuts, furnishing a rigorous comparative assessment of the antenna's far-field performance fidelity under practical electromagnetic measurement conditions.

The measured radiation patterns exhibit strong correspondence with the simulated far-field responses across all investigated resonant frequencies. In both the E-plane and H-plane cuts, the antenna sustains stable broadside radiation with only marginal inter-state variations in beam morphology and sidelobe levels. This close simulated-to-measured agreement corroborates that the dual PIN diode switching mechanism achieves frequency reconfiguration without appreciably perturbing the fundamental radiative behavior of the circular microstrip aperture.

Localized discrepancies between the simulated and measured pattern cuts are observed at certain angular positions. These deviations are primarily attributable to photolithographic fabrication tolerances, FR-4 substrate parameter uncertainties, and connector transition and solder joint parasitics, DC biasing network implementation, measurement cable coupling, and unavoidable angular alignment errors during anechoic chamber characterization. Nevertheless, these discrepancies remain within acceptable engineering tolerances and do not materially alter the overall far-field radiation characteristics.

The measured results further substantiate that the DGS and slot-loaded circular aperture effectively perturb the resonant conditions of the antenna while preserving stable far-field performance. Despite inter-state variations in surface current density topology, the principal radiation direction remains essentially invariant across switching configurations, confirming that the reconfiguration mechanism predominantly governs the resonant and impedance characteristics rather than the fundamental radiation mechanism.

Measured realized gain values at the representative resonant frequencies retain close agreement with simulated predictions, confirming that the antenna sustains satisfactory

radiation efficiency throughout the investigated spectral range. The limited gain variation across switching states indicates that spectral reconfiguration is achieved without incurring significant degradation in radiative performance.

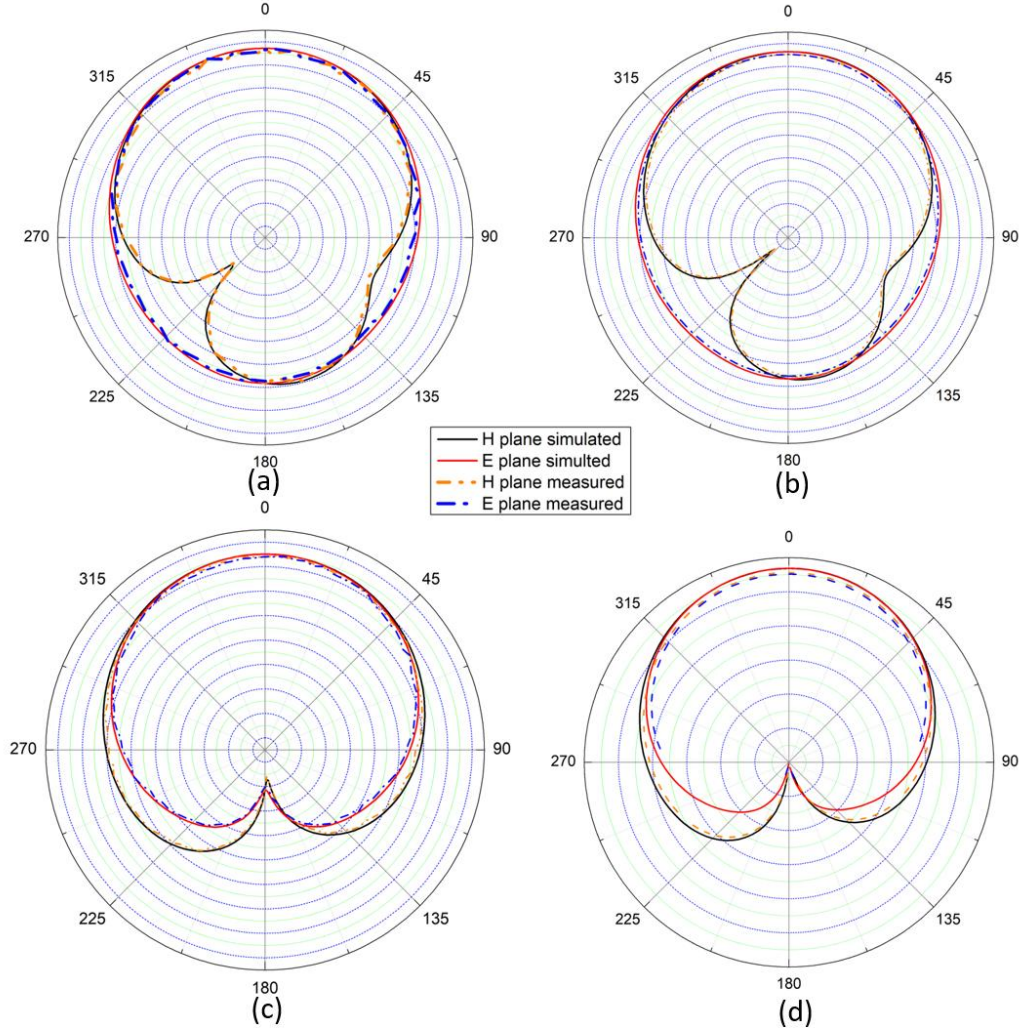


Figure 5.8 Simulated vs Measured E & H plane Radiation Patterns at (a) 5.25 GHz (b) 5.41 GHz (c) 6.05 GHz and (d) 6.21GHz

Collectively, the experimental far-field measurements validate the full-wave electromagnetic analysis presented in the preceding sections. The strong E-plane and H-plane simulated-to-measured correspondence substantiates the practical feasibility of the design and confirms that the synergistic combination of slot-induced current redistribution, dual PIN diode actuation, and defected ground engineering constitutes a reliable and electromagnetically efficient approach to compact frequency-reconfigurable antenna design for contemporary multi-band RF communication applications.

5.5 Comparative Performance Evaluation

To benchmark the electromagnetic and practical merits of the proposed architecture, its performance is systematically juxtaposed against recently reported frequency-reconfigurable microstrip antenna designs available in the open literature. The comparative evaluation encompasses critical design parameters including aperture footprint, number of switching elements, achievable spectral allocations, frequency reconfiguration range, and maximum realized gain. This benchmarking exercise furnishes an objective quantitative assessment of the proposed design and delineates its technical advantages relative to previously reported reconfigurable antenna architectures.

Table 5.3 Performance comparison of the proposed antenna with recently reported frequency reconfigurable antennas.

Ref. No	Antenna Size (mm ²)	Operating Frequencies (GHz)	PIN diodes	Peak gain (dBi)
[20]	25 x 25	4.478, 4.986	1	4
[33]	18.3 x 50	3.49, 3.36, 3.25, 3.10, 2.49, 2.37, 2.26, 2.18, 2.12–3.49	5	4.8
[35]	50 x 50	2.43, 2.85, 3.33, 4.4	3	5.3
[39]	25 x 27	2.3, 4.5, 5.8	3	2.8
Proposed	25 x 25	3.78, 3.80, 5.18, 5.41, 6.05, 6.21,	2	3.42

To evaluate the efficacy of the proposed radiator, its performance is benchmarked against recently reported frequency-reconfigurable microstrip antennas in the open literature. The assessment spans key figures of merit — aperture footprint, switching-element count, achievable resonant bands, reconfiguration span, and peak realized gain — furnishing an objective measure of the design's merit relative to existing reconfigurable topologies.

As Table 5.3 indicates, several reported designs attain multi-band operation through numerous switching elements, intricate geometries, or comparatively large substrates. While yielding reasonable frequency agility, this added complexity typically imposes elaborate biasing networks, greater fabrication burden, and higher implementation cost.

The proposed antenna, by contrast, employs only two PIN diodes to realize four switching states spanning multiple resonant frequencies across critical wireless bands. The synergy of a slot-loaded circular patch and an inverted U-shaped defected ground structure yields

effective spectral agility without enlarging the aperture or introducing parasitic elements, simplifying fabrication and easing integration into compact platforms.

Gain comparison confirms sustained radiation efficiency across all switching states with stable far-field characteristics. Close correlation between simulated and measured results further validates the design methodology and confirms practical feasibility.

Overall, the benchmarking exercise establishes that the proposed antenna strikes an effective balance among compactness, switching simplicity, multi-band coverage, and radiation performance. Its minimal two-diode configuration, paired with a slot-perturbed circular patch and defected ground structure, delivers efficient reconfigurability while remaining straightforward to fabricate and validate — positioning it as a strong candidate for compact, adaptive multi-band wireless systems.

5.6 Summary

This chapter delineated the systematic development, full-wave electromagnetic optimization, physical realization, and experimental validation of a compact dual PIN diode frequency-reconfigurable circular microstrip antenna incorporating a defected ground structure. The architecture employed a slot-perturbed circular radiating aperture integrated with two Skyworks SMP1345-079LF PIN diodes to achieve spectral reconfiguration through controlled modulation of the effective conduction topology across both the radiating patch and ground metallization. The synergistic interaction of the T-shaped slot, U-shaped slot, and inverted U-shaped DGS enabled excitation of multiple discrete resonant conditions while sustaining a compact planar form factor.

The antenna geometry was refined through iterative full-wave electromagnetic simulation, with the electrodynamic operating principle substantiated through $|S_{11}|$ spectral analysis and surface current density mapping. The simulated responses confirmed that each binary switching permutation establishes a distinct resonant mode by perturbing the effective electrical path length of the aperture. Surface current density analysis further corroborated the electromagnetic mechanisms governing frequency reconfiguration and delineated the complementary electromagnetic roles of the slot-loaded patch and defected ground structure across all switching states.

Experimental validation was conducted on an FR-4 substrate prototype characterized via a calibrated VNA and RF-absorber-lined anechoic chamber facility. The measured $|S_{11}|$ responses and far-field radiation characteristics exhibited strong correspondence with simulated predictions, substantiating the effectiveness of the reconfiguration mechanism under practical operating conditions. Residual discrepancies between simulated and measured responses were attributed to photolithographic fabrication tolerances, substrate parameter uncertainties, solder joint parasitics, and measurement system limitations, all remaining within acceptable engineering bounds.

Comparative benchmarking against recently reported frequency-reconfigurable antenna architectures confirmed that the design achieves an effective trade-off among aperture compactness, switching complexity, spectral coverage, and radiation performance. Despite employing only two PIN diodes, the antenna successfully excites six discrete resonant frequencies — 3.78 GHz, 3.80 GHz, 5.18 GHz, 5.41 GHz, 6.05 GHz, and 6.21 GHz — while sustaining stable far-field radiation characteristics and practical fabrication compatibility, establishing it as a viable candidate for compact multi-band RF front-end applications requiring adaptive spectral operation with minimized hardware complexity.

CHAPTER-6

Conclusion, Major Contribution and Future Scope

6.1 Conclusion

The accelerating densification of modern wireless infrastructure has intensified demand for miniaturized antenna architectures capable of spanning heterogeneous communication standards while maintaining spectral efficiency across dynamically allocated bands. Fixed-frequency radiating structures inherently constrain operational adaptability, rendering them ill-suited for cognitive and software-defined radio platforms that require real-time reconfigurability. PIN diode-switched antennas circumvent this limitation by electronically perturbing the boundary conditions of the radiating element, thereby consolidating multiple functional states within a single aperture without resorting to antenna arrays or switched diversity modules.

This work details the systematic design, full-wave electromagnetic simulation, fabrication, and experimental characterization of compact PIN diode-integrated microstrip antennas engineered for independent and simultaneous frequency and radiation pattern reconfiguration. Three progressively complex planar configurations were developed on low-loss dielectric substrates to delineate distinct reconfiguration paradigms while preserving geometric simplicity, sub-wavelength footprints, and RF front-end compatibility.

The first configuration established a frequency-agile microstrip topology incorporating a single PIN diode strategically positioned to modulate the effective electrical length of the radiating patch. Controlled forward- and reverse-bias switching redistributed the surface current distribution, yielding discrete resonant frequency shifts without any physical alteration to the antenna geometry. This configuration served as the electromagnetic baseline governing the topological decisions adopted in subsequent iterations.

The second configuration extended reconfiguration dimensionality by achieving orthogonal control over both resonant frequency and far-field radiation pattern through an optimized multi-diode switching matrix. Each bias state produced a distinct combination of operating frequency and beam orientation while sustaining $|S_{11}| \leq -10$ dB impedance bandwidth and

front-to-back ratio stability. Measured scattering parameters and radiation patterns exhibited strong correlation with full-wave simulation outputs, substantiating the viability of co-integrating frequency agility and pattern diversity within a unified planar structure.

The third configuration introduced a circular microstrip radiator incorporating dual PIN diodes in conjunction with a defected ground structure (DGS). The electromagnetic interaction among reactive slot loading, switched current-path reconfiguration, and ground-plane perturbation collectively excited six discrete resonant modes while sustaining acceptable realized gain and pattern integrity across all switching states. Surface current density mapping at each resonance elucidated the underlying modal reconfiguration mechanism, while Vector Network Analyzer measurements and anechoic chamber radiation pattern acquisitions rigorously validated the simulated electromagnetic behavior.

Collectively, the three antenna configurations substantiate that wideband frequency tunability and beam reconfigurability are attainable through judicious PIN diode placement and ground-plane engineering, without escalating circuit complexity or violating compactness constraints. The realized antennas address spectral allocations pertinent to WLAN (2.4/5.8 GHz), WiMAX (3.5 GHz), LTE (700 MHz–2.7 GHz), and sub-6 GHz 5G (3.3–3.8 GHz) standards, while sustaining controlled impedance matching, polarization stability, and lithographic fabrication compatibility.

The electromagnetic analyses, fabrication workflows, and experimental validations presented throughout this thesis collectively establish that PIN diode-driven microstrip antennas constitute a technically rigorous and hardware-efficient solution for multi-band reconfigurable front ends. By juxtaposing frequency agility, reduced switching element count, and verified electromagnetic fidelity within compact planar geometries, this research advances the foundational design methodology for next-generation reconfigurable apertures operating across converged wireless communication infrastructures.

6.2 Major Research Contributions

The investigations conducted in this thesis advance the domain of compact reconfigurable microstrip antennas through rigorous electromagnetic design, parametric optimization, substrate-level fabrication, and experimental characterization of PIN diode-integrated

radiating structures targeting contemporary multi-standard wireless front ends. The principal technical contributions are delineated below.

a. Compact Frequency-Reconfigurable Microstrip Antenna

A sub-wavelength microstrip radiator achieving discrete frequency reconfiguration via a single PIN diode was systematically designed and characterized. Forward- and reverse-bias switching states redistributed the effective surface current path, yielding multiple distinct resonant frequencies without dimensional augmentation of the radiating patch. This configuration established a low-hardware-overhead methodology for frequency agility that governed the topological framework of subsequent designs.

b. Simultaneous Frequency and Radiation Pattern Reconfigurable Antenna

A planar antenna architecture capable of orthogonally and concurrently modulating its resonant frequency and far-field radiation pattern was developed and experimentally substantiated. An optimized PIN diode switching matrix generated multiple independent electromagnetic operating states, each sustaining $|S_{11}| \leq -10$ dB impedance bandwidth, controlled front-to-back ratio, and spatial pattern diversity — all within an unaltered compact footprint.

c. Circular Microstrip Antenna with Dual PIN Diodes and Defected Ground Structure

A circular microstrip aperture integrating dual PIN diodes with a defected ground structure (DGS) was engineered to elevate resonant mode multiplicity. The electromagnetic interplay among reactive slot loading, switched current-path perturbation, and ground-plane discontinuity collectively excited six discrete resonant frequencies while sustaining acceptable realized gain and far-field pattern stability across all bias states.

d. Full-Wave Electromagnetic Analysis

Systematic full-wave simulations were executed to characterize reflection coefficient ($|S_{11}|$), surface current density distribution, far-field radiation patterns, and broadside gain across all switching configurations. These analyses elucidated the modal excitation mechanisms underpinning frequency and pattern reconfigurability, and directly informed iterative geometric and topological optimization of each antenna configuration.

e. Experimental Characterization and Validation

All fabricated antenna prototypes underwent rigorous experimental characterization using a calibrated Vector Network Analyzer for scattering parameter extraction and a fully anechoic chamber for far-field radiation pattern and gain measurement. The strong correlation between measured and simulated electromagnetic responses validated both the design methodology and the fidelity of the full-wave computational models, confirming practical RF front-end applicability.

f. Benchmarking Against State-of-the-Art Reconfigurable Designs

The realized antenna configurations were systematically benchmarked against recently published reconfigurable antenna architectures across key performance metrics — including normalized aperture size, switching element count, operational band coverage, realized gain, and radiation pattern stability. This comparative analysis confirmed that the developed structures achieve a technically defensible equilibrium among compactness, frequency agility, reduced RF switching complexity, and experimental reproducibility, positioning them as viable candidates for integration into compact multi-band wireless communication terminals.

6.3 Future Scope

The antenna architectures realized in this research establish a technically grounded foundation for compact reconfigurable radiating structures targeting contemporary multi-standard wireless front ends. Nonetheless, several well-defined research trajectories remain open for extending the present contributions toward emerging communication paradigms and increasingly stringent RF system requirements.

a. Continuous Frequency Tuning via Varactor-Based Reactance Control

The PIN diode-switched configurations developed herein inherently constrain frequency reconfiguration to discrete resonant states determined by binary bias conditions. Replacing or supplementing PIN diodes with varactor diodes would introduce voltage-controlled junction capacitance variation, enabling quasi-continuous frequency tuning across wider spectral ranges. Such reactance-tunable architectures are particularly consequential for

cognitive radio and software-defined radio front ends, where real-time spectrum sensing demands continuous frequency agility rather than stepped switching.

b. Extension toward Sub-THz and 6G Spectral Allocations

While the realized designs address sub-6 GHz 5G allocations, further parametric optimization targeting millimeter-wave bands (24–86 GHz) and emerging sub-terahertz 6G spectral windows would substantially broaden applicability. This necessitates substrate selection with low dielectric loss tangent at elevated frequencies, refined fabrication tolerances, and radiation efficiency optimization to counteract increased ohmic and dielectric attenuation inherent at millimeter-wave and sub-THz regimes.

c. MIMO Integration with Reconfigurable Diversity

Extending the present single-element reconfigurable topologies into multiple-input multiple-output (MIMO) array configurations represents a high-impact trajectory. Integrating frequency reconfiguration with spatial multiplexing demands rigorous inter-element isolation engineering — achievable through neutralization lines, decoupling networks, or orthogonal polarization diversity — to suppress mutual coupling below acceptable envelope correlation coefficient thresholds while sustaining channel capacity gains.

d. Advanced RF Switching Devices

RF-MEMS actuators, graphene-based field-effect switches, liquid-crystal phase-shifters, and phase-change materials such as vanadium dioxide (VO_2) warrant systematic evaluation as alternatives to PIN diode implementations. Each technology offers distinct trade-offs in insertion loss, actuation power, switching speed, linearity, and integration complexity. Characterizing these devices within reconfigurable microstrip topologies would delineate their practical suitability for low-power and high-linearity wireless front-end applications.

e. Conformal and Wearable Antenna Realizations

Transposing the reconfiguration methodologies developed herein onto flexible dielectric substrates — including polyimide, liquid crystal polymer, and textile-based laminates — would extend their utility to body-centric wireless networks and biomedical telemetry systems. Such investigations must rigorously quantify $|S_{11}|$ drift, radiation pattern distortion,

and gain degradation as functions of substrate bending radius and mechanical deformation, while ensuring specific absorption rate (SAR) compliance for on-body deployment.

f. Multidimensional Hybrid Reconfigurable Apertures

Future architectures may simultaneously exercise control over resonant frequency, far-field radiation pattern, polarization state, and electronically steered beam direction within a single compact planar aperture. Realizing such multidimensional reconfigurability demands co-design of the switching network, feed architecture, and radiating geometry to preclude inter-parameter coupling artifacts. Antennas exhibiting this level of electromagnetic versatility are directly relevant to next-generation terrestrial 6G nodes, non-terrestrial satellite links, intelligent transportation infrastructure, UAV-mounted communication payloads, and integrated radar-communication sensing platforms.

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List of Publications

1. S. Mansuri and S. S. Modasiya, "Reliable Single Diode Patch Antenna with Dual Mode Frequency and Pattern Reconfigurability with Compliance Analysis," Reliability: Theory & Applications, vol. 20, no. 4 (89), pp. 1006–1016, 2025, doi: 10.24412/1932-2321-2025-489-1006-1016. **(Scopus Indexed)**
2. S. Mansuri, S. Modasiya, and P. Panchal, "A Multi-Mode Frequency Reconfigurable Antenna for 5G and WLAN Applications," Indian J. Natural Sciences, vol. 14, no. 82, pp. 69167–69173, Feb. 2024. **(Web of Science Indexed)**
3. S. H. Mansuri and S. S. Modasiya, "Octagonal frequency reconfigurable slotted patch antenna," India Design Patent 440489-001, Jun. 19, 2025. **(Design Patent granted)**
4. S. H. Mansuri and S. S. Modasiya, "Slotted triangular frequency reconfigurable patch antenna with stubs," India Design Patent 440491-001, Dec. 11, 2025. **(Design Patent granted)**
5. S. H. Mansuri et al., "Reconfigurable antenna design using Slotted Circular Patch (CMSA) with 2 PIN Diodes," India Patent Application 202621073063, published in The Patent Office Journal No. 30/2026 dated 24/07/2026.