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Title

Desgin and analysis of a reconfigurable patch antenna using pin diode for wireless Applications

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بِسْمِ ٱللَّهِ ٱلرَّحْمَٰنِ ٱلرَّحِيمِ



DEDICATION



raise be to Allah, who has showered us with gratitude and appreciation. By His grace,

Isee today a long-awaited dream become a reality of which I am

proud.And now, with the help of Almighty Allah, I complete this modest work....

I dedicate this

To my mother

To the one for whom God has made paradise beneath her feet, who gave me life and endless love.Your constant support, your endless prayers, and your encouragement have been the strong foundation for my success. You taught me kindness, resilience, and the true meaning of strengt. Thanks to your sacrifices and guidance, I have become who I am today.

,

To my father

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To my sisters

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To the friend of beautiful moments and my work partner, to the one who has always been with me in every moment, I appreciate your presence by my side and all that you have given me,

my dear... Manal

BOUAFFANE NADA





To my grand mother

To the heart that never stopped praying for me, to the gentle voice that calmed my fears,

and to the hands that carried me with love even in silence.

Your unwavering faith, your warmth, and your wisdom have been a guiding light.

You are a part of every step I take, and I dedicate this work to you with love and gratitude.

To my mother

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To the one who gave me life, embraced me with her tenderness, and supported me with her prayers—both in silence and aloud.

You have always been my strength and my safe haven throughout this journey.

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To the one who has always been like a second mother to me,

With your kindness, encouraging words, and comforting smile that eased my difficult days.

You've always been close to my heart, a quiet support wrapped in love.

I dedicate this work to you in deep appreciation of your place in my life and with endless gratitude.

To my friends

To the friend of beautiful moments and my work partner, to the one who has always been with me in every moment, I appreciate your presence by my side and all that you have given me,

my dear... Nada

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List of Symbols and Abbreviations

Abbreviation	Meaning
2D	Two-Dimensional.
3D	Three-Dimensional
5G	Fifth Generation
AESAs	Active Electronically Steered Arrays.
ATC	American Technical Ceramics.
BER	Bit Error Rate.
Bw	Bandwidth.
CP	Circular Polarization.
DC	Direct Current.
dBd	decibels relative to a dipole.
dBi	decibels relative to isotropic.
EA	Electronic Attack.
EMI	Electromagnetic Imaging.
ES	Electronic Support.
EW	Electronic Warfare.
FET	Field-Effect Transistors.
GHz	Gigahertz.
GPS	Global Positioning System.
HFSS	High Frequency Structure Simulator.
IEEE	Institute of Electrical and Electronics Engineers.
IoT	Internet of Things.
LHCP	Left-Hand Circular Polarization.
LOS	line-of-sight.
LP	Linear Polarization.
MEMS	Micro-Electro-Mechanical Systems.
MESFET	Metal–Semiconductor Field-Effect Transistor.
MHz	Megahertz.
MIMO	Multiple Input Multiple Output.
MPA	Microstrip Patch Antenna.
NLOS	non-line-of-sight.
OFDM	Orthogonal Frequency-Division Multiplexing.
PCB	Printed Circuit Board.
PDAs	Personal Digital Assistants.
PIN diode	Positive-Intrinsic-Negative diode.
PTFE	Polytetrafluoroethylene.
RF	Radio Frequency.
RF MEMS	Radio Frequency Micro-Electro-Mechanical Systems.
RFID	Radio Frequency Identification
RHCP	Right-Hand Circular Polarization.
S11	The reflection coefficient.
SDR	software-defined radio.
SHF	Super High Frequency.
SMD	Surface-Mount Device.
SNR	Signal-to-Noise Ratio.

SWR	standing wave ratios
UAS	Unmanned Aerial Systems.
UAV	Unmanned Aerial Vehicle.
VCOs	voltage-controlled oscillators.
Vmax	the maximum voltage.
Vmin	the minimum voltage.
VNA	vector network analyzer
Vswr	Voltage Standing Wave Ratio
WiMAX	Worldwide Interoperability for Microwave Access.
WSN	Wireless Sensor Network.
WLAN	Wireless Local Area Network.

Abstract

This project presents the design and simulation of a reconfigurable patch antenna using a PIN diode for dynamic frequency tuning. By integrating a PIN diode into the antenna design, it becomes possible to dynamically adjust the operating frequency, allowing support for multiple applications using the same component without the need for replacement or additional hardware. Key parameters such as gain, VSWR, and S11 were optimized using HFSS to ensure efficient performance within the targeted frequency bands. The results confirm that the proposed design achieves reliable reconfigurability, making it suitable for advanced multi-band communication applications.

Resume

Ce projet présente la conception et la simulation d'une antenne patch reconfigurable utilisant une diode PIN pour un réglage dynamique de la fréquence. L'intégration d'une diode PIN à la conception de l'antenne permet d'ajuster dynamiquement la fréquence de fonctionnement, permettant ainsi la prise en charge de plusieurs applications utilisant le même composant sans remplacement ni ajout de matériel. Des paramètres clés tels que le gain, le ROS et le S11 ont été optimisés par HFSS afin de garantir des performances optimales dans les bandes de fréquences ciblées. Les résultats confirment que la conception proposée offre une reconfigurabilité fiable, la rendant ainsi adaptée aux applications de communication multibandes avancées.

ملخص

يقدم هذا المشروع تصميمًا ومحاكاةً لهوائي رقعة قابل لإعادة التهيئة باستخدام ثنائي PIN لضبط التردد ديناميكيًا. بدمج ثنائي PIN في تصميم الهوائي، يُمكن ضبط تردد التشغيل ديناميكيًا، مما يسمح بدعم تطبيقات متعددة باستخدام نفس المكون دون الحاجة إلى استبدال أو إضافة أجهزة. تم تحسين المعلمات الرئيسية، مثل الكسب، ونسبة الموجة الدائمة للجهد (VSWR)، وS11، باستخدام HFSS لضمان أداء فعال ضمن نطاقات التردد المستهدفة. تؤكد النتائج أن التصميم المقترح يحقق إعادة تهيئة موثوقة، مما يجعله مناسبًا لتطبيقات الاتصالات المتقدمة متعددة النطاقات.

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GENERAL INTRODUCTION

The rapid advancement of wireless communication systems and the growing demand for flexible, adaptive solutions have led to increased interest in the development of smart antennas capable of meeting diverse requirements across dynamic environments. In this context, reconfigurable antennas have emerged as a promising solution, offering the ability to dynamically alter key characteristics—such as frequency, bandwidth, radiation pattern, and polarization—according to operational needs.

This project focuses on the design and analysis of a reconfigurable patch antenna using a PIN diode. The concept of reconfigurability in this type of antenna relies on the integration of active components—specifically PIN diodes—into the antenna structure, allowing its electromagnetic behavior to be altered as needed. By controlling the ON/OFF states of the diode, the antenna can adapt to various scenarios without any physical modification of its structure.

The objective of this work is to conduct an in-depth study of the design process for such antennas, from fundamental principles to simulation and performance optimization, using the High-Frequency Structure Simulator (HFSS) and MATLAB. The study begins by reviewing the basic characteristics of patch antennas and proceeds to explore the incorporation of PIN diodes into the design. The impact of these elements on overall antenna performance is then analyzed. Particular attention is given to optimization techniques aimed at improving, impedance matching, bandwidth, and radiation behavior under different diode configurations. The project is structured into three chapters, each addressing a key aspect of the design, simulation, and optimization process.

Chapter I: will first lay the foundation by presenting general concepts related to antennas. We will examine the fundamental principles of antennas, their various classifications, as well as their characteristics and types. Special attention will also be given to patch antennas, including a description of their structure, advantages and disadvantages, and their practical applications.

Chapter II: presents the various types of reconfigurable antennas, including frequency-reconfigurable antennas, radiation pattern-reconfigurable antennas, and antennas capable of polarization reconfiguration. The chapter also discusses different reconfiguration

techniques, starting with electrical reconfiguration using components such as PIN diodes, varactor diodes, and MEMS, and extending to optical, mechanical, and material reconfiguration methods. Special emphasis is placed on PIN diodes due to their practical and effective role in designing this type of antenna. A comprehensive definition of PIN diodes will be provided, along with the polarization techniques used to activate them, the necessary components involved, as well as an overview of their advantages, disadvantages, and various applications. This chapter provides a solid foundation for understanding the subsequent developments related to the design and analysis of reconfigurable antennas.

Chapter III : represents the core of this research, focusing on the design, modification, optimization, and simulation of reconfigurable patch antennas using HFSS software and MATLAB. We begin by studying a conventional patch antenna operating at 5 GHz, analyzing key performance parameters such as the reflection coefficient (S11), Voltage Standing Wave Ratio (VSWR), as well as 2D and 3D radiation patterns.

The second part of the chapter presents the development of several reconfigurable antenna structures capable of switching between different frequency bands. These include antennas reconfigurable from one to two bands, from one to three bands, and from one to three bands. For each design, a detailed analysis of essential performance metrics is carried out, including return loss, VSWR, and radiation patterns in both 2D and 3D. The optimization of antenna parameters is conducted using MATLAB to identify configurations that meet desired performance thresholds. Additionally, a comparative study is conducted between the conventional antenna and the proposed reconfigurable designs to evaluate improvements in frequency agility and radiation characteristics. Furthermore a comparison with other reconfigurable antennas reported in the literature is conducted to highlight the effectiveness and competitiveness of the proposed solutions.

Finally, this research aims to present case studies and practical applications that demonstrate the importance and effectiveness of reconfigurable patch antennas. By combining theoretical and practical approaches, this study seeks to highlight the design and analysis of a reconfigurable patch antenna using PIN diodes, focusing on the impact of reconfiguration techniques on improving the performance of wireless communication **systems.** The research also aims to contribute to advancing knowledge in antenna design for modern wireless communication systems, enhancing their ability to adapt to changing and challenging environments.

CHAPITRE I:
Generalities on Antennas

1. Introduction

Antennas are essential components of modern communication systems, playing a crucial role in transmitting and receiving electromagnetic waves. They enable the transfer of information in various fields such as telecommunications, broadcasting, wireless networks, radar systems, and satellite communications.

The objective of this chapter is to present the fundamental concepts related to antennas by exploring their operating principles, key characteristics, and different types. A thorough understanding of these concepts is essential for addressing the challenges associated with antenna design and performance optimization, especially in the context of emerging technological advancements. Through this study, we will highlight the factors influencing antenna performance and their impact on transmission quality.

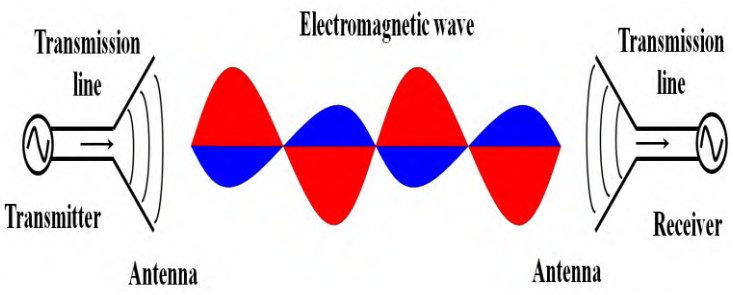
2. Generalities on Antennas:

2.1 Definition :

According to the IEEE Standard Definitions of Terms for Antennas (IEEE Std 145-1983), an antenna or aerial is defined as "a means for radiating or receiving radio waves."In other words, an antenna serves as a transitional structure between free space and a guided wave system.

Antennas are crucial components of any wireless communication system. They enable the conversion of signals into electromagnetic waves that propagate through space and can be received by another antenna. The receiving antenna performs the inverse function, converting an electromagnetic wave into an electrical signal or voltage at its terminals, which can then be processed by the receiver [1].

Together, the transmitting and receiving antennas form a fundamental radio communication system, as illustrated in the FigureI.1.



FigureI.1: A typical radio system [1].

2.2 Histories:

The first design of printed antennas was proposed by Deschamps in 1953 in the U.S.A, and in France three years later by Baissinot and Gutton. In 1960**,** Lewinmade an observation and a study on the radiation phenomenon caused by discontinuities in straplines [2, 3].

A little later, in 1970**,** Byron described a planar structure consisting of a conductive plate printed on a dielectric substrate with a relative permittivity (Ɛr) **≤10**, placed on a ground plane. The first implementations of this technology were mainly reserved for military applications.

In the 1990s**,** Howel and Munson brought this technology to the industrial stage [2]. By 1994**,** most research aimed to improve certain subsystems of this new technique. At that time, it was given several names, including carrier-free technology**,** baseband technology, or impulse technology**.**

3.Types of antennas :

A general classification of antennas is presented based on their radiation characteristics. Antennas are divided into two main categories: directional antennas, which are characterized by their ability to focus energy in a specific direction, providing high gain. They are commonly used in long-distance communication, with examples including parabolic antennas and Hertzian dipoles. On the other hand, omnidirectional antennas offer relatively uniform gain in the horizontal plane, making them suitable for applications that require wide coverage, such as radio and television broadcasting, as well as mobile communications. A common example of this type is the vertical monopole antenna. This classification is summarized in the table I.1 [4] .

Table I.1: types of antennas**.**

Types	Characteristic	Use	types of antennas
directional antennas	high G0 gain	-Hertzian beams	parabolic antennas
omnidirectional antennas	more or less constant gain in the horizontal plane or in a given sector	-radio/tv -mobile communications	vertical strand

3.1- Wire antennas:

Wire antennas are among the most commonly used types due to their widespread applications in automobiles, infrastructure, marine vessels, aircraft, and spacecraft. These antennas consist of linear conductors, typically with a circular or square cross-section. Since the cross-section is relatively small compared to the length of the conductor, it is assumed that the current distribution along the wire is linear, simplifying the analysis of their radiation characteristics.

Wire antennas come in various forms, including straight designs such as monopoles and dipoles, loop structures (rectangular or circular), and helical antennas, which are particularly suited for specific applications [5].

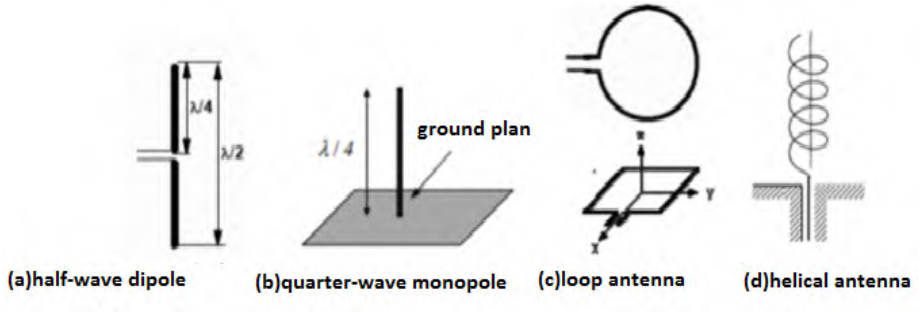


Figure I.2: Representation of Some Wire Antennas[5].

Among the most commonly used linear antennas, the half-wave dipole and the quarter-wave monopole (whip antenna) stand out due to their practicality and efficiency.

a) Half-Wave Dipole:

The half-wave dipole is one of the earliest wire antennas, yet it remains widely utilized. It consists of two metallic elements aligned along the same axis and fed at the center (Figure I .2.a). The open-ended structure ensures that the current at both extremities is zero, leading to a standing wave distribution with maximum current at the center [5].

b) Monopole Antenna:

A monopole antenna serves as a more compact alternative to a dipole by incorporating a large ground plane (FigureI.2.b). This principle is commonly applied in vehicle-mounted antennas. The ground plane creates a virtual image that mimics the other half of a dipole, effectively forming a quarter-wave monopole where the fundamental resonant length is λ/4[5].

c) Resonant Loop:

A magnetic loop antenna consists of a conductor forming a closed loop (FigureI.2.c). It can take on various geometric shapes, such as square, rectangular, circular, or diamond-shaped. Depending on the loop size, radiation can be either longitudinal or transverse. These antennas are widely used in radio broadcasting reception, where multiple wire turns are wound around a frame. Additionally, RFID systems (Radio Frequency IDentification) employ loop antennas, particularly for their ability to detect magnetic fields and metallic objects [5].

d) Helical antenna:

A helical antenna (FigureI.2.d) combines properties of electric dipoles and magnetic loops. Its radiation pattern is influenced by the diameter of the supporting cylinder. The antenna can operate in either axial mode (longitudinal radiation) or normal mode (transverse radiation). By optimizing the helix diameter, it is possible to achieve circular polarization, making it suitable for various communication applications [5].

3.2 Radiating Aperture Antennas:

Radiating aperture antennas are widely used in microwave applications. These antennas feature metallic structures with openings, where electromagnetic fields, rather than electric currents, serve as excitation sources. The radiation characteristics of such antennas can be analyzed using mathematical models designed to calculate the field emitted by a planar aperture of any shape. This section focuses on two key types: the open-ended waveguide and the horn antenna [6].

Radiating aperture antennas can be classified into two main categories:

- **Horn antennas**: where the radiating element is a hollow opening at the mouth of the horn.
- **Parabolic antennas**: where the radiating surface is a reflective dish that directs the emitted waves.

a. **Horn Antenna**:

A horn antenna enables the radiation of an electromagnetic wave that propagates through a rectangular or conical waveguide. This is achieved by keeping the waveguide's end open, allowing the energy to disperse into free space (Figure I.3).



Figure I.3: Horn Antenna[6].

A horn antenna is a waveguide with a gradually widening cross-section that culminates in a radiating aperture**.** It is crucial for enabling a seamless transition between guided wavepropagation and free-space radiation, ensuring minimal impedance mismatch in both directions [6].

b. Parabolic Antenna:

Parabolic reflector antennas are commonly used for long-range communication, particularly in satellite transmissions. They consist of a primary feed source (often a horn) placed at the focus of a parabolic reflector, which is typically metallic but can also be made of dielectric materials.

Although these antennas experience some losses, they can achieve significant gain levels of up to 50 dB and provide a highly focused radiation pattern with minimal secondary lobes (around -20 dB) [7] .



Figure I .4: parabolic antenna[7].

In a parabolic antenna, the primary feed source is usually a horn antenna, which must fulfill the following criteria:

- It should capture microwaves concentrated at the reflector's focal point while minimizing interference and noise.
- It must not introduce any additional noise into the received signal.
- It should ensure accurate signal reception with the appropriate polarization (linear or circular) while effectively filtering out unwanted polarizations [7].

3.3 Dielectric Antennas:

Dielectric lenses function similarly to the reflector in a parabolic antenna. With a carefully chosen shape and material**,** these lenses can effectively transform various energy beams into plane waves (Figure I.5).

At frequencies beyond the SHF (Super High Frequency) range**,** dielectric lenses are anticipated to outperform traditional reflector antennas in efficiency [8].

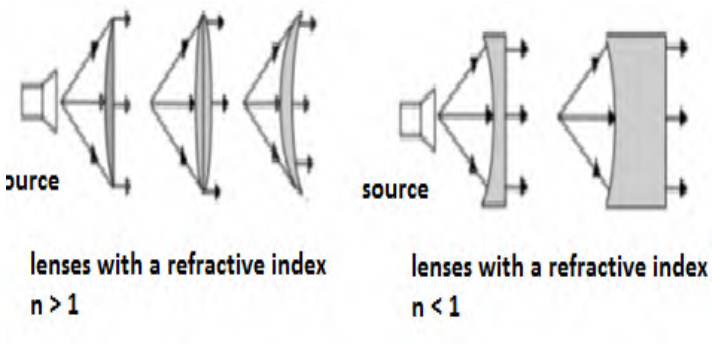


Figure I.5: Dielectric Lenses[8] .

4. Characteristics of Printed Antennas:

Considering the simplest wireless communication system, it comprises two primary components: a transmitting block and a receiving block, separated by a propagation channel that allows the transmitted signal to travel before being received.

In the transmitting block, the transmission circuit generates a modulated current, which is then converted into electromagnetic waves that can propagate through the channel. This conversion is achieved by the transmitting antenna.

In the receiving block, when the waves reach the receiver, it is the receiving antenna's role to transform them back into a current that can be processed by the reception circuit.

An antenna can be defined by its function: it is a passive transducer that converts electrical quantities (voltage and current) from a conductor or transmission line

into electromagnetic quantities (electric and magnetic fields) in space, and vice versa.

Therefore, an antenna can serve both transmission and reception purposes. Moreover, according to the Lorentz reciprocity theorem, the characteristics of an antenna remain the same whether it is used for transmission or reception. This property is particularly beneficial, as it allows a communication device with both transmitting and receiving components to use the same antenna for both roles [9].

The antenna, which facilitates the transmission and reception of waves, can also be viewed as an impedance matching device between the propagation medium and an electronic circuit [9].

Electrically small antennas and "standard" sized antennas exhibit similar characteristics, including input impedance, bandwidth, and gain. These characteristics will be examined in greater detail in the following subsections.

4.1 Input impedance:

A radio frequency transmission line typically consists of at least a generator and a load. When the antenna is used for transmission, the generator is represented by the transmitter's output circuit, while the antenna acts as the load, radiating electromagnetic signals. In contrast, during reception, the antenna serves as the generator that collects electromagnetic signals, and the input circuit of the receiver functions as the load.

From a circuit perspective, an antenna is a component characterized by its impedance,

called the antenna input impedance. The expression for this impedance $Z_{ant}$is presented in complex form, consisting of a real part R_{ant} and an imaginary part X_{ant}, connected by the following expression:

$$Z_{ant} = R_{ant} + jX_{ant} \qquad (1)$$

The real part of the input impedance consists of the radiation resistance and the loss resistance R_{loss}, as described in equation (2). The radiation resistance represents the energy radiated by the antenna, while the loss resistance accounts for conduction losses, dielectric losses, and surface wave losses in the antenna [9].

$$R_{ant} = R_{ray} + R_{pertes} \qquad (2)$$

4.2 The reflection coefficient:

Generally, when an incident wave transitions between different propagation mediums or encounters a new interface, part of the wave is reflected while the other part is transmitted into the new medium. The reflection coefficient Γ Gamma and the

transmission coefficient T quantify these two components, respectively. These coefficients are related by the following expression (3), which represents energy conservation [9]:

$$|\Gamma|2 + |T|2 = 1 \qquad (3)$$

For maximum power transfer between the various elements of a circuit, the magnitude of the reflection coefficient should be minimized. To achieve this, the components of a radio frequency transmission/reception chain are designed to match a characteristic impedance Z_0. The characteristic impedance may vary depending on the application but is most commonly set to 50Ω. Using the characteristic impedance and the antenna's input impedance, the reflection coefficient can be defined as:

$$\Gamma = \frac{Z_{ant} - Z_0}{Z_{ant} + Z_0} \qquad (4)$$

Where:

Z_0 : is the characteristic impedance of the transmission line (typically 50 Ω)

The reflection coefficient of an antenna is defined as the ratio of the amplitudes of the incident wave to the reflected wave.

A perfect match ($Z_{ant} = Z_0$) gives Γ=0, meaning no reflection, while any mismatch results in |Γ|>0. The magnitude of Γ ranges from 0 (perfect match) to 1 (total reflection).

It can also be expressed in decibels and it is called $S_{11}\,dB$as:

$$S_{11}\,dB = 20\,log_{10}(\Gamma) \qquad (5)$$

Typically, S11<−10 dB is considered acceptable for good antenna performance, meaning less than 10% of the power is reflected.

4.3 Voltage Standing Wave Ratio (VSWR):

Voltage Standing Wave Ratio (VSWR), also known simply as the Standing Wave Ratio, is defined as the ratio of the maximum voltage Vmax to the minimum voltage Vmin along a transmission line. It quantifies the level of signal reflection due to impedance mismatches.

Mathematically, VSWR can be expressed in terms of the reflection coefficient (Γ) as follows:

$$VSWR = \frac{Vmax}{Vmin} = \frac{1 + |\Gamma|}{1 - |\Gamma|} \qquad (6)$$

4.4 Bandwidth:

Impedance Bandwidth (BW) or simply bandwidth is the range of frequencies where an antenna performs optimally. It is usually considered to be when the reflection coefficient (S11) is less than -10 dB (S11≤−10 dB) and is often referred to as the percentage bandwidth (see Figure 6) [11].

For a narrowband antenna, the impedance bandwidth, called fractional bandwidth in this case, is expressed as:

$$BW(\%) = \frac{f_H - f_L}{f_C} \times 100 \qquad (7)$$

On the other hand, the bandwidth of the broadband antenna is commonly expressed as the difference between the higher and lower frequencies at which the antenna performs acceptably:

$$BW = f_H - f_L \qquad (8)$$

Where:

− f_C: is center frequency

− f_H and f_L: are higher and lower frequencies, respectively

Quality factor (Q) of an antenna defines how well an antenna radiates and is inversely related to bandwidth and is given by the following expression [11]:

$$Q = 2\pi \frac{storedenergy}{powerlost\ per\ cycle} \qquad (9)$$

Where:

- Stored Energyrefers to the average reactive energy (electric and magnetic energy temporarily stored in the near field of the antenna).
- Energy lost (or dissipated) per cycle is the net energy lost from the system per oscillation cyclemostly through radiation (and possibly small losses like conduction or dielectric losses).

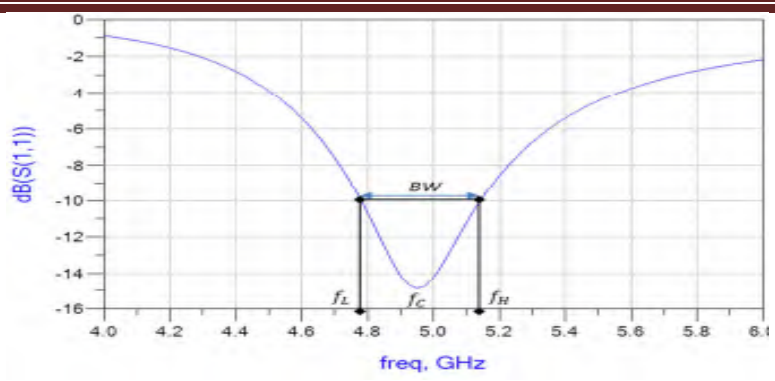


Figure I .6: Bandwidth measurement through reflection coefficient [11].

4.5 Efficiency:

Antenna efficiency considers all power losses that occur both at the input terminals and within the antenna's structure. These losses include reflection losses caused by impedance mismatch between the transmission line and the antenna, as well as conduction and dielectric losses within the antenna materials [12].

The total efficiency of an antenna can be alternatively represented as:

$$e_0 = e_r e_c e_d \qquad (10)$$

Where,

e_0 = total efficiency

e_r = reflection (mismatch) efficiency = $1 - |\Gamma|^2$

e_c = conduction efficiency

e_d= dielectric efficiency e_c and ed are usually difficult to calculate, but can be determined experimentally. Since it is impossible to separate them through measurements, equation (11) is typically written in a more convenient form:

$$e_0 = e_r . e_{cd} = e_{cd} . (1 - |\Gamma|^2) \qquad (11)$$

Antenna radiation efficiency, represented by e_{cd} or η, which is used to correlate the directivity and gain [12].

4.6 Radiation characteristics:

a. Radiation Pattern:

The radiation pattern describes the spatial distribution of an antenna's emitted energy, typically represented as a mathematical function or graphical depiction. It is usually analyzed in the far-field region, where the pattern is expressed as a function of directional

coordinates. Key radiation characteristics include power flux density, radiation intensity, field strength, directivity, phase, and polarization. Of these, the primary focus is often the two-dimensional spatial distribution of the radiated energy relative to the observer's position. A visual representation of the radiation pattern is typically shown in (figureI.7).

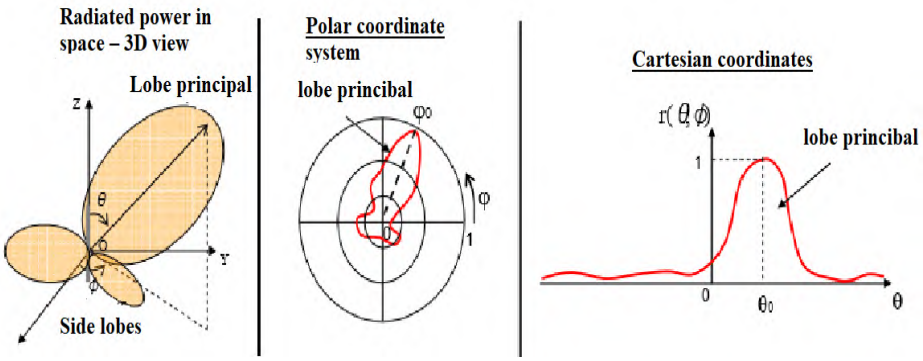


Figure I .7: Representation of the Antenna Radiation Pattern[13].

Traditionally, the radiation pattern is commonly represented using either rectangular or polar coordinates, within two perpendicular planes. The E-plane is defined as the plane that includes the antenna axis and the electric field, while the H-plane is defined as the plane that includes the antenna axis and the magnetic field. As illustrated in figure (I.7), three primary radiation models are typically used to describe the radiation characteristics of an antenna: isotropic, omnidirectional, and directive.

- **Isotropic antenna**: This is defined as "a hypothetical, lossless antenna that radiates uniformly in all directions." Although it is an idealized concept and physically unachievable, it is frequently used as a reference to evaluate the directivity of real antennas.
- **Omnidirectional Antenna**: An "omnidirectional antenna is characterized by having a radiation pattern that is essentially non-directional in one specific plane (for example, the azimuth plane), while it exhibits a directional radiation pattern in all orthogonal planes. In this sense, an omnidirectional antenna is a special case of a directional antenna."
- **Directional Antenna**: A "directional antenna is defined as one that radiates or receives electromagnetic waves with higher efficiency in specific directions compared to others.

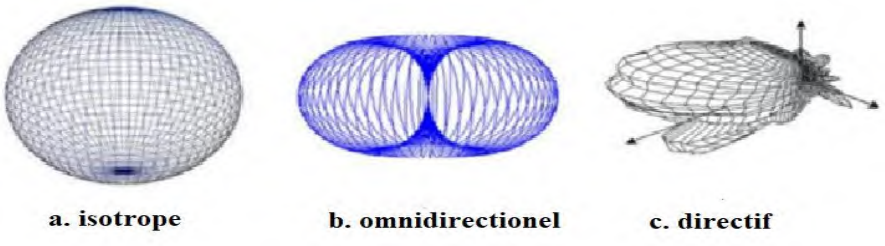


Figure I .8: Radiation Models of an Antenna[13].

b. Beamwidth:

The beamwidth (referred to as half-power beamwidth) defines the extent of the main lobe, as illustrated in figure (I.7). The -3 dB beamwidth, denoted as $2\theta_3$dB indicates the region of space where the majority of the radiated power is concentrated. This angle is the difference between the two directions surrounding the main lobe, within which the radiated power drops to half of the peak power in the maximum radiation direction

c. Radiation Zones:

The radiation zones surrounding an antenna are commonly classified into three regions: the reactive near-field region (Rayleigh zone), the radiative near-field region (Fresnel zone), and the far-field region (Fraunhofer zone), as depicted in (figureI.9) [13]

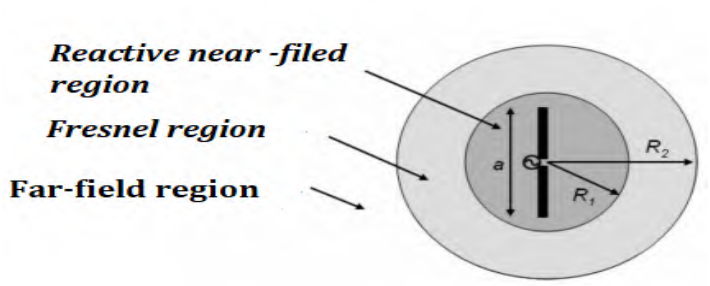


Figure I.9: The Radiation Zones of an Antenna[13].

(1). Reactive Near-Field Region (Rayleigh Zone):

This region surrounds the radiating source, where reactive power (entirely imaginary) is dominant. The power density remains nearly uniform within this area, and the boundaries of this region are defined by a sphere with a radius $r1$ denoted as reactive.

$$r1 = \frac{D^2}{2\lambda} \qquad (12)$$

Where,

D :is the largest dimension of the antenna.S

λ :is the wavelength.

(2). Intermediate Radiation Zone (Fresnel Zone):

This is the intermediate zone where the power density fluctuates, and the beam divergence becomes noticeable. It is defined by the distance range $r_1 \leq r \leq r_2$[13].

$$r2 = \frac{2D^2}{\lambda} \qquad (13)$$

(3). Région de champ lointain (zone de Fraunhofer) :

It is the region, defined by a radial distance r>$r_2$where electromagnetic energy is radiated in all directions within the space covered by the antenna's radiation pattern. The radiated power is entirely real and does not depend on the radial distance [14].

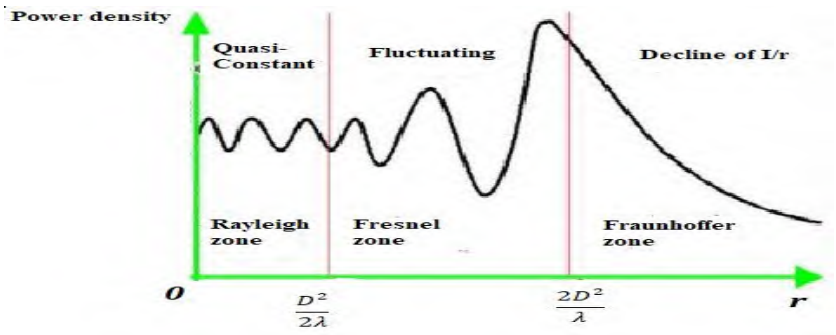


Figure I.10 : Radiation zones of an antenna[14].

d. Radiated Power by an Antenna:

An antenna is used to convert electrical power P_{in}into radiated power, which is carried by an electromagnetic wave capable of propagating in all directions of space. The center of the radiating element is positioned at the origin of a spherical coordinate system (figureI.11) and is connected to a source that provides it with electrical power P_{in}. The spherical coordinates (r,θ,φ) represent a coordinate system that is especially suitable for studying antennas.

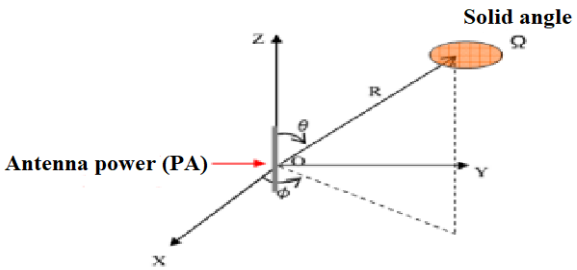


Figure I.11: Power radiated by an antenna in an arbitrary direction Δ[13].

It is sometimes referred to as the radiation intensity, expressed in watts per steradian. The power radiated per unit area at a distance R , or power density, is given by: $\frac{Pa}{4\pi R^2}$ since thesurface area of the sphere is$4\pi R^2$.

-we will denote it by the lowercase p [13]:

$$P(\theta,\varphi) = \frac{Pa}{4\pi R^2}\left(\frac{W}{m^2}\right) \qquad (14)$$

4-7. Directivity:

As we know, an antenna's directivity, expressed in dBi, is defined as the concentration of radiated power in a specific direction. When an antenna has 100% radiation efficiency, its gain is equal to its directivity.

The directivity of a patch antenna can be estimated easily, as its efficiency typically exceeds 90%. The radiating edges of the patch, positioned above a ground plane, act as two radiating slots. Due to the concentrated radiation above the patch, the directivity increases by approximately 3 dB. This results in an excellent front-to-back ratio, where maximum radiation occurs above the patch and minimum radiation is observed on the opposite side.

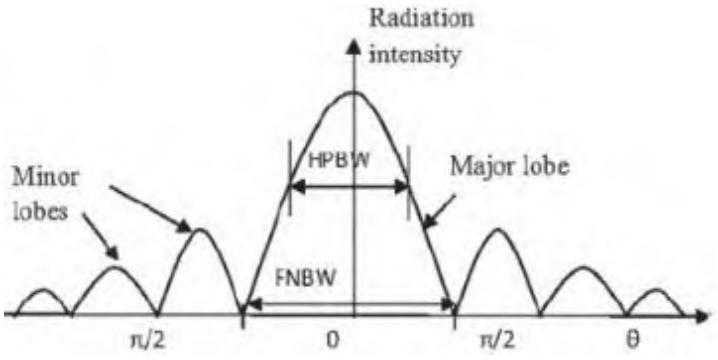


Figure I.12: Antenna beam width representations[15].

Directivity increases as the angle of observation moves from lower elevation angles toward the broadside direction (perpendicular to the patch surface).

The unit dBi (decibels relative to isotropic) is used when comparing an antenna's directivity to that of an isotropic antenna, which radiates equally in all directions and has a directivity of 0 dBi.

Alternatively, directivity can be expressed in dBd (decibels relative to a dipole), where a dipole antenna has a directivity of 2.15 dBi. This means the dipole is more directive than an isotropic radiator. Therefore, when using dBd, you're referencing performance relative to a standard dipole rather than an isotropic source [15].

4.8 Gain:

The gain $G(\theta,\varphi)$ of an antenna in a given direction (θ,φ) is defined as the ratio between the power radiated in that direction $P(\theta,\varphi)$ and the power that would be radiated by an isotropic antenna Pa, assuming both are fed with the same input power [16]:

$$G(\theta,\varphi) = \frac{P(\theta,\varphi)}{Pa/4\pi} \qquad (15)$$

The gain can also be expressed in terms of the **directivity** D and the **efficiency**η of the antenna:

$$G = \eta \cdot D \qquad (16)$$

If the antenna efficiency is 100% (η=1) , then the directivity is equal to the gain.

5. Description of a printed or "patch" antenna:

In recent years, significant advancements in miniaturization technologies have led to more compact and lightweight consumer communication devices. As previously emphasized, antennas play a vital role in the radio communication chain, acting as the interface between the signals processed by the electronic systems of the transmitter or receiver and the propagation medium.

Various types of antennas exist, including wire antennas, aperture antennas, reflector antennas, lens antennas, printed antennas, and array antennas. This section focuses specifically on printed antennas.

Printed antennas have gained widespread use due to their ability to meet numerous design and integration constraints imposed by modern communication systems. The concept of the printed antenna was initially introduced in 1952 by Greig and Engleman, followed by

Deschamps in 1953. However, practical applications did not emerge until the 1970s [17].

Thanks to their low-profile structure and compact form factor, printed antennas are particularly well-suited for integration into a wide range of systems, especially in mobile and personal communication devices.

In its most basic form, a printed antenna consists of a conductive patch (the radiating element) printed on the top surface of a dielectric substrate, with the bottom surface being fully metalized to serve as the ground plane (see FigureI.13) [17].

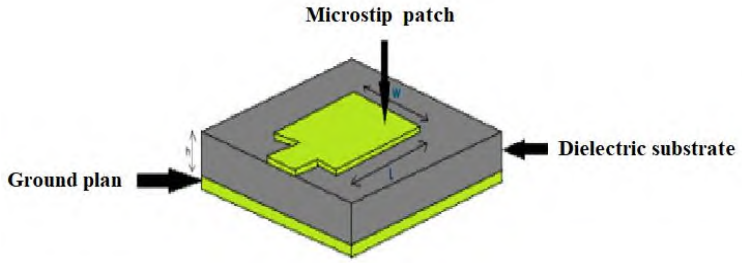


Figure I.13 :structure of a patch antenna[17].

5.1 Different shapes of a patch antenna:

The radiator must be made of a material with low dielectric loss and should have high conductivity at the operating frequency, which can be fixed to a dielectric substrate. The shape can take any form like an ordinary rectangle; square, circle, triangle, ellipse, ring, hexagon, ptson, or such variations. (FigureI.14) shows some typical shapes of the radiating patch. The selection of a particular shape depends on specific requirements like Operating frequency, bandwidth, return loss, gain, polarization etc. Generally, The characteristics of patch antenna is defined by its operating modes which in turn depend on the shape and dimensions of patch, the thickness, dielectric constant and loss tangent of the substrate, and also on the feed arrangement [18].



Figure I .14: the different shapes of a patch antenna[18].

5.2 Application fields of patch antenna:

Microstrip patch antennas are known for their performance, robust design, and widespread usage in various fields like medical, satellites, and military systems. They are easy to design and lightweight, making them a popular choice in commercial aspects due to their low cost and fabrication. As their usage expands, they may replace conventional antennas for maximum applications .

-Mobile and satellite communication application:

Microstrip patch antennas are suitable for mobile communication due to their small, low-cost, low-profile design. They can be used for satellite communication with circularly polarized radiation patterns, either using square or circular patches with one or two feed points [19].

-Global Positioning System applications:

Nowadays microstrip patch antennas with substrate having high permittivity sintered material are used for global positioning system. These antennas are circularly polarized, very compact and quite expensive due to its positioning. It is expected that millions of GPS receivers will be used by the general population for land vehicles, aircraft and maritime vessels to find there position accurately [19].

-Radio Frequency Identification (RFID):

RFID systems, utilizing frequencies between 30 Hz and 5.8 GHz, are utilized in various sectors such as mobile communication, logistics, manufacturing, transportation, and healthcare [20].

- Worldwide Interoperability for Microwave Access

The IEEE 802.16 stanard is known as WiMAX. It can reach up to 30-mile radius theoretically and data rate 70 Mbps. MPA generates three resonant modest 2.7, 3.3 and 5.3 GHz and can, therefore, be used in WiMAX compliant communication equipment [21].

- Radar Application:

Radar detects moving targets like people and vehicles using low profile, light weight antenna subsystems. Photolithography fabrication technology allows bulk production of microstrip antennas with repeatable performance at lower costs and shorter timeframes [22]

- Rectenna Application:

Rectenna is a rectifying antenna that converts microwave energy into DC power. It consists of four subsystems: antenna, ore rectification filter, rectifier, and post rectification filter. High directive characteristics are required for long-distance links, and increasing the electrical size of the antenna is necessary for effective DC power transfer [23].

-Telemedicine Application:

The wearable microstrip antenna, operating at 2.45 GHz, is suitable for telemedicine

applications due to its higher gain and front-to-back ratio. It features a semi-directional radiation pattern, overcoming unnecessary radiation to the user's body, and meets on-body and off-body requirements. The antenna has a gain of 6.7 dB and a F/B ratio of 11.7 dB [24].

- Medicinal applications of patch:

It is found that in the treatment of malignant tumors the microwave energy is said to be the most effective way of inducing The patch radiator is designed to induce hyperthermia by posing light weight, ease of handling, and ruggedness. Initial designs used printed dipoles and annular rings on S-band, later based on circular microstrip disks at L-band. The instrument measures body temperature using two coupled microstrip lines separated with a flexible separation, operating at 430 MHz [25].

5.3 Advantages and disadvantages of Patch Antennas :

-Advantages of Patch Antennas:

- **Microstrip Patch Antennas (MPAs):**

are highly efficient for high-frequency applications due to their compact, low-profile design and compatibility with portable wireless devices such as cell phones, pagers, and PDAs (Personal Digital Assistants)**.** They are extensively used in telemetry, missile communication systems, and satellite communications like GPS. Additionally, MPAs are widely employed in Electronic Warfare (EW) systems, including conformal antennas integrated into EW UAS (Unmanned Aerial Systems) platforms, directional EA (Electronic Attack) or ES (ElectronicSupport**)** antennas for sensor networks, and embedded antennas within the bodies of EW-capable unmanned systems[26].

- **Compact Size & Minimal Volume:**

Patch antennas have a small footprint, with a typical length equal to half a wavelength (approximately **30 cm at 1 GHz**). Their overall volume is minimal, with millimeter-scale heights, making them ideal for space-constrained applications.

- **Lightweight Structure:**

Their small size inherently reduces weight, making them perfect for aircraft, missiles, portable military systems, and sensor fields that require easy deployment.

- **Flexible & Conformal Design**

These antennas can be designed in flat or curved configurations, allowing seamless integration onto both uniform and irregular surfaces, making them highly adaptable for

diverse platforms.

- **Cost-Effective & Easy Fabrication:**

Patch antennas are manufactured using standard PCB (Printed Circuit Board) fabrication techniques, making them affordable and easy to mass-produce. Their scalability in production further lowers costs, making them a cost-effective choice for various industries [26].

-disadvantages of Patch Antennas :

- **Radiation Efficiency:**

The radiation efficiency of an antenna is defined as the ratio of radiated power to the real input power at the antenna's port, assuming negligible ohmic losses. Any energy that is not radiated is dissipated as surface waves along the dielectric substrate. In practical applications, the total efficiency is crucial, as it accounts for both dielectric and surface-wave losses. Lossy dielectrics behave similarly to lossy transmission lines, where standing waves form within the substrate due to its finite size. Increased losses lead to higher standing wave ratios (SWR). Compared to reflector antennas, patch antennas typically exhibit 1 to 2 dB lower total efficiency.

- **Low Gain:**

The gain of patch antennas is relatively low compared to conventional antennas. However, this limitation can be mitigated by implementing antenna arrays, which enhance the overall gain. Due to their low-cost manufacturing potential, arrays of patch antennas offer a practical and scalable solution for applications requiring higher gain.

- **Unwanted Radiation:**

Patch antennas experience extraneous radiation from their feed networks and junctions, which can distort the antenna's radiation pattern and contribute to energy losses. This parasitic radiation from the microstrip feed network can negatively impact the antenna's directivity and efficiency [26].

5.4. Patch antenna radiation mechanism:

The radiation of a microstrip patch antenna is primarily caused by the fringing fields at its edges, as illustrated in (Figure I.15) When the patch is excited, charge distribution occurs between the metallic patch and the ground plane. The region beneath the patch accumulates a positive charge, while the ground plane carries a negative charge, creating an electrostatic attraction between them. The patch operates as a resonant cavity, with its

metallic patch and ground plane forming electric walls, while the edges act as magnetic or impedance boundaries. Optimal impedance matching is achieved when the patch resonates as a cavity, maximizing its radiation efficiency. The field lines maintain a uniform width but exhibit sinusoidal variations along their length. The electric field (*E-field*) reaches its peak at the two radiating edges, whereas the current is most concentrated at the patch's center.

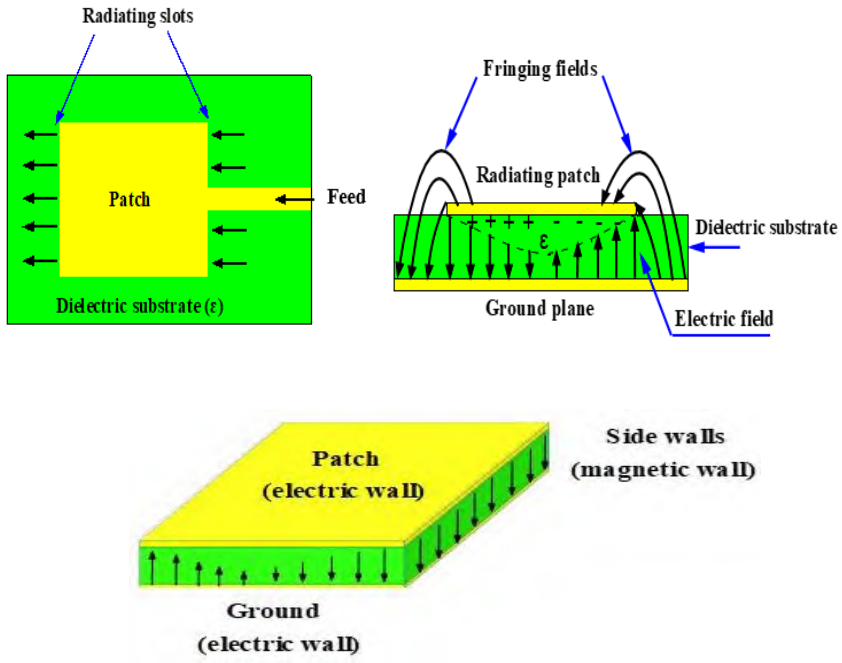


Figure 15: (a) The microstrip patch antenna's radiating mechanism
(b) a cavity model representation[27].

Unlike a conventional transmission line, which emits minimal power due to the cancellation of fringing fields by opposing nearby fields, power radiation in microstrip patch antennas primarily occurs at open circuit points and discontinuities. The amount of emitted power depends on the radiation conductance load associated with the patch. The edges of the patch function as radiating slots, with their excitation governed by the internal fields within the cavity.

For optimal antenna performance, a thick dielectric substrate with a low dielectric constant is preferred, as it enhances efficiency, increases bandwidth, and improves radiation characteristics. However, this comes at the cost of a larger antenna size. On the other hand, antennas designed with higher dielectric constants result in reduced efficiency and a narrower bandwidth, making them more suitable for miniaturized designs. Consequently, a trade-off must be made between performance and antenna size [27].

5.5. Feeding techniques for microstrip (patch) antennas:

The four most commonly used feed techniques are the microstrip line, coaxial probe (contacting schemes), aperture coupling, and proximity coupling (noncontracting schemes).

5.5.1 Microstrip (Offset Microstrip) LineFeed:

Microstrip (Offset Microstrip) Line Feed is a technique where a conducting strip is connected to the edge of a microstrip patch, providing a planar structure and allowing for good impedance matching without additional matching elements. This method is easy to fabricate and model, but it can lead to surface waves and spurious feed radiation, affecting the antenna's bandwidth and causing undesirable cross polarization effects. Proper control of the inset position can ensure good impedance matching. However, as the dielectric substrate thickness increases, surface waves and spurious feed radiation can also occur, affecting the antenna's performance [28].

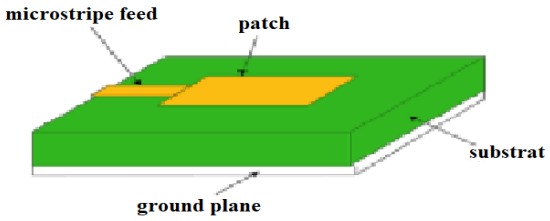


Figure I .16: Microstrip Line Feed[28].

5.5.2 Coaxial Feed :

The coaxial feed, also known as probe feed, is a common technique for feeding microstrip patch antennas. It involves the inner conductor of the coaxial connector being soldered to the radiating patch and the outer conductor connected to the ground plane [28].

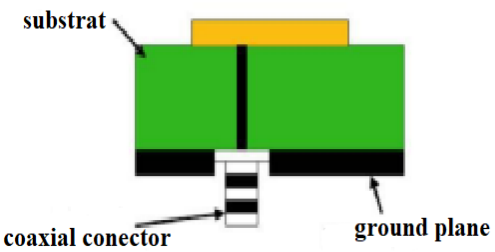


Figure I .17: Coaxial feed[28]

The feeding scheme allows for impedance matching at any position within a patch, making it easy to fabricate and low in spurious radiation effects. However, it has narrow

bandwidth and is difficult to model due to drilling holes into the substrate. For thicker substrates, increased probe length can make input impedance more inductive, leading to matching problems. The microstrip line feed and coaxial feed also face issues like spurious feed radiation and matching problems. Non-contacting feed techniques can address these issues [28].

5.5.3 Aperture Coupled Feed:

Aperture coupling involves etching a radiating microstrip patch element on the antenna substrate and a microstrip feed line on the feed substrate, allowing for independent selection of thickness and dielectric constants to optimize radiation and circuitry electrical functions. The aperture is typically centered under the patch, resulting in lower cross-polarization due to symmetry. The amount of coupling from the feed line to the patch is determined by the aperture's shape, size, and location. The ground plane separates the patch and feed line, minimizing spurious radiation [28]

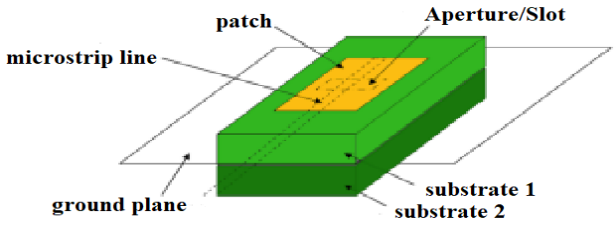


Figure I .18: Aperture coupled feed[28].

The feeding technique involves using a high dielectric material for the bottom substrate and a thick, low dielectric constant material for the top, aiming to optimize radiation from the patch. This technique offers a high bandwidth of 21% and minimizes spurious radiation effects. However, it is challenging to fabricate due to multiple layers and increased antenna thickness [28].

5.5.4 Proximity Coupled Feed :

The electromagnetic coupling scheme is a feed technique that uses two dielectric substrates with a feed line between them and a radiating patch on top. This technique eliminates spurious feed radiation and provides a high bandwidth of about 13% due to increased electrical thickness of the microstrip patch antenna. It also offers choices between two different dielectric media for patch and feed line to optimize individual performance **[**28]**.**

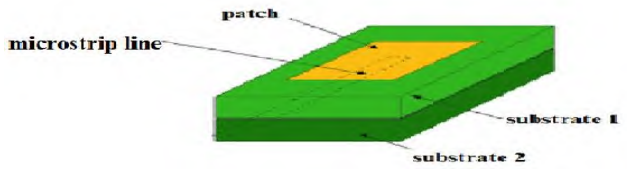


Figure I .19: Proximity coupled feed[28].

5.6 Antenna losses:

The limited resistivity of metallic layers causes Joule effect losses in conductors. As this resistivity increases, the magnetic field generated by inductance induces currents with a non-uniform density distribution, affecting both the conductor and the substrate. These currents are the primary cause of losses at microwave frequencies and are mainly associated with the skin effect [29].

5.6.1 Skin Effect:

When an alternating current flows through a conductor, it generates a magnetic field around it. One of the most significant effects is the tendency of the current to concentrate in the outer layers of the conductor as the frequency increases. This phenomenon is referred to as the skineffect. Inside the conductor, the current density J(z) decreases exponentially.

This behavior defines a characteristic parameter known as "skin depth"δ\delta, which is inversely related to frequency and can be expressed mathematically.

The skin depth provides an initial estimate of the width of the region where the current is most concentrated in a conductor. It is essential for determining the effective resistance at a specific frequency. In these calculations, the real component is often disregarded in favor of the imaginary component due to the high conductivity of metals [30].

$$\delta = \sqrt{\frac{2}{w\mu\sigma}} = \sqrt{\frac{2\rho}{w\mu}} = \sqrt{\frac{1}{\sigma\mu\pi f}} \qquad 19$$

δ: skin thickness in metres [m]

W:pulsation in radians per second [rad/s]

f: current frequency in hertz [Hz]

μ :magnetic permeability in henry per meter [H/m]

p: resistivity in ohm-meter : electrical conductivity in siemens permeter [S/m].

To calculate effective resistance at a given frequency for a conductor with a diameter greater than 0, assume only the outer part of the thickness contributes to conduction. The proximity effect, caused by the varying magnetic field generated by the antenna, induces

an image current in the substrate, known as eddy current, which opposes initial variations in the magnetic field [30].

5.6.2 Losses in the substrate:

The literature extensively studies the radiation characteristics of printed antennas, revealing three types of wave that increase coupling: guided waves, which reflect the propagation of the electromagnetic field between two conductive planes, and ground waves, which are useful for signal propagation along a microstrip line [31].

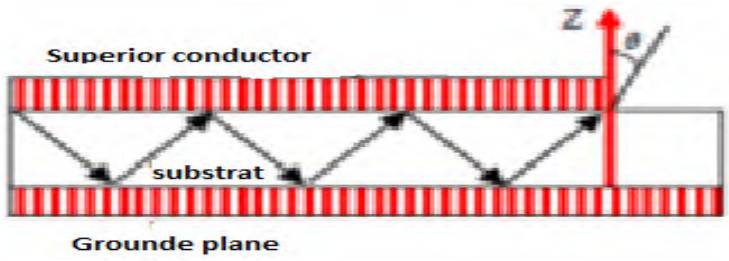


Figure I .20: Guided waves[31].

5.6.3 Radiation diagram:

Radiated waves, emitted by metal parts in antennas, contribute to the radiation of the antenna by dispersing freely in space. In printed antennas, all coupling is linked to the radiated waves, allowing for efficient signal propagation and radiation [31].

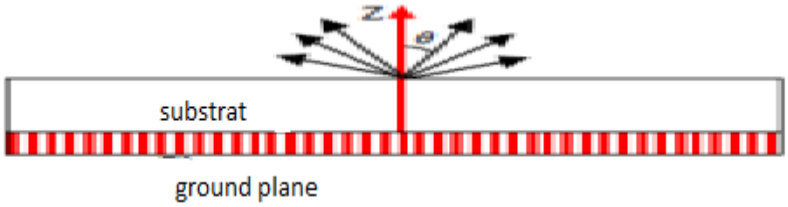


Figure I.21: Radiated waves[31] .

5.6.4 Surface waves:

The study of printed antennas must consider surface waves, which pass through the substrate with an incidence θangle ranging fromπ /2 to arcsin (1/$\sqrt{\varepsilon r}$), propagating in the dielectric between the ground plane and the air-dielectric interface.

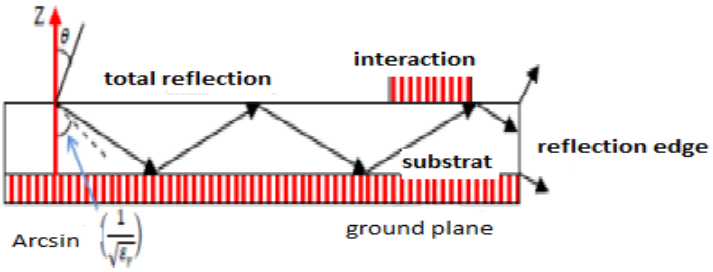


Figure I. 22: Surface waves[31].

The choice of substrates is crucial to maximize the performance and optimize the performance of designed antennas. The best antenna performance is achieved when the dielectric constant is low and the substrate thickness is limited to avoid losses due to surface waves [31].

Conclusion:

Antennas are a fundamental component of modern communication systems, ensuring the transmission and reception of electromagnetic waves. They play a crucial role in various fields such as telecommunications, broadcasting, wireless networks, radar systems, and satellite communications. The performance of an antenna depends on several factors, including frequency, gain, directivity, and impedance matching, all of which directly influence the quality and efficiency of transmissions.

With the advancement of technologies such as 5G, the Internet of Things (IoT), and satellite communication systems, the design and optimization of antennas have become a strategic challenge. Improving performance, miniaturization, and adaptability to complex environments are key challenges to meet the growing demand for high-speed connectivity and efficient data transmission.

Thus, the evolution of antennas is closely linked to technological progress. Future antenna designs will need to incorporate innovative approaches such as smart materials, reconfigurable antennas, and artificial intelligence to enhance efficiency and integration into increasingly complex and high-performance systems.

CHAPITREII:
Reconfigurable Antennas

1. Introduction

Reconfigurable antennas are designed to reconfigure their characteristics such as frequency, pattern, bandwidth, and polarization to adapt to the environment. This concept has gained significant attention due to the introduction of future wireless communication concepts like cognitive radio, which employs wideband sensing and reconfigurable narrowband communication [32]. Frequency reconfigurable antennas can reduce the size of front end systems and allow pre-filtering at the receiver, supporting many wireless applications in one single terminal system.

The idea of reconfigurable antennas appeared in the early 1930s, with the first pattern reconfigurable antenna designed for satellite communication in 1979 [33]. The proposed antenna can reconfigure six different beam angles [34]. In 1999, a reconfigurable leaky patch antenna using PIN diode (Positive-Intrinsic-Negative diode) was presented [35]. Microstrip antennas have been used as a platform to design reconfigurable antennas since 1999.

The effective length of an antenna plays a crucial role in determining the operating frequency. To achieve frequency reconfiguration, the effective length can be changed by adding or removing part of the length using electronic switches. Electronic switches, such as PIN diodes, FETs (Field Effect Transistors), and RF MEMS (Radio Frequency Micro-Electro-Mechanical Systems), are commonly used for frequency switching. PIN diodes are preferred by researchers due to their acceptable performance, low cost, and ease of fabrication. Variable reactive loading (typically capacitance) such as varactor diodes can also be used to change the resonant frequency, but they have limitations such as limited frequency range switching [36]. The antenna can switch between two modes: the standard mode (with PIN diodes on) and the other mode where PIN diodes is in the states.

2. Reconfigurable antennas:

Reconfigurable antennas are dynamic antennas that can reconfigure their characteristics like frequency, diagram, bandwidth, and polarization after fabrication to adapt to the environment. These reconfigurations can be a combination of different characteristics depending on the application [36]. They are achieved by changing the distribution of the electrical current, affecting electromagnetic and impedance properties. There are three types of reconfigurations based on reconfigurability:

- frequency reconfiguration :
- wave diagram reconfiguration, and polarization reconfiguration.

2.1 Frequency reconfigurable antennas:

An antenna can be tuned to different frequencies by modifying its electrical length. In such antennas, the conductor is adjusted using switching components such as PIN diodes, varactor diodes, or other switching mechanisms. This alteration changes the antenna's electrical length, enabling frequency reconfiguration. The first patented design for a reconfigurable antenna was introduced in 1983 by Schaubert [37].

After an extensive literature review, several frequency reconfigurable designs have been examined:

1. In Figure II.1, a frequency-reconfigurable antenna capable of operating in three different applications was proposed by Schaubert [37]. The reconfiguration was achieved using two switches:

- When Switch 1 was OFF and Switch 2 was ON, the antenna operated at two center frequencies: 2.44 GHz and 5.5 GHz, with bandwidths of 0.31 GHz and 1.83 GHz, respectively.
- When both switches were OFF, a single impedance bandwidth from 2.30 GHz to 2.64 GHz was observed.
- When both switches were ON, three frequency bands appeared at 2.41 GHz, 3.36 GHz, and 5.62 GHz, with bandwidths of 0.23 GHz, 0.62 GHz, and 1.35 GHz, respectively.

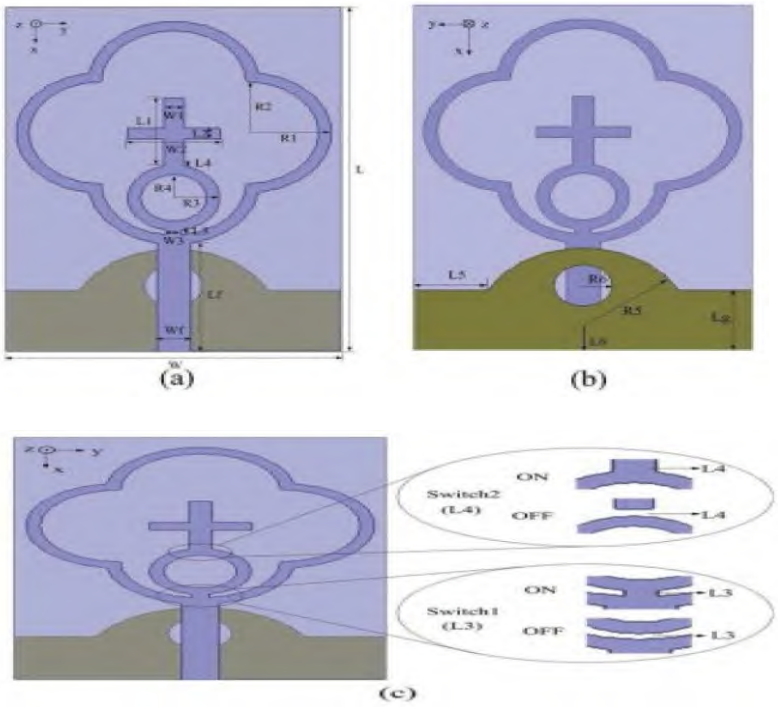


Figure II.1 : Geometry of the antenna . (a) Top view (b) bottom view and (c) reconfigurable mechanism[37].

The antenna design included a conductor L3, which connected the antenna to a circular ring, acting as Switch 1 in simulation and modifying the antenna's electrical length. Similarly, L4 connected an inverted T-shaped stub to the circular ring, acting as Switch 2. However, while this design demonstrated good impedance matching and far-field characteristics, the practical implementation did not account for PIN diode losses in simulations and experiments.

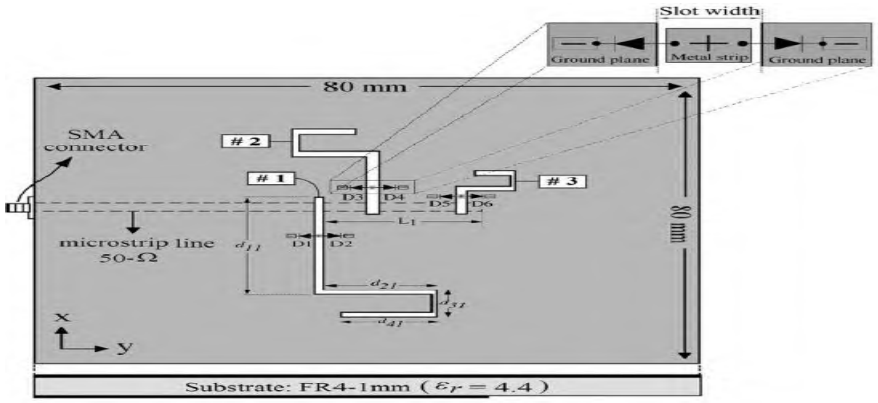


Figure II.2: Geometry of the multifrequency triple slot antenna[38]

2. In figure II.2,the design introduced a slot-reconfigurable antenna capable of operating at three different frequencies using seven switching states controlled by PIN diodes. The PIN diodes were mounted between the ground plane and metal strips inside the slots. Various diode biasing configurations resulted in different resonance frequencies[38].

- State 1: D3, D4, D5, and D6 were biased, while D1 and D2 were unbiased → Resonance at 2.4 GHz
- State 2: D3 and D4 were unbiased, all others biased → Resonance at 3.5 GHz
- State 3: D5 and D6 were unbiased, all others biased → Resonance at 5.6 GHz
- State 4: Only D5 and D6 biased → Dual-band at 2.4 GHz and 3.5 GHz
- State 5: Only D3 and D4 biased → Dual-band at 2.4 GHz and 5.6 GHz
- State 6: D1 and D2 biased → Dual-band at 3.5 GHz and 5.6 GHz
- State 7: All diodes unbiased → Triple-band at 2.4 GHz, 3.5 GHz, and 5.6 GHz

The change in electrical length modified the antenna's resonance frequency. However, the design was too large for portable wireless devices, and experimental results deviated from

simulated outcomes.

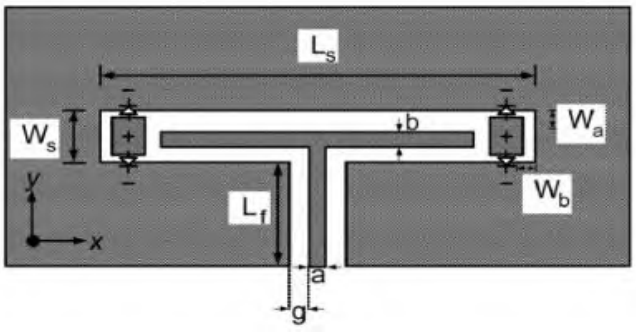


Figure II.3 : Configuration of the reconfigurable slot antenna[39]

In figure II.3: the researchers proposed a coplanar single-folded slot antenna where the slot length was adjusted using a low-cost PIN diode[39].

- Slot length (Ls) = 21.22 mm achieved resonance at 5.25 GHz.
- Metallic strips in the slot were connected to the ground plane via PIN diodes.
- When diodes were biased, the strips were connected to the ground plane, reducing the slot perimeter and shifting the resonance to 5.775 GHz.
- The PIN diodes were controlled via bias lines, which were disconnected when unbiased [37].

2.2 Pattern Reconfiguration:

Reconfigurable antennas with pattern selectivity enhance system security, improve communication reliability, and reduce energy loss, leading to better overall system performance. A widely used and effective method for modifying radiation patterns independently of frequency behavior involves electrically tuned or switched parasitic elements. The lengths of these parasitic elements can be adjusted using FET or PIN diode switches or varactors, which in turn modify the magnitude and phase of currents on the parasitic elements relative to the driven element.

By varying the lengths of the parasitic elements, the main beam tilt in a given plane can be dynamically switched or continuously swept. This approach offers key advantages, including isolation of the driven element(s) from the tuned element(s) and access to a variety of available topologies and functionalities. The fundamental principle of pattern tuning relies on mutual coupling between closely spaced driven and parasitic elements, enabling effective array behavior from a single feed point. Consequently, variations in radiation patterns result

from changes in element coupling, which influence the effective source currents on both the driven and parasitic elements [40].

2.3 Polarization-Reconfigurable Antennas:

The polarization of an antenna is determined by the distribution of surface currents on its radiating structure. The direction of current flow at different time instances directly influences the polarization of the electric field. The movement of these currents—either clockwise or counterclockwise—defines the polarization sense, categorized as either Left-Hand Circular Polarization (LHCP) or Right-Hand Circular Polarization (RHCP).

Different polarization states can be achieved by modifying the flow of surface currents. Ideally, the impedance and frequency characteristics should remain consistent across different polarization states. However, in practical applications, slight variations in the physical structure of the antenna introduce minor discrepancies. The key design challenge is ensuring consistent performance across all polarization states.

Antennas with switchable polarization capabilities can effectively double system capacity by enabling frequency reuse. Circularly polarized antennas are widely employed in modern wireless communication systems, including WLAN (Wireless Local Area Network), RFID (Radio Frequency Identification), and GPS (Global Positioning System), as they mitigate

multipath fading and enhance signal strength. The concept of polarization diversity in antenna systems has gained significant interest in contemporary wireless technologies [41].

Previously, dual-polarized and circularly polarized antennas were developed with fixed polarization states. However, recent advancements have enabled polarization-switchable antennas, which can transition between Linear Polarization (LP) and Circular Polarization (CP), encompassing both LHCP and RHCP. Various techniques for achieving CP have been explored in the literature. Compact polarization-switchable antennas are increasingly in demand for present and future wireless applications. Several techniques can be implemented to achieve polarization reconfigurability [41]:

1. **Antenna Rotation**:
- Physically rotating the antenna alters its polarization orientation.
- Simple yet effective for adjusting linear or circular polarization.
- Commonly used in mechanically steerable antennas.
2. **Switchable Feeds**:

- Polarization can be toggled by switching between multiple feed points.
- Enables quick transition between vertical, horizontal, and circular polarization states.
- Used in dual-polarized and reconfigurable patch antennas.

3. **Phase Shifters**:

- Adjusting the phase of the feeding signal modifies the polarization angle.
- Enables smooth transitions between different polarization modes.
- Frequently utilized in phased arrays and Active Electronically Steered Arrays (AESAs).

4. **Met materials Integration**:

- Embedding engineered metamaterial structures into the antenna modifies wave polarization.
- Provides precise control over polarization without mechanical movement.
- Suitable for miniaturized and high-frequency antenna applications.

5. **Reflect arrays**:

- Consist of planar arrays of passive elements that reflect incident waves with a controlled phase shift.
- By adjusting the phase of individual elements, the polarization of the reflected wave can be modified.
- Used in beam-steering and polarization-agile antenna designs [42].

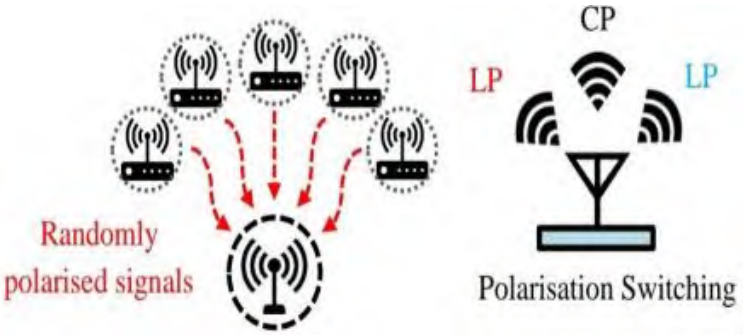


Figure II.4 : Antenna Polarization Reconfiguration[42]**.**

3. Switching Devices for Reconfigurable Antennas:

3.1 Electrical Reconfiguration:

Electrical reconfiguration is a technique used to modify an antenna's electrical properties without altering its physical shape or size. This allows the antenna's performance characteristics to be adjusted to meet specific operational requirements.

This reconfiguration is achieved using switchable components such as diodes, MEMS, and varactors. These elements enable modifications to key electrical parameters of the antenna,

including impedance, radiation pattern, and polarization. By adjusting these properties, the antenna can function across multiple frequency bands or exhibit different radiation patterns, enhancing its adaptability to diverse communication environments.

The process works by manipulating the surface currents on the antenna. By altering the distribution of these currents, critical parameters such as frequency, polarization, and radiation pattern can be tuned. This can be accomplished through various methods, including incorporating reactive elements or utilizing switches to dynamically adjust the antenna's geometry[43].

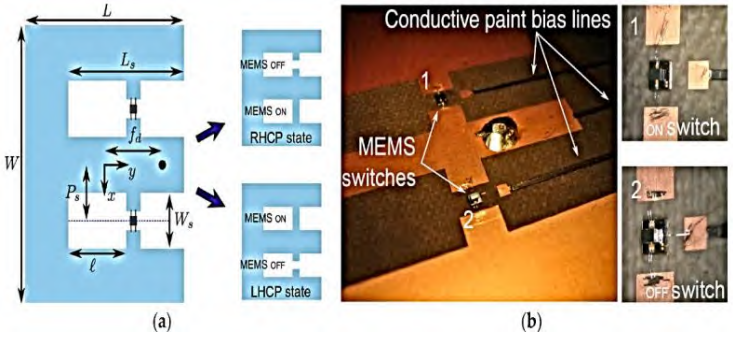
3.1.1 MEMS :

Reconfigurable antennas with MEMS switches have gained tremendous research interest. MEMS switches are devices that operate through mechanical movement to achieve a short or open circuit in RF circuits. These switches can be designed in different configurations based on signal path (series or shunt), actuation mechanism (electrostatic, thermal, or magnetostatic), type of contact (ohmic or capacitive), and structural design (cantilever or bridge). The required force for mechanical movement can be achieved through various actuation mechanisms, such as electrostatic and magnetostatic forces [44].

RF MEMS switches capable of handling power up to P = 20W and operating at a switching cycle of $\mathbf{10^{12}}$ have been widely used in radar systems, network analyzers, satellite communication systems, and base stations [44].

An RF MEMS shunt switch is a type of MEMS switch that differs from a series switch in that it consists of a suspended movable thin metal bridge over the center conductor, fixed and anchored at both ends to the ground line of the transmission path. MEMS switches for RF applications operate by alternating between short and open circuits to control signal transmission [44], the characteristics of RHCP/LHCP reconfigurable antennas are analyzed. Figure II.5a illustrates the design configuration: The schematic consists of an E-shaped radiation patch with a coaxial probe feed. To facilitate RF switch integration and achieve a wide impedance bandwidth, a multilayer configuration is utilized in the proposed design [44].

A pair of MEMS switches are placed across the slots of the E-shaped patch. Figure 4b depicts the MEMS implementation and bias lines. The RHCP and LHCP characteristics are realized when one switch is **ON** and the other is **OFF** [44].



FigureII.5:(a) Configuration of the micro-electromechanical system(MEMS) reconfigurable antenna and (b) magnified view of the switch implementation[44].

3.1.2 Varactor Diodes:

A varactor diode is a semiconductor device that functions as a variable capacitor (see Figure II.6). The junction capacitance changes nonlinearly with the applied reverse voltage, decreasing as the reverse bias increases. Unlike PIN diodes, which provide discrete variations, varactor diodes allow continuous tuning of antenna characteristics based on the bias voltage.

This nonlinear capacitance behavior makes varactor diodes essential in applications such as voltage-controlled oscillators (VCOs), continuous phase shifters, modulators, and frequency multipliers (harmonic generators).

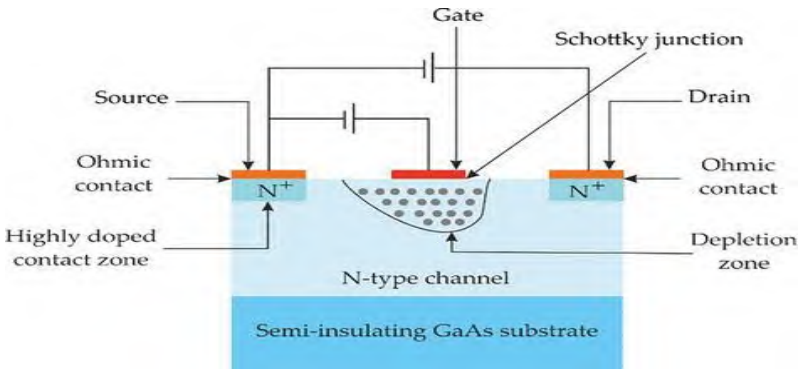


Figure II.6 : Gas MESFET structure[44]

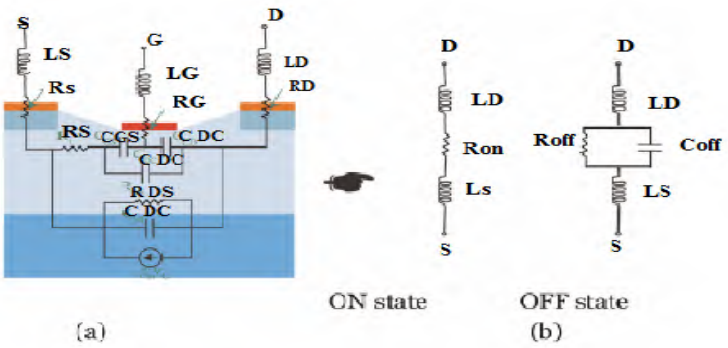


Figure II.7: Location components of (a) MESFET equivalent circuit (b)ON and OFF equivalent circuit[44].

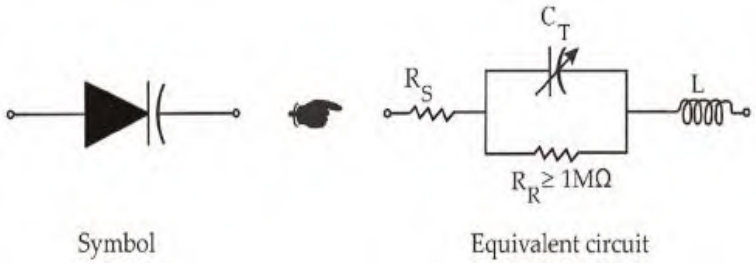


Figure II.8: Symbol and equivalent circuit of a varactor diode[45]

Varactor diodes are primarily classified into two types:

1. **p-n Junction Varactor** – Commonly used in lower-frequency applications.
2. **Schottky Varactor** – Typically employed at microwave and millimeter-wave frequencies.

As the number of varactor diodes in a circuit increases, the complexity of the polarization network also grows. These diodes are frequently used for frequency reconfiguration, often in combination with PIN diodes to achieve a broader frequency tuning range [45].

As the number of varactor diodes in a circuit increases, the complexity of the polarization network also grows. These diodes are frequently used for frequency reconfiguration, often in combination with PIN diodes to achieve a broader frequency tuning range [45].

3.1.3 PIN diode :

a. Definition :

PIN diodes are most commonly used in remote systems. Their operation involves forward and reverse biasing (both on and off states). When designing antennas, considerations such as size and direct current (DC) parameters should be carefully addressed.

PIN diodes offer maximum tuning speed with a peak DC bias in the "on" state and provide good

power balancing capability. Their cost-effectiveness and reliability make them a preferred choice [46].

The PIN diode is a semiconductor commonly utilized in microwave applications. Under a forward bias, it transitions to its "ON" state, exhibiting extremely low impedance, effectively functioning as a short circuit. Conversely, when a reverse bias is applied, the diode shifts to its "OFF" state, characterized by very high impedance [47]. This diode is employed to enable frequency reconfigurability, radiation pattern adjustment, and polarization control, offering advantages such as low cost, easy integration, and minimal bias voltage requirements.

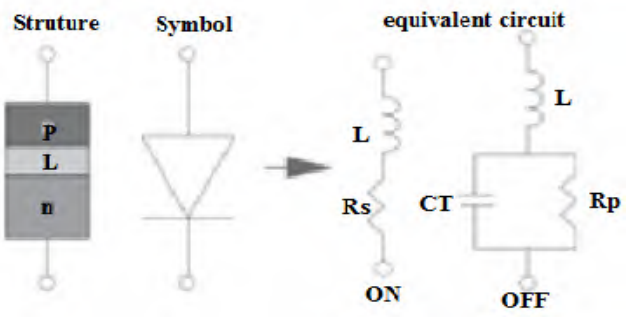


Figure II.9 : Equivalent circuits of a PIN diode in ON and OFF states **[47].**

b. Polarization Techniques (DC Supply) for PIN Diodes:

In antenna reconfiguration, active components require a direct current (DC) supply at a specific potential. Consequently, routing these DC signals to the component integrated into the antenna can be challenging. A major difficulty arises from the fact that powering components such as PIN diodes often necessitates the addition of conductive lines or metallic structures. These structures may be positioned in regions of high current density, leading to unintended coupling of current or radiation. This coupling can, in turn, disrupt the frequency response and radiation characteristics of the antenna[47]. Additionally, depending on the operational mode of the antenna, these structures may need to function over a broad or ultra-wide frequency band. Therefore, they must be designed to minimize interference with the overall antenna performance across the entire frequency spectrum of interest[47].

1. Short Circuits :

The simplest method to bias such structures is to use a conducting wire to connect a radiating element (such as a patch) to the ground plane located beneath it. A commonly used technique involves drilling a hole in the ground plane, allowing the shorting wire to pass through and connect to the reconfigurable component located behind the ground plane (Fig. II.10) [48].

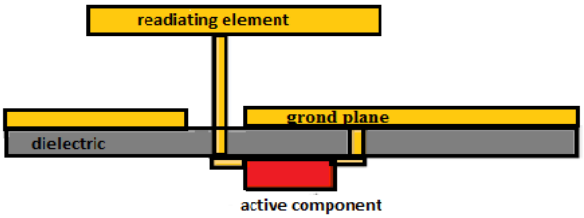
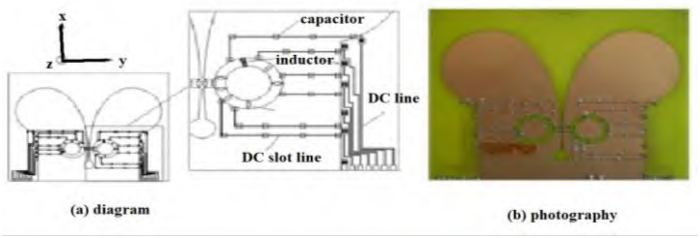


Figure II.10: Polarization of a reconfigurable short-circuit under the ground[48**]**

This configuration offers a major advantage: the ground plane acts as shielding, protecting the components and polarization circuits from the near-field effects of the radiating element. As illustrated in Figure II.12, this shielding helps maintain the antenna's performance by reducing unwanted interference [49].

2. Slots:

Polarizing this type of structure is more complex because it requires applying a different voltage to each side of the slot, such as when powering a diode [49]. This necessitates the addition of extra slots that do not contribute to the antenna's functionality but serve to block direct current (Fig. II.11).



FigureII.11 : Polarization of a slot (top view) loaded by diodes[49]

However, these additional slots often disrupt RF current paths. To minimize this disturbance, decoupling capacitors must be used, as they block DC signals while allowing RF currents to pass through [49].

However, these additional slots often disrupt RF current paths. To minimize this disturbance, decoupling capacitors must be used, as they block DC signals while allowing RF currents to pass through [49].

3. Polarization Lines:

The use of polarization lines (DC lines) is often essential. These conductive lines do not inherently contribute to the antenna's radiation but are solely intended to route the control voltage to the active components (Fig. II.12). However, in the RF domain, these lines act as

propagation paths where part of the useful signal may couple, potentially disrupting the antenna's performance. To minimize or eliminate this impact, the first step is to reduce the number of these lines as much as possible [50].

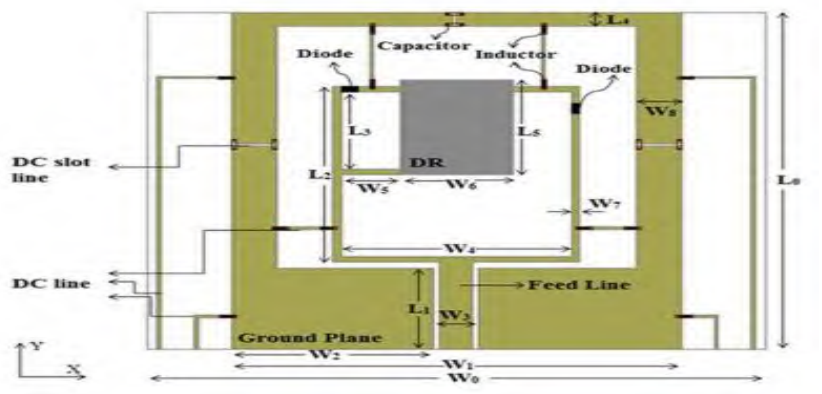


Figure II.12: Example of an antenna with polarization lines (DC line)[50].

Additionally, it is crucial to determine the exact number of DC potentials required for the antenna's operation and to maximize the sharing of lines among different active components. For example, two diodes need only three distinct potentials to function independently. Another critical aspect is minimizing RF signal coupling into these lines. One approach is to reduce the track width as much as technologically feasible, thereby increasing their impedance. A higher impedance helps reflect RF signals. However, excessive reduction in track size has its limitations—a section that is too small may cause thermal issues, particularly during component soldering or when carrying high supply currents, which may lead to melting [50].

Despite these precautions, the use of decoupling inductors is often necessary. These inductors effectively block RF signals while allowing the passage of direct current (DC) [50].

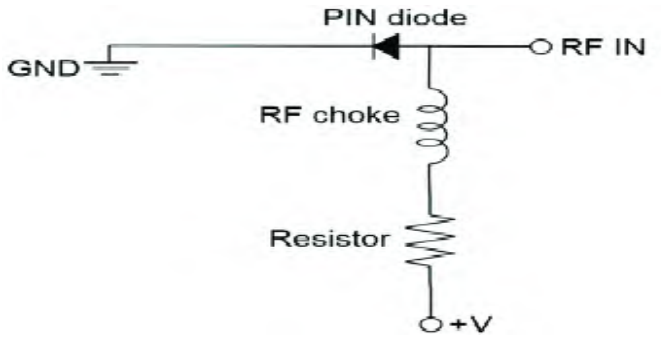
4. Components Used for Polarization:

Supplying power to the active components integrated into the antenna for reconfiguration may necessitate the use of passive coupling and decoupling elements, such as capacitors or inductors.

Capacitors serve the function of allowing high-frequency currents to pass while blocking DC signals. The capacitance value must be as high as possible to ensure that RF signals remain unaffected, even at the lowest frequencies within the operating band. Decoupling capacitors,

also referred to as DC-blocks, that meet the required criteria (small size, high capacitance) are typically made from ceramic materials, such as the ATC 520L series from American Technical Ceramics (ATC). These capacitors generally support a wide frequency range (from a few megahertz to several tens of gigahertz) and exhibit low insertion losses, approximately 0.25–0.5 dB at lower gigahertz frequencies [50].

The second type of passive component used has the opposite function of capacitors—it blocks high-frequency currents while allowing DC signals to pass. These are inductors, such as the WE-MK Multilayer Ceramic SMD Inductor series (Multilayer Ceramic Surface-Mount Device) from WE (Würth Elektronik is a German company). The selection criteria remain similar: the component should be as compact as possible, with the highest feasible inductance value [50].



FigureII.13 : Biasing Circuit for PIN Diode [50].

c. Characteristics of the PIN Diode:

- **Variable High-Frequency Resistance:** The resistance at high frequencies is inversely proportional to the DC bias current. When forward-biased, the PIN diode functions as a variable resistor, with resistance values typically ranging from 0.1 Ω to 10 kΩ, though the practical range may be more limited [51].
- **High Reverse Breakdown Voltage:** The intrinsic layer's wide depletion region provides the diode with excellent reverse breakdown capabilities, making it suitable for high-power applications [51].
- **Amplitude Modulation Capability:** By varying the control current, the PIN diode can modulate the amplitude of an RF signal, making it useful in communication systems [51].
- **Fast Switching Speed:** The diode exhibits rapid switching, with response times of less than 100 nanoseconds, making it ideal for high-frequency applications [51].

d. Advantages and Disadvantages of PIN Diodes:

- Advantages:

- **High-Voltage Rectification:** PIN diodes can function as high-voltage rectifiers**,** making them suitable for power electronics applications [51].
- **Enhanced Reverse Voltage Tolerance:**The**intrinsic layer** increases the separation between the **P and N regions**, enabling the diode to withstand **higher reversevoltages**during reverse bias. This characteristic makes PIN diodes **ideal RF switches** for high-frequency applications [51].
- **Improved Photodiode Performance:** In photodiodes, the**depletion region** is responsible for converting light into current. By introducing an**intrinsic layer**, the depletion region is extended, significantly enhancing the diode's **efficiency and sensitivity**in optical applications [51].

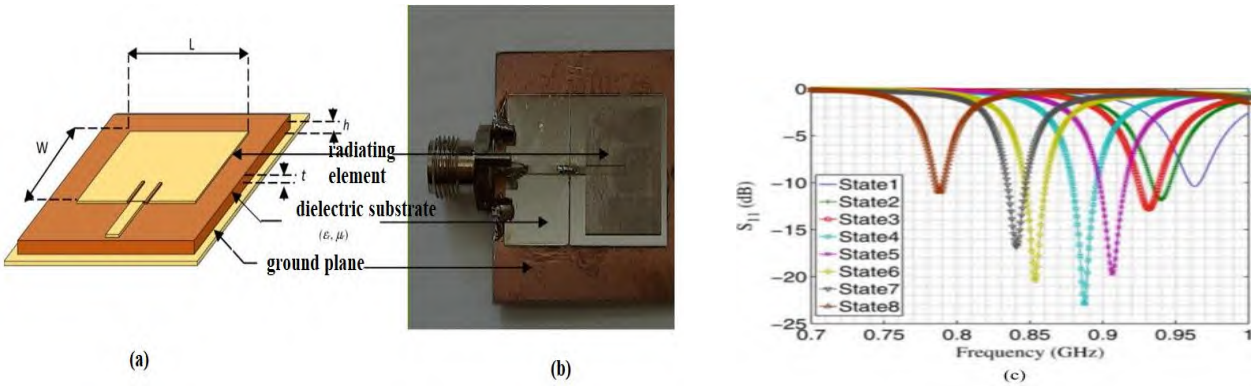
-Disadvantages :

- **Slow Recovery Time:** One of the main drawbacks of PIN diodes is their long transition time when switching from the ON state to the OFF state**.**
- **Power Losses:** Due to reverse recovery time**,** PIN diodes experience power dissipation**,** which can impact efficiency in high-speed applications [51].

3.2 Optical reconfiguration :

Optical reconfiguration techniques rely on photoconductive switches, which are made from semiconductor materials such as silicon and germanium. These switches do not require biasing circuits or metal wires, reducing interference within the circuit. Additionally, photoconductive switches exhibit fast switching speeds. Various techniques for optical control of reconfigurable antennas using commercially available devices have been discussed in previous studies [52].

An optically controlled frequency-switchable patch antenna using a silicon-based switch is reported. The geometry and photograph of the antenna are shown in Figures II.14a and II.14b, respectively. The frequency response for different operating states of the antenna is depicted in Figure II.14c. Several optically reconfigurable antennas with frequency, polarization, and beam-switching capabilities have been reported in the scientific literature [52].



FigureII.14: Optically shorted stub-loaded frequency-switching patch antenna**a** geometry,**b** photograph, and **c** frequency response of the antenna for eight states of operation[52].

3.3 Physical Reconfigurable Antenna:

Physical reconfiguration is one of the fundamental and traditional techniques used in early antenna designs. In this approach, antenna characteristics are modified by altering the antenna structure through mechanical systems. Over time, innovative methods have been introduced using actuation mechanisms to adjust the antenna structure and shift radiation components, enabling reconfigurable antenna parameters.

For instance, devices such as stepper motors and linear actuators have been utilized to fully or partially change the physical dimensions of the antenna. Motor-controlled and rotatable antennas have been successfully implemented. Additionally, reconfigurable antennas using electrostatic and magnetic actuators have been introduced, demonstrating satisfactory performance [53].

A frequency-reconfigurable antenna incorporating parasitic elements was proposed by Choo, Rogers, and Ling[54]. as illustrated in Fig. II.15a, frequency tuning is achieved using a piezoelectric actuator.

Another example, shown in Fig. II.15b, demonstrates frequency reconfiguration through inclination angle adjustment, with magnetic control ensuring the required resonant

frequency[55]. Furthermore, liquid metal-based physical adjustments can be employed to achieve reconfigurability, such as in stretchable antennas (Fig. II.15c) and metal parasitic beam-steering antennas [56].

Although physical modifications have proven effective in various designs, they present challenges such as slower response time, shorter operational lifespan, and dependence on the

antenna's physical dimensions. Nonetheless, this approach remains a promising solution for high-frequency applications where other reconfiguration technologies face limitations due to electrical constraints.

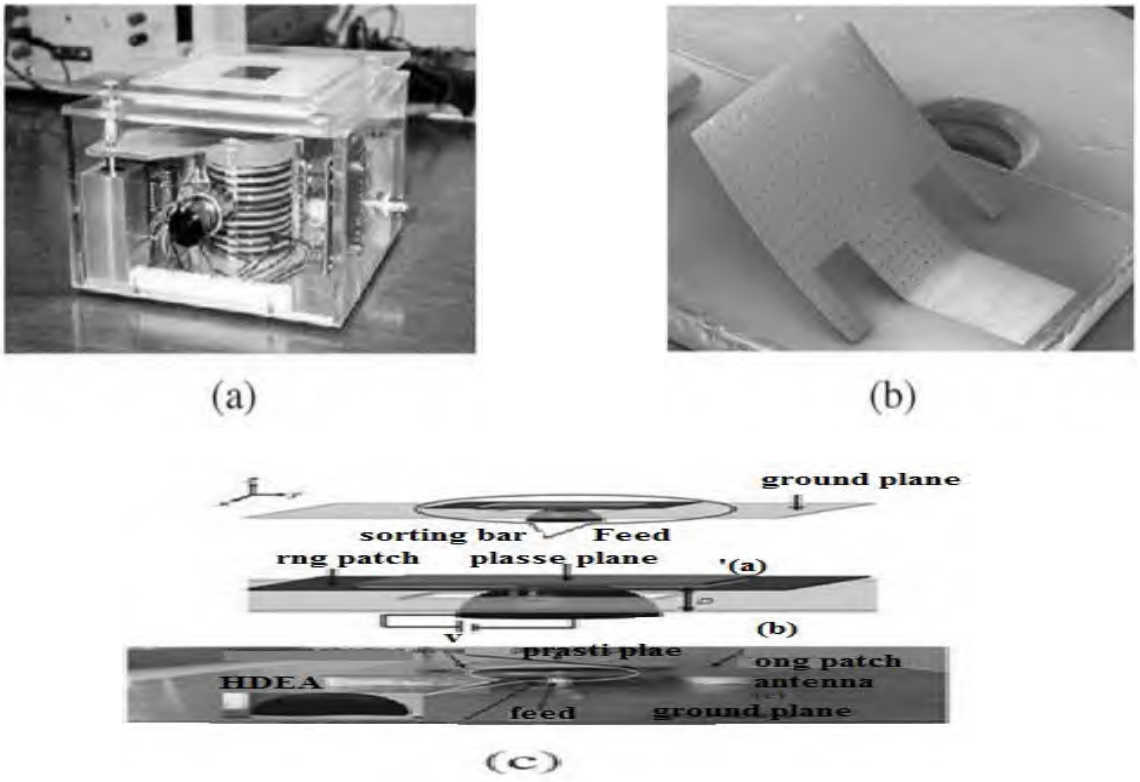


Figure II.15: (a) Peizoelectric actuator, (b) magnetic actuator, (c) electromechanical system[56]

3.4 Material Reconfiguration Techniques:

Reconfigurable antennas based on smart materials alter their characteristics by adjusting the material properties, specifically the relative dielectric constant and permeability. Developing such antennas presents challenges, and research is ongoing to enhance their reliability and efficiency.

A frequency-reconfigurable patch antenna utilizing low-loss transformer oil is explored in reference [57]. This antenna incorporates a two-layer substrate between the patch and the ground plane. The upper layer consists of a homogeneous polytetrafluoroethylene (PTFE)

substrate, while the lower layer features a transparent container containing both air and transformer oil. By modifying the height of the transformer oil layer, the air-to-liquid volume ratio is adjusted, allowing for tunable effective permittivity of the entire substrate, thereby enabling frequency reconfiguration. The antenna geometry is illustrated in Fig. II.16. Additionally, various material-based reconfigurable antennas have been reported, including a

low-profile broadband polarization-reconfigurable water spiral antenna and a liquid-metal polarization-pattern-reconfigurable dipole antenna [57].

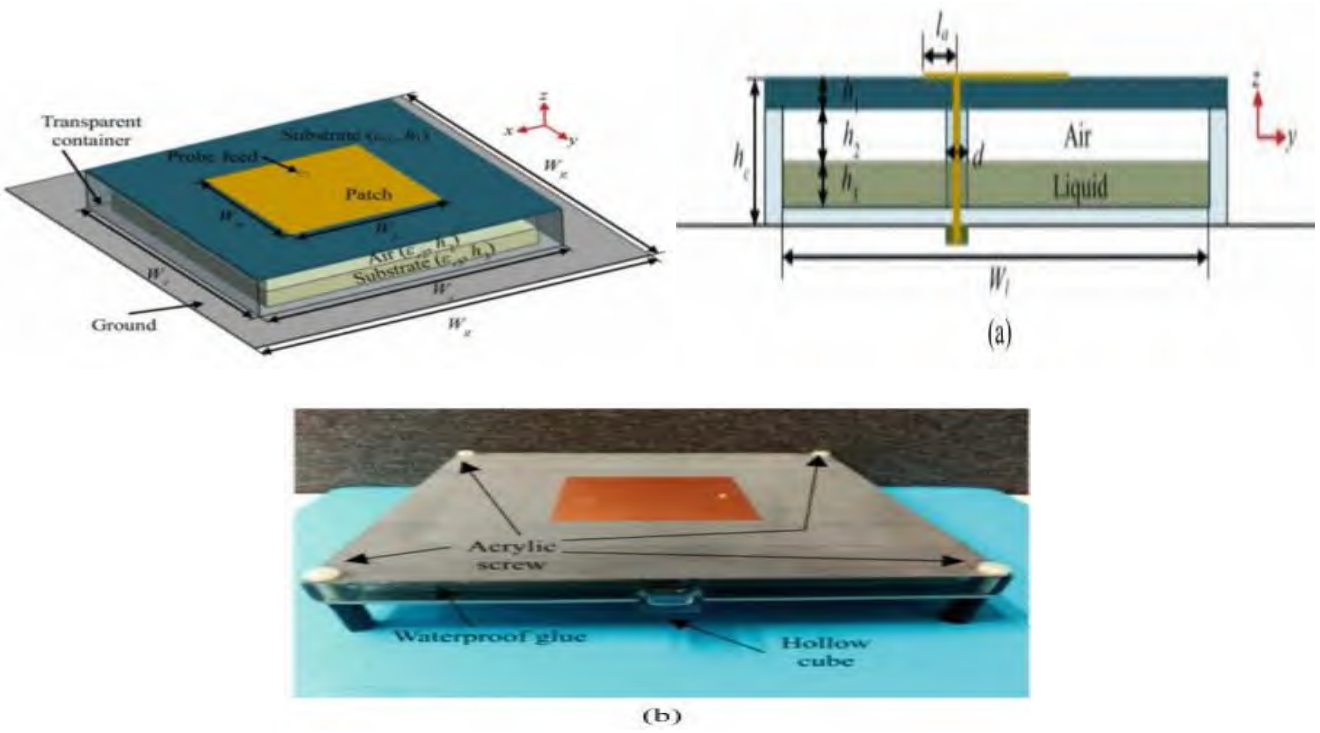


Fig. II.16:frequency reconfigurable patch antenna using low-loss transformer oil,

a geometry,b photograph and c frequency response of the antenna with different value of h_3 [57]

4. Applications of Reconfigurable Antennas:

1- WLAN System Performance with Reconfigurable Antennas:

A pattern-reconfigurable antenna, proposed by [58] ,designed for IEEE 802.11 b/g (wireless local area network standards) enables discrete beam switching at 30° in the vertical plane with a 45° interval. A 2.5 GHz WLAN system with a 10 MHz bandwidth is tested using two nodes: node A with an omnidirectional antenna and node B with a multifunctional reconfigurable antenna.Performance evaluation in an indoor environment compares SNR, data rate, and BER. The reconfigurable antenna shows a 10 dB improvement in face-to-face orientation over the omnidirectional antenna. Across different transmission power levels, it achieves an average SNR gain of 5–6 dB and an additional data rate of ~2 bits/sec/Hz, outperforming omnidirectional antennas [59].

2-**5G Communication System Using Reconfigurable Antennas:**

The 5G wireless network aims to enhance data rates, reliability, and coverage. A pattern-reconfigurable antenna has been developed by [60]to meet 5G technology requirements, enabling beam steering and beamwidth adjustment. This antenna supports nine beam steering

modes and three beamwidth modes, with a control algorithm optimizing its operation based on channel conditions.

The performance of this antenna was tested in a 5G cellular system utilizing OFDM transmission. Two deployment scenarios were considered:

1. Uniform user density – users are evenly distributed.
2. Hotspot deployment – users are clustered within 20-meter radius of random centers.

When compared to traditional patch antennas, the reconfigurable antenna demonstrated a 29% improvement in coverage and a 16% increase in capacity.

3- Cellular Network Performance Using Reconfigurable Antennas:

The performance of a pattern-reconfigurable antenna is evaluated in a hexagonal homogeneous cellular network to enhance cell edge performance in [61] .The antenna system consists of a dipole radiating element with metallic reflectors, arranged in a three-sector configuration around the base station.

The analysis focuses on trade-offs in beamwidth variation within a uniform cellular deployment. The main objectives are:

- Enhancing capacity for users at the cell edge
- Optimizing the average user capacity

Several factors influence these considerations, including:

- Mechanical tilt adjustments
- Inter-site distance variations
- Pathlossmodels
- Proximity to celledges

The reconfigurable antenna is simulated and analyzed at 1.9 GHz, a common frequency in cellular networks. The system uses azimuth beam switching, varying the beamwidth between 50° and 180°. Numerical analysis indicates that adjusting the beamwidth between 60° and 110° can increase cell edge capacity by 20%.

4- Underground Mining Communication Using Reconfigurable Antennas

The performance of pattern-reconfigurable antennas is analyzed for underground mining communication, considering both line-of-sight (LOS) and non-line-of-sight (NLOS)

propagation conditions in [62]. The goal is to enhance the wireless communication link, as fixed antennas struggle to adapt to dynamic channel variations.

Experimental evaluations are conducted to capture the complex channel impulse responses for both conventional and reconfigurable antennas. Findings reveal that in environments with strong multipath interference, the reconfigurable antenna provides a more stable connection.

- For LOS scenarios, the impact of distance and tunnel structure on the reconfigurable antenna is examined.
- For NLOS scenarios, the effectiveness of the reconfigurable antenna is assessed across different tunnel dimensions.

A comparative analysis between the reconfigurable antenna and a dipole antenna is performed for both LOS and NLOS conditions, focusing on path loss and delay spread. Experimental results show that, compared to fixed antennas, the pattern-reconfigurable antenna improves path loss by 20% and reduces delay spread by 34% [59].

5-Multiple Input Multiple Output (MIMO) System:

The rising demand for high-speed wireless data has driven the development of advanced antenna technologies to meet performance requirements. Among these, multiple input multiple output (MIMO) antenna systems have emerged as a key enabler in modern wireless communication, significantly enhancing data throughput, signal quality, and network reliability.

The integration of reconfigurable antennas in MIMO systems presents a promising approach to increase channel capacity and improve link robustness. The performance of pattern and polarization reconfigurable antennas is analyzed for narrowband and broadband MIMO applications. The effectiveness of these antennas is examined under both line-of-sight (LOS) and non-line-of-sight (NLOS) conditions in [63].Pattern reconfiguration is achieved by exciting higher-order modes within a two-port circular patch antenna.

- Polarization reconfiguration is implemented by controlling the phase shift between two orthogonal modes on the same patch.

The experimental analysis is conducted in an indoor environment, where reconfigurable antennas are deployed at either one or both ends of the MIMO link. The findings demonstrate that pattern and polarization reconfiguration enhances signal diversity, resulting in a 17.5% increase in channel capacity within a narrowband communication system. Moreover,

reconfigurable antennas exhibit significant capacity gains compared to conventional circular patch antennas [63] .

6-Wireless Sensor Network (WSN):

Traditionally, monopole and dipole antennas with omnidirectional radiation patterns have been employed in wireless sensor network (WSN) nodes. However, pattern reconfigurable antennas present substantial performance improvements over their omnidirectional counterparts, particularly in terms of energy efficiency, communication range, and signal sensitivity [64].

Additionally, pattern reconfigurable antennas possess the capability to adapt dynamically to the surrounding radio environment, allowing them to optimize their reception characteristics for enhanced system performance. A parasitic slot antenna array is introduced, and its performance is experimentally assessed within a sensor network system [64].

- The study investigates the influence of an electronically tunable antenna integrated into a manhole cover, within an operational WSN system.
- The evaluation focuses on scenarios where communication was previously degraded between two specific nodes in the network.

7- G. Electromagnetic Imaging (EMI):

Reconfigurable antennas play a vital role in electromagnetic imaging (EMI) systems, particularly in detecting fluid accumulation in the human torso. In this context, a metasurface-based pattern-reconfigurable antenna is introduced for EMI applications. The proposed antenna operates within a 0.8 to 1.05 GHz frequency range, allowing beam steering from -30° to 30°, enabling precise scanning of the human chest using controllable unidirectional radiation patterns [65].

To validate the practicality of the antenna, it is integrated into a realistic EMI setup. The system consists of:

- A stationary antenna positioned in front of an artificial torso model with a 94 cm chest circumference, incorporating major cardiovascular organs such as the heart, lungs, ribs, and adipose tissue.
- To simulate fluid accumulation, 20 ml of water is introduced into the phantom's lungs.

For comprehensive scanning, the torso model is rotated in 22.5° increments, while the antenna remains stationary, capturing data from 16 different positions. At each rotation angle, the

antenna adjusts its radiation pattern in three distinct modes (Mode 1, Mode 2, and Mode 3).

- Scattering parameters corresponding to each mode are recorded using a vector network analyzer (VNA).
- The system successfully detects 20 ml of fluid accumulation, distinguishing between healthy and unhealthy condition**s**

8- Unmanned Aerial Vehicle (UAV):

A test setup is designed to evaluate the efficiency of unmanned aerial vehicles (UAVs) in aerial-to-ground communication links The experimental framework consists of a software-defined radio (SDR) and a pattern-reconfigurable antenna. The proposed reconfigurable antenna comprises four dipole elements arranged in a square configuration with a microstrip line feed.

The UAV platform has a weight of 2.2 kg and can sustain a flight duration of 15 minutes. The system's performance is assessed through SNR measurements across different indoor and outdoor flight conditions. Experimental results indicate that the system employing the pattern-reconfigurable antenna demonstrates superior SNR performance compared to omnidirectional antennas in both line-of-sight (LOS) and non-line-of-sight (NLOS) scenarios[66].

5. Advantages and Disadvantages of Reconfigurable Antennas:

a. Advantages of Reconfigurable Antennas:

- **Frequency Adaptability:** Unlike conventional antennas, reconfigurable antennas can adjust their operating frequency to support new communication standards that were not initially considered.
- **Regional Flexibility:** They can adapt to different frequency allocations across countries, ensuring seamless operation when moving between regions.
- **Compact Design:** By integrating multiple functionalities into a single structure, they eliminate the need for multiple antennas and RF components, reducing system size and complexity.
- **Enhanced System Performance:** Reconfigurable antennas improve overall system efficiency by dynamically optimizing frequency bands and radiation patterns.

b. Disadvantages of Reconfigurable Antennas :

- **Higher Power Consumption:** Active components require continuous biasing, increasing energy consumption in both DC and RF domains.
- **Reduced Efficiency:** The presence of resistive components in active elements leads to power losses and reduced radiation efficiency.
- **Complex Design and Manufacturing:** The integration of control circuits and active elements increases system complexity, making fabrication and simulation more challenging.
- **Higher Cost:** The need for advanced materials, additional components, and sophisticated design techniques makes reconfigurable antennas more expensive than traditional antennas [67].

Conclusion:

Reconfigurable antennas play a crucial role in telecommunications and are the most commonly used solution to meet telecommunication system standards. This chapter

introduced the concept of reconfigurable antennas, detailing their various types and the techniques used for frequency, radiation pattern, and polarization reconfigurability**.**

Furthermore, we examined the functions of different switching components, including RF-MEMS switches, varactor diodes, and PIN diodes, in achieving antenna reconfiguration. Finally, we concluded the chapter by discussing the benefits andlimitationsof reconfigurable antennas.

Chapter **III**: Design and Optimization of Reconfigurable patch Antenna

1-introduction:

After establishing the theoretical and methodological foundations in the previous chapters, this chapter focuses on the practical aspects of the design, simulation, and optimization of patch antennas to meet specific performance requirements. HFSS (High Frequency Structure Simulator) has been adopted as the primary tool for precise design and electromagnetic analysis. Details of the various design steps are provided in the appendix (see appendix). The main objective of this work is to design and analyze a reconfigurable patch antenna using a PIN diode, operating in the frequency range of 1 GHz to 7 GHz. The design aims to provide flexibility in adjusting the antenna's characteristics, allowing control over its frequency response and radiation performance to meet the requirements of modern wireless applications. This is particularly relevant in the context of advanced communication systems such as 5G.

2-Conventionnal antenna of 5 GHz:

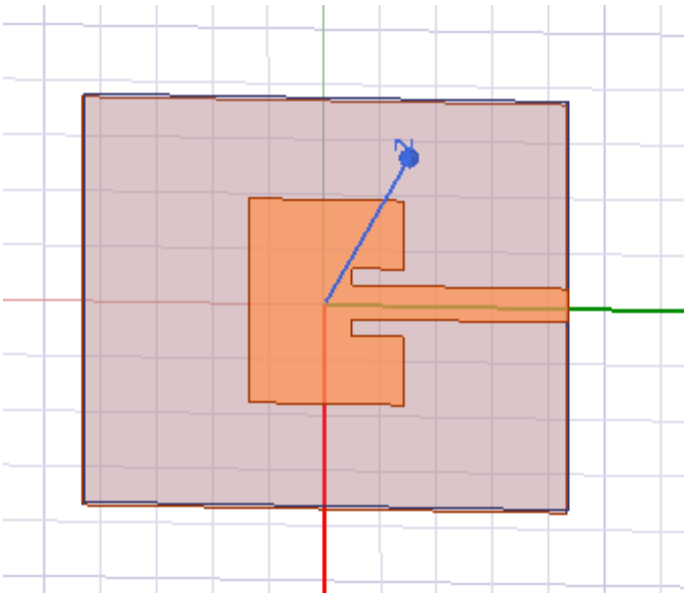


Figure III.1: 5GHz patch antenna

Figure III.1 represents the conventional patch exploited in this study. This antenna resonates at 5GHz and it consists of multiple layers: a bottom ground plane, followed by a dielectric substrate of FR4. The patch and feeding line are on the top layer.The ground plane serves asan electrical reference and helps shape the radiation pattern.

The dielectric substrate separates the ground from the patch and influences the resonant frequency and efficiency. The patch is the radiating element that emits electromagnetic

waves.The feeding line delivers the signal to the patch and affects impedance matching and transmission efficiency.

The values of the different parameters of the 5 GHz antenna are shown in table III.1**.**

Table III.1 Dimensions of the 5 GHz antenna

	Antenna parameters	**Dimensions (cm)**
Substrate	Length	4.32
	Width	3.7
	Thickness	0.16
Patch	Length	1.85
	Width	1.38
Feed	Length	0.306
	Width	1.927

2.1 Reflection coefficient (S11):

The reflection coefficient (S11) of the initial antenna is illustrated in Figure III.2, and wasobtained using the HFSS software. This coefficient, measured at the antenna's input, indicatesthe amount of energy reflected by the antenna and therefore not transmitted. Its value dependson the frequency. To ensure good impedance matching within the desired frequency band, itis generally accepted that S11 should be less than -10 dB.An S11 value of –10 dB means that only 10% of the power is reflected back, while 90% is accepted (transmitted into the antenna).

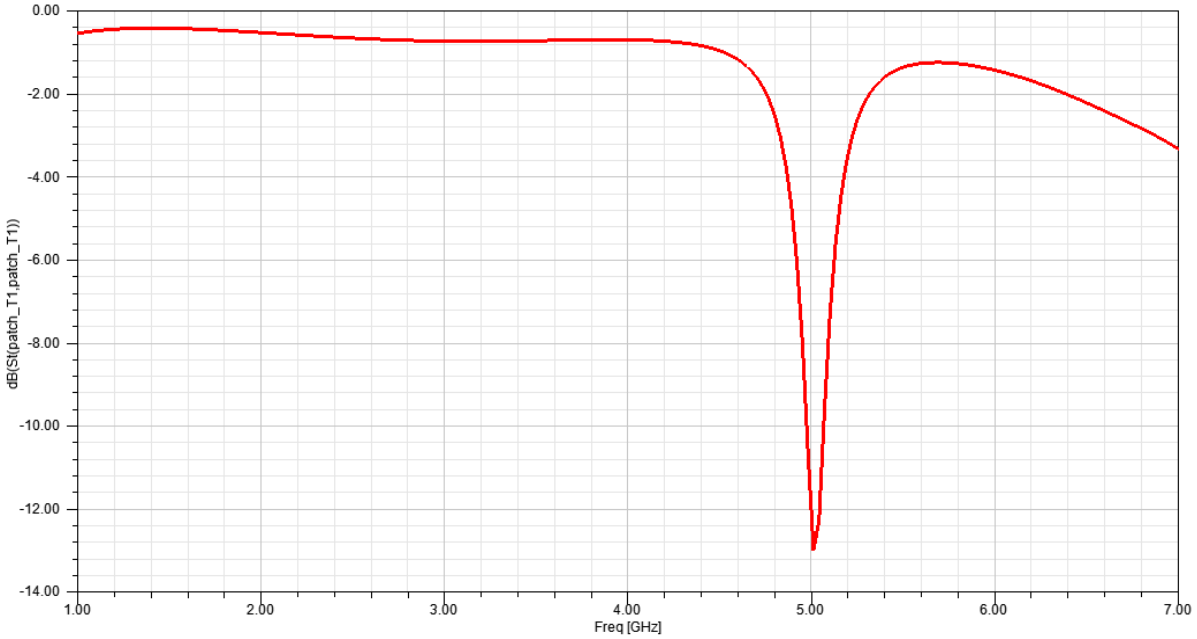


Figure III.2: Reflection coefficient (S11) as a function of frequency (in GHz) for the 5GHz antenna

Figure III.2 illustrates the reflection coefficient (return loss) in decibels (dB) as a function of frequency.The x-axis corresponds to frequency in GHz, while the y-axis shows S11 values in dB. A resonant frequency is observed at 5.0101 GHz, where the S11 reaches –12.99 dB, indicating good impedance matching according to the common criterion of S11 < –10 dB.The effective bandwidth [4,97-5,07]is defined as the frequency range over which S11 remains below –10 dB, signifying efficient signal transmission with minimal reflection.

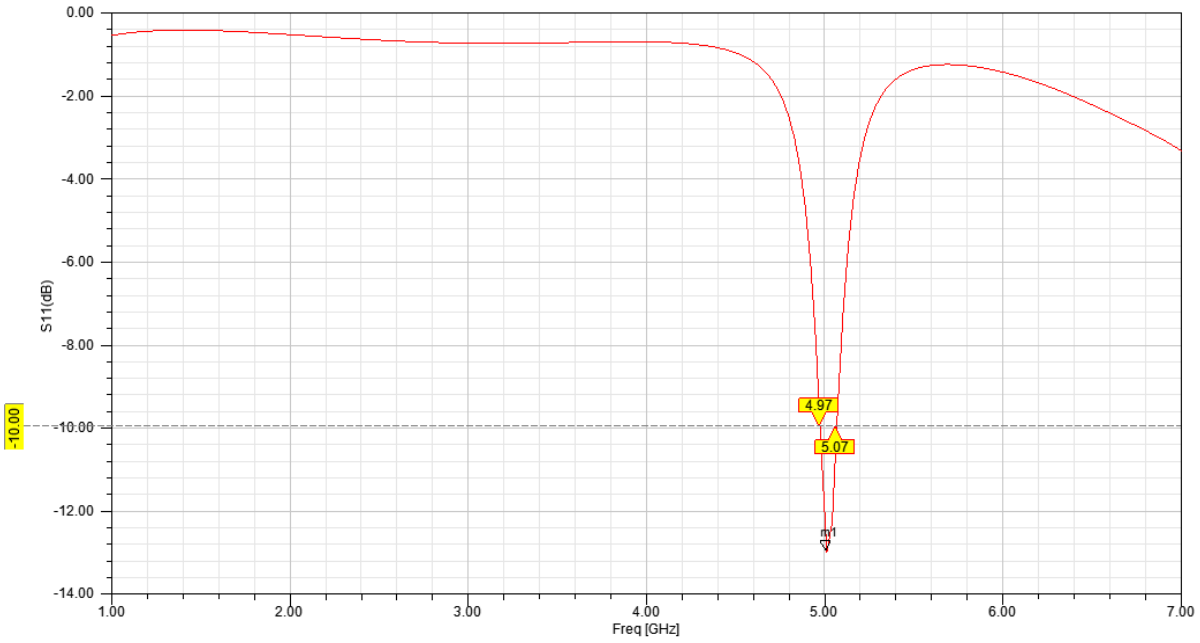
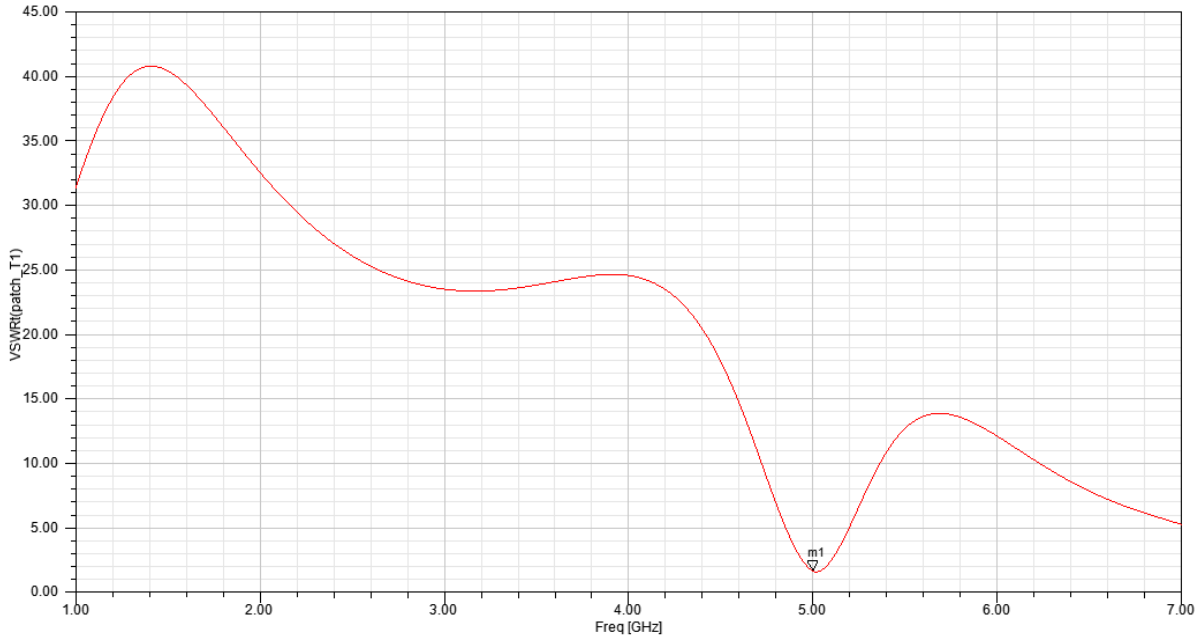


Figure III.3: Bandwidth of the 5 GHz Antenna

2.2- Voltage Standing Wave Ratio (VSWR):



FigureIII.4: VSWR as a function of frequency (in GHz) for the antenna

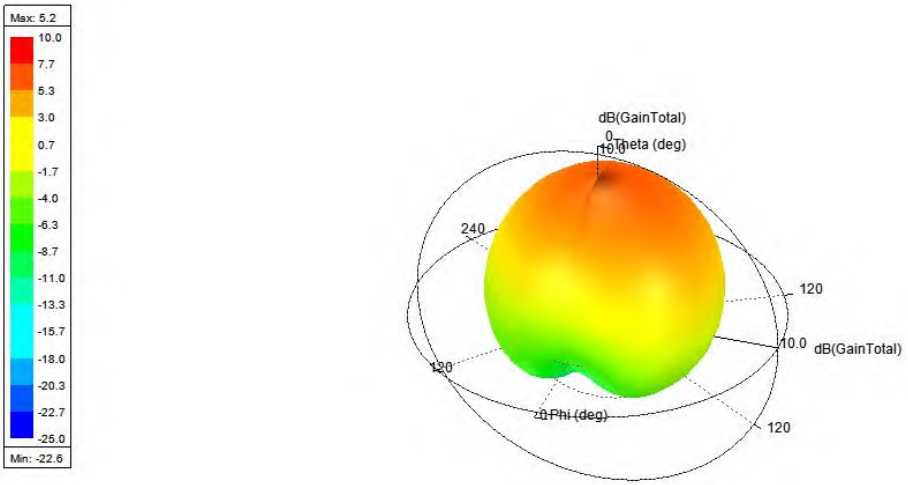
Figure III.4 represents the analysis of the Voltage Standing Wave Ratio (VSWR) for the 5GHzpatchantenna over a frequency range from 1 to 7 GHz. The VSWR value indicates how well the antenna is matched to the transmission line, with the ideal value being **1**, which signifies perfect matching and no reflections.

The conventional patch antenna achieves a minimum VSWR of approximately 1.5 at 5.0101 GHz, indicating good impedance matching and low reflected power. A VSWR below 2 is generally considered acceptable in antenna design.

This point represents the resonant frequency of the antenna, where its performance is optimal in terms of minimizing reflections and maximizing radiation efficiency.

Across the rest of the frequency range, the VSWR is significantly higher, reaching values above 40 at certain frequencies. This implies strong reflections and high losses, indicating that the antenna is not well matched and performs poorly outside the resonant frequency.

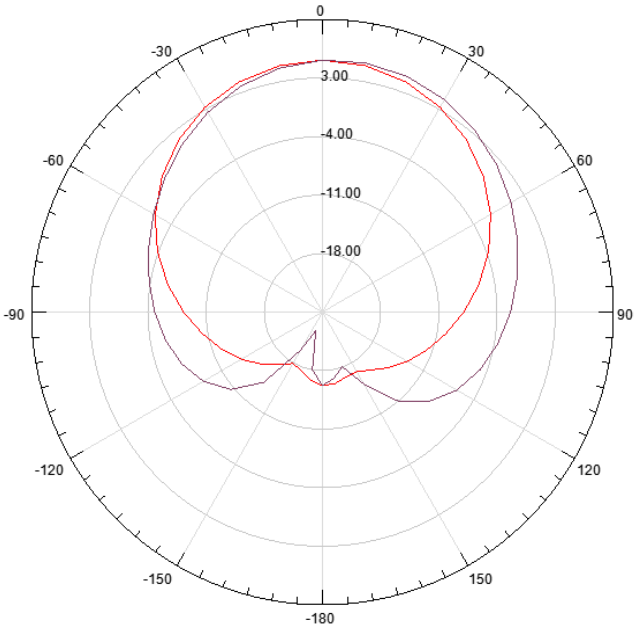
2.3-3D Radiation Patterns:



FigureIII.5: 3D Radiation Patterns of the5 GHz antenna

Figure III.5 represented 3D radiation pattern of an antenna, illustrating the total gain distribution in space in decibels (dB). The maximum gain is 5.2 dB in the $\theta \approx 0°$ direction, indicating that the antenna is directional or semi-directional**.** The radiation is non-symmetrical, with a significant drop in the rear direction, suggesting that the antenna is designed to focus energy in a specific direction.

2.4-2D Radiation Patterns:



FigureIII.6: 2D Radiation Patterns of the5 GHz antenna

Figure III.6 represents the two-dimensional radiation pattern of the 5GHz antenna, illustrating the gain distribution (in decibels, dB) as a function of the angleθfrom 0° to 360° and horizontal plane (H-plane: φ= 90°) or vertical plane (E-plane: φ = 0°). This representation is commonly used to analyze the antenna's behavior in terms of radiation directivity and its efficiency in focusing electromagnetic energy toward specific directions. A maximum gain value is obtained at θ = 0° for both planes.

It is also evident from the plot that the gain significantly decreases at angles of θ =±180∘, reflecting a reduction in back lobe radiation. This implies that the antenna has a good front-to-back ratio, which is a desirable characteristic in applications requiring directional radiation.

Table III.2: Summary of Key Performance Metrics for the 5 GHz Antenna

Parameter	**value**
S11 (dB)	-13.5
VSWR	1.57
gain (dB)	5.2

Bandwidth (GHz)	0.10

Table III.2 summarizes the main performance parameters of the 5 GHz antenna, including return loss (S11), Voltage Standing Wave Ratio (VSWR), gain, and bandwidth. The values confirm good impedance matching, moderate gain, and a usable bandwidth around the 5 GHz resonance.

3- Reconfigurable Antenna:

After validating the performance of the 5 GHz patch antenna, a reconfigurable version is proposed to introduce frequency agility while preserving the fundamental characteristics of the original design. The new antenna is based on the same structure as the previously designed 5 GHz antenna, with the addition of a parasitic patch of dimensions $Xss \times Yss$ placed above the main patch. A PIN diode is inserted between the original patch and the parasitic element, enabling dynamic switching between different operating states.

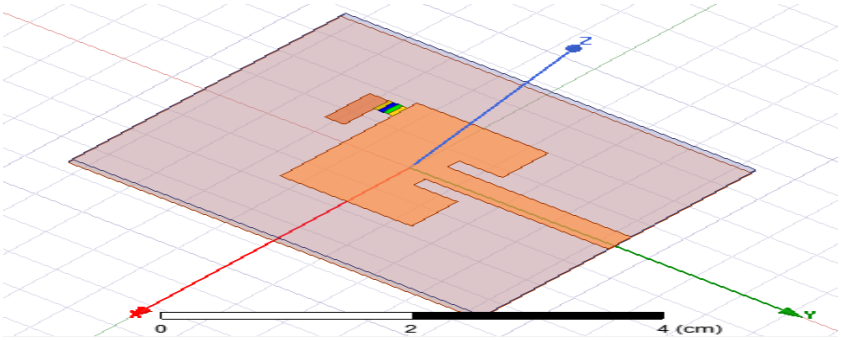


Figure III.7: Reconfigurable Patch Antenna Using a PIN Diode

Figure III.7represents a 3D model of patch antenna designed using electromagnetic simulation software such as HFSS. A key feature of this design is the inclusion of a PIN diode, represented by the small colored layers at the top of the patch. This diode acts as an electronic switch, allowing the antenna's characteristics—such as resonant frequency or radiation pattern—to be reconfigured by modifying the diode's state (ON/OFF).Furthermore, the dimensions of the parasitic patch were modified according to the variations shown in Table III.4, and from these, the optimal dimensions that yield the desired antenna behavior were selected for both the ON and OFF states. This makes the antenna particularly well-suited for advanced wireless applications such as 5G communication systems and modern radar technologies, where adaptability and multi-functionality are essential.



(a) **(b)**

Figure III.8:Equivalent model of PIN diode using HFSS, (a): OFF state, (b): On state

Figure III.8illustrates the equivalent circuit model of the PIN diode, simulated in HFSS using four rectangular blocks corresponding to the components R, L, C_1, and C_2. The PIN diode acts as a switch in RF circuits. In the ON state, it conducts with low resistance and high capacitance, allowing signal transmission. In the OFF state, it has high resistance and low capacitance, blocking the signal. Parasitic effects like inductance and capacitance are considered at high frequencies. **(Refer to the Appendix).**

Table III.4 Range and Step Size for Xss and Yss Parameter Variation.

	Min Value (mm)	**Step(mm)**	**Max Value (mm)**
Xss	6	1	18
Yss	-12	1	-2

Table III.4 presents the values of *X*ss and *Y*ss corresponding to different configurations of the parasitic patch. The first row shows values of *X*ss ranging from 6 mm to 18 mm with a step of 1mm, while the second row shows values of *Y*ss varying from -12 mm to -2 mm, also with a step of 1mm. These parameters were used to study the effect of the parasitic patch's dimension on the antenna's performance. It should be noted that the same set of *Xss* and *Yss* values was used for both the ON and OFF states of the PIN diode.

For each combination of *Xss* and *Yss*, simulations were performed in HFSS for both the ON and OFF states of the PIN diode. The S11 parameter was obtained for every configuration, allowing us to analyze the antenna's behavior under different switching conditions and patch placements as illustrated in figure III.8

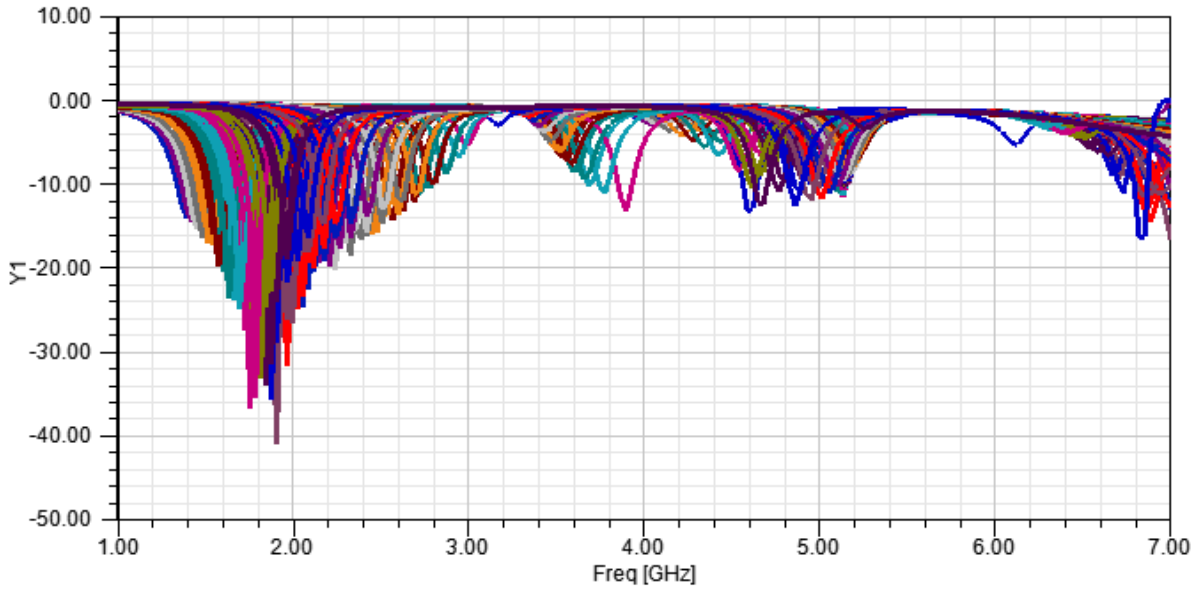


Figure III.9: S11 Response of the reconfigurable Antenna for different values of *X*ss and *Y*ss in ON State

Figure III.9 illustrates the reflection coefficient (S11) curves of the reconfigurable patch antenna, in the "ON" state, where PIN diode within the antenna structure is forward biased and act as conductive paths (closed circuits). In this configuration, the diode alters the distribution of surface currents, which in turn modifies the effective electrical length of the antenna and directly affects its resonant frequencies. The plot shows multiple sharp dips in the S11 values, reaching below -30 dB in some cases, indicating high radiation efficiency at various frequencies. The antenna exhibits multi-band behavior, with efficient operation across a wide frequency range from 1.75 GHz to 6.84 GHz. This performance diversity highlights the antenna's ability, in the "ON" state, to adapt to different operating environments.

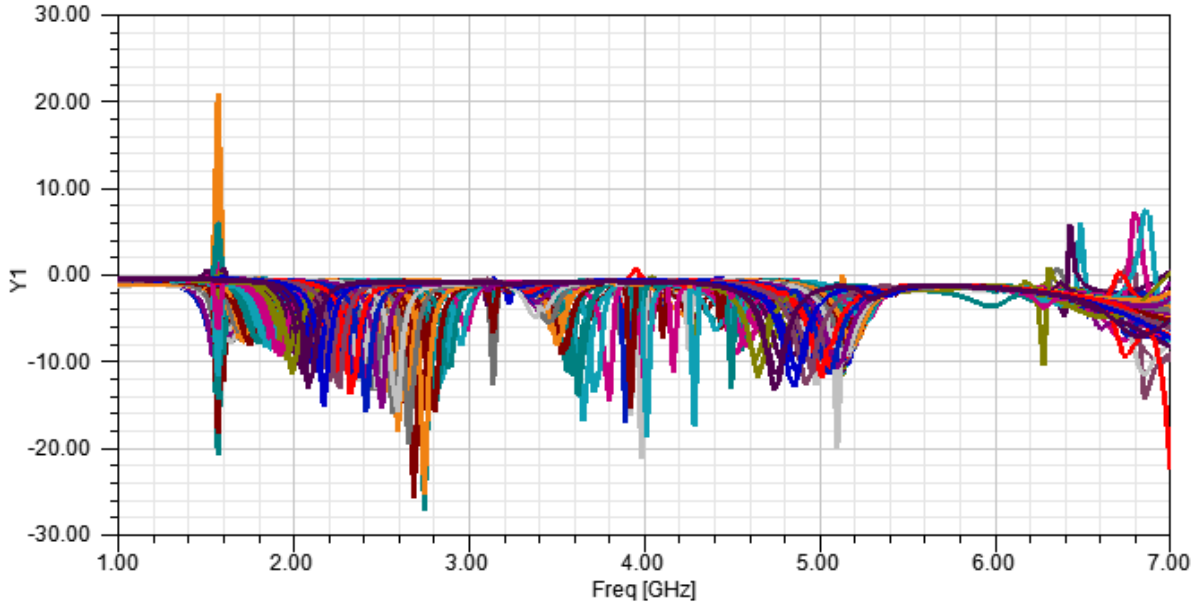


Figure III.10: S11 Response of the reconfigurable Antenna for different values of *X*ss and *Y*ss in in OFF State

Figure III.10 represents the reflection coefficient S11 for the reconfigurable antenna incorporating PIN diodes in the OFF state, meaning no forward bias is applied. In this state, PIN diodes behave as high-impedance elements that block signal transmission. However, due to parasitic effects such as intrinsic capacitance and inductance, they still interact with high-frequency signals. This is evident in the numerous sharp dips observed across the frequency range from 1 to 7 GHz, indicating significant signal absorption or resonance at specific frequencies. The overlapping of multiple curves suggests the presence of several paths or components within the system, each contributing uniquely to the overall response and increasing unwanted interactions. This behavior highlights that even in the OFF state, PIN diodes impact the RF performance of the circuit, and such effects must be carefully considered in high-frequency system design to ensure optimal matching and isolation.

For each state (ON and OFF), a total of 143 S11 curves were generated corresponding to different combinations of Xss and Yss values. Given the large volume of data, it is impractical to analyze these curves visually and individually. To address this challenge, we implemented a MATLAB program that automates the visualization and processing of the S11 data, enabling efficient identification of key characteristics such as resonant frequencies, bandwidths, and multi-band behaviors.

Optimization of HFSS-Generated S11 Curves for Reconfigurable Antennas:

The organization of the process is illustrated in FigureIII.11 and it is describedas follows: after generating the S11 curves using HFSS, the results are exported and saved for further analysis in MATLAB. The first step in the MATLAB script is to load the dataset containing all the S11 curves. For each curve, the code identifies the frequency points where the S11 value is less than –10 dB, which indicates good impedance matching. Based on the number of distinct frequency bands that meet this criterion, the code classifies the antenna behavior as single-band, dual-band, triple-band, or quad-band. The indices of the corresponding curves are saved accordingly for further interpretation and optimization. Furthermore, to refine the selection process and ensure high-performance configurations, another threshold of –11 dB is applied. While the –10 dB criterion is commonly used to define the lower limit of acceptable return loss (indicating that at least 90% of the input power is delivered to the antenna), the –11dB threshold corresponds to a return loss of approximately 92.06%, signifying even better impedance matching. This condition allows the identification of antenna configurations that exhibit not only multiband behavior but also enhanced efficiency, which is critical in modern high-performance communication systems.

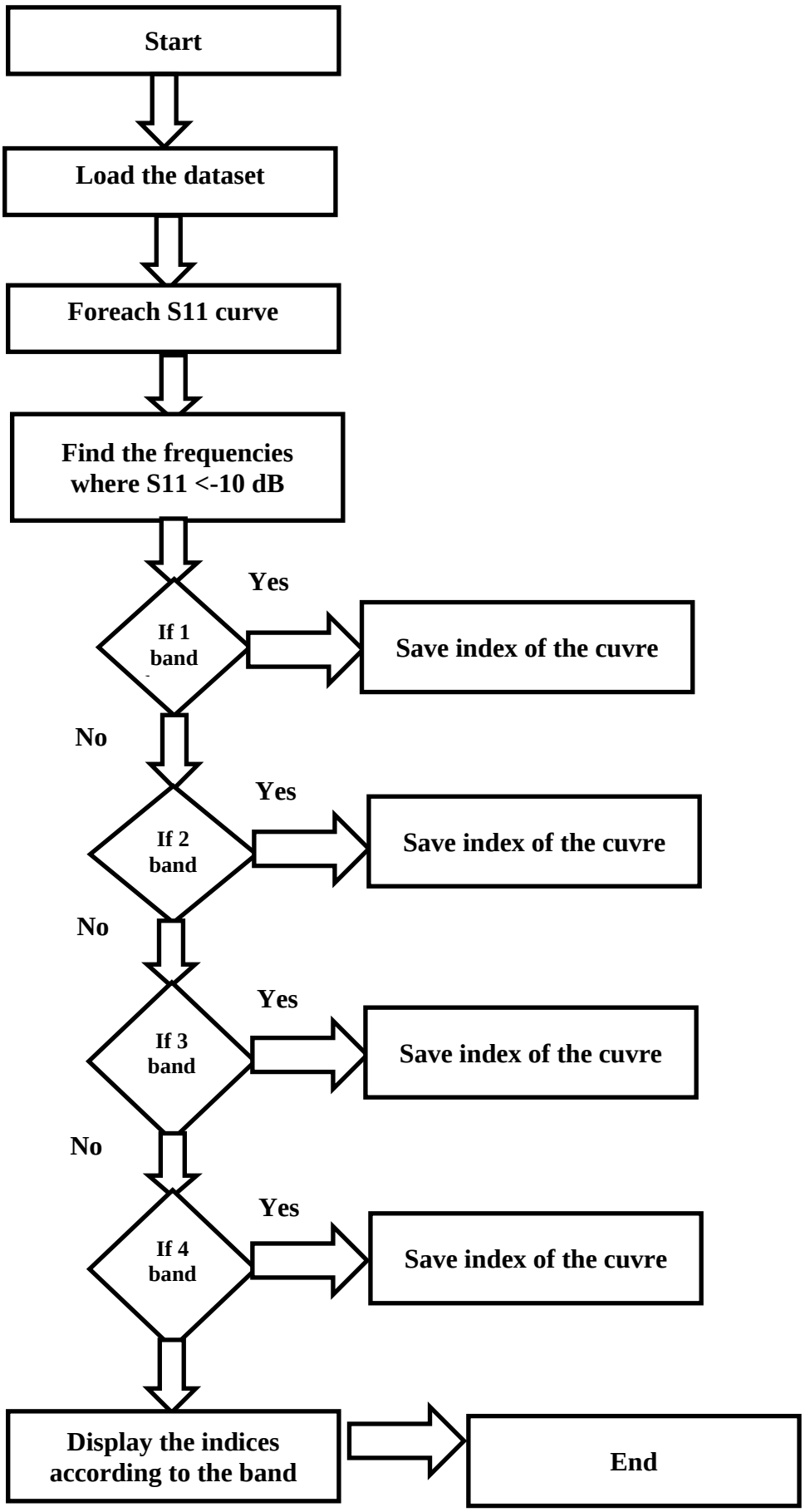

Start
Load the dataset
Foreach S11 curve
Find the frequencies where S11 <-10 dB
If 1 band
Yes
Save index of the cuvre
No
If 2 band
Yes
Save index of the cuvre
No
If 3 band
Yes
Save index of the cuvre
No
If 4 band
Yes
Save index of the cuvre
Display the indices according to the band
End

Figure III.11: Flowchart of the antenna selection and optimization process based on S11 analysis using HFSS and MATLAB.

The results of the optimization process yield several reconfigurable antenna configurations, each corresponding to specific values of Xss and Yss, for both the ON and OFF states of the PIN diode.

3.1- Reconfigurable Antenna(I) from 1 to 2 bands:

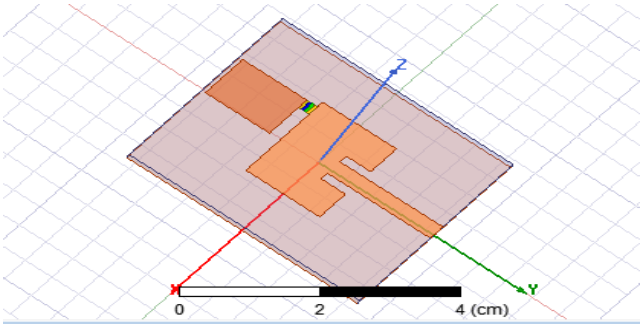


Figure III.12: Reconfigurable Antenna (I) from 1 to 2 bands: xss=9 and yss=-12

By setting the parasitic patch dimensions to Xss=9mm and Yss=-12mm, the antenna exhibits a reconfigurable behavior that allows it to switch between single-band and dual-band operation. This configuration leverages the PIN diode's ON and OFF states to dynamically alter the antenna's resonant frequencies, enabling adaptable performance for different wireless applications.

3.1.1 Reflection coefficient:

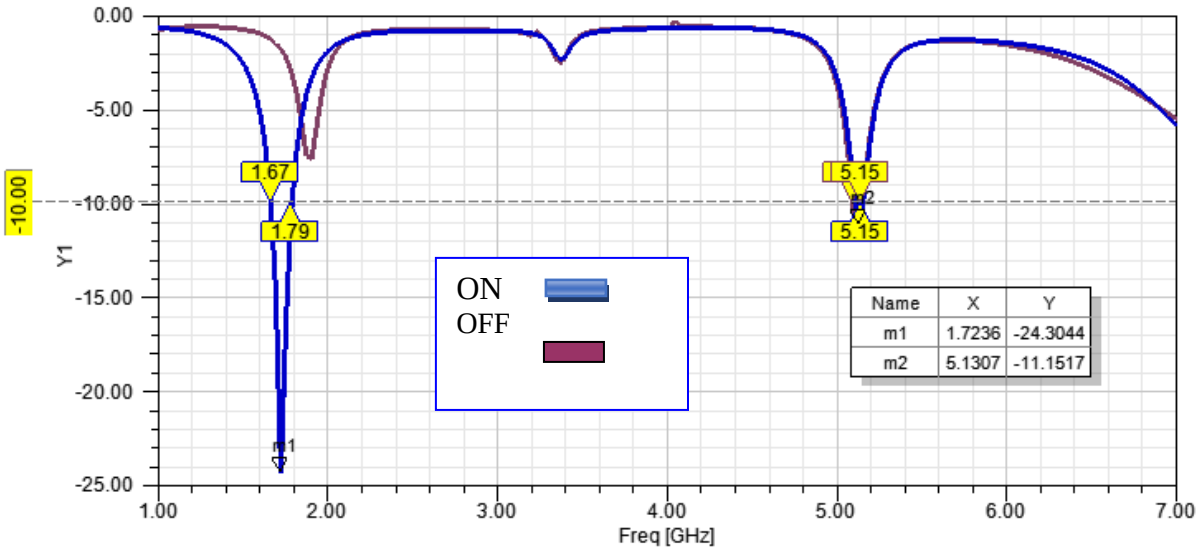


Figure III.13:Reflection coefficient and bandwidth for the reconfigurable antenna (I) for ON and OFF states

Figure III.13 representsthe S11 parameter (in dB) versus frequency (GHz) for two states of aPIN diode (ON and OFF) in an RF system.

The purple curve corresponds to the OFF state, exhibiting a clear single-band behavior with a S11 value of -11.7566dB around 5.1307GHz. The bleu curve represents the ON state, showing a dual-band behavior with two resonant frequencies near 1.7236GHz and 5.1307 GHz with S11 values of -24.3044dB and of -11.1517dB, respectively. For both states of the diode (ON and OFF) S11 values indicate efficient signal transmission. The effective bandwidths are approximately [5.09–5.15] GHz for the single band in the OFF state, and [1.67–1.79] GHz and [5.11–5.15] GHz for the dual bands in the ON state.

3.1.2Voltage Standing Wave Ratio:

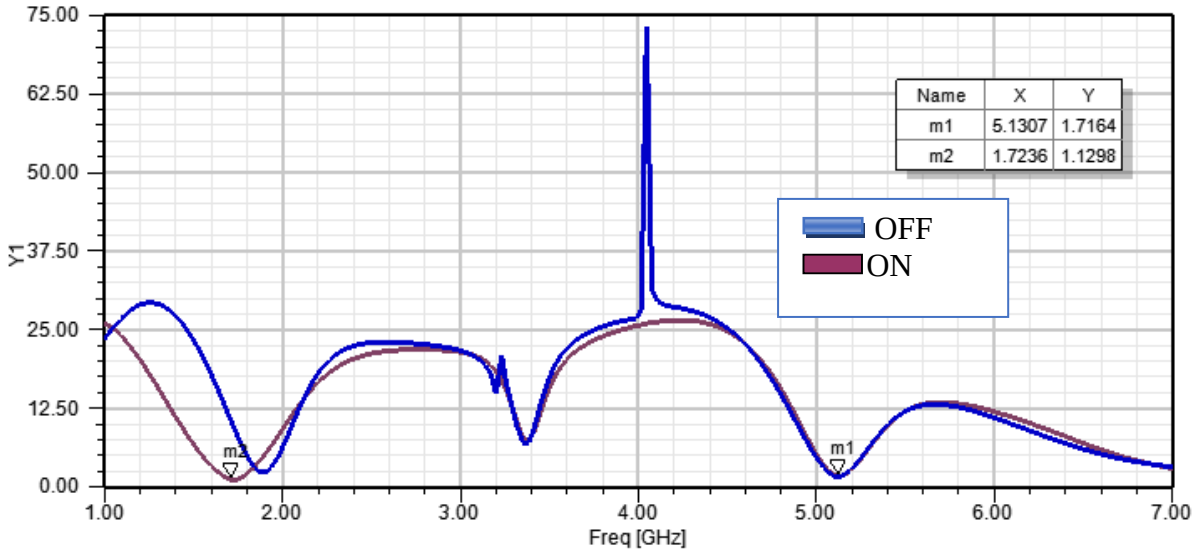


Figure III.14: VSWR for the reconfigurable antenna (I) for ON and OFF states

Figure III.14 shows the variation of the Voltage Standing Wave Ratio (VSWR) across the frequency range of 1 to 7 GHz. The purple curve represents the ON state, while the blue curve corresponds to the OFF state of the PIN diode integrated into the antenna design. In the OFF state, a VSWR of 1.7164is observed, indicating good impedance matching. In the ON state, VSWR values of 1.1296 and 1.7164are recorded at the two operating frequencies, also reflecting satisfactory matching conditions.

This behavior confirms that the antenna is frequency-reconfigurable, with its performance varying according to the state of the integrated switching diode. Such a feature makes the design suitable for multi-band applications or systems requiring dynamic switching between frequency bands.

3.1.32D Radiation Patterns:

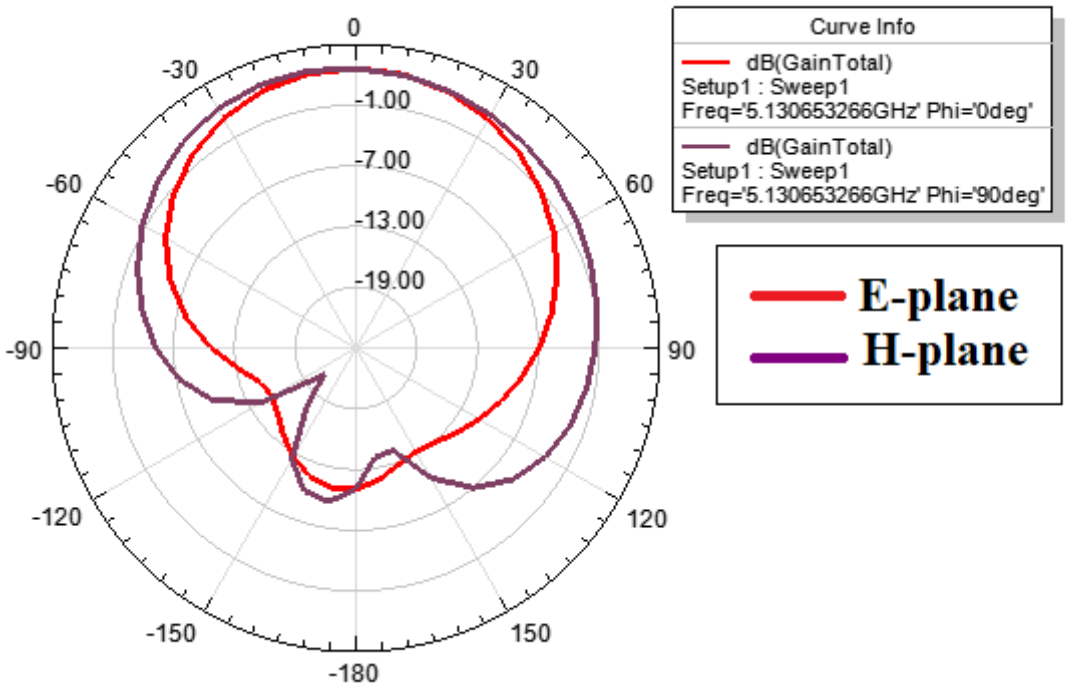
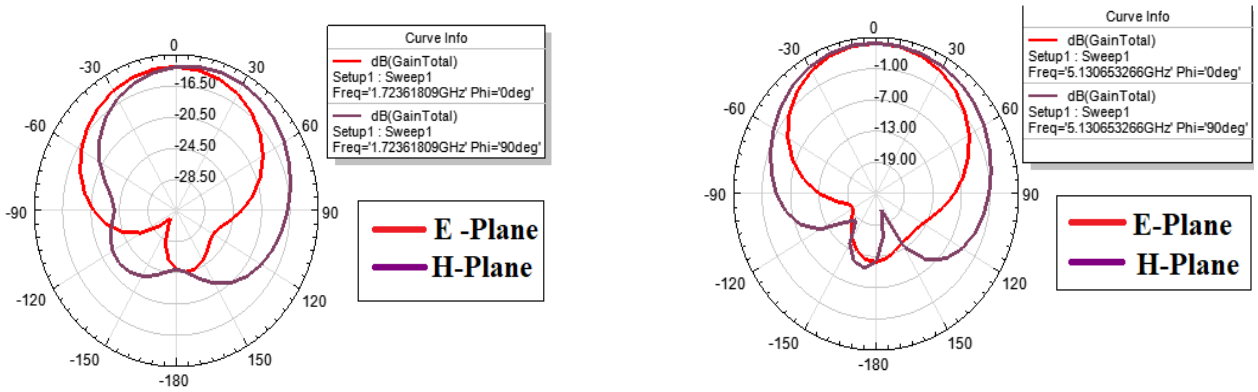


Figure III.15: 2D Radiation Patterns for Antenna reconfigurable I from 1 to 2 bands in OFFstate for the frequency 5.1307GHz



(a) (b)

Figure III.16: 3D Radiation Patterns for the reconfigurable Antenna (I) in ON state: (a) for resonant frequency1.7236 GHz, (b) for resonant frequency 5.1307GHz.

FigureIII.15and Figure III.16 represent two-dimensional radiation patterns of an antenna displayed in E-plane = 0 deg and H-plane=90 deg

For the OFF state at the frequency of 5.1307GHz, the 2D radiation pattern shows a main lobe in the E-plane (θ = 0°) and in the H-plane in the direction (θ = 90°).

For the ON state at the frequency of 1.7236GHz, the 2D radiation pattern shows a main lobe in the E-plane (θ = 0°) and in the H-plane (θ = 90°). At the second frequency of 5.1307GHz in the OFF state, the radiation pattern similarly exhibits a main lobe in the E-plane (θ = 0°) and the H-plane (θ = 90°), indicating consistent directional behavior.

3.1.4 3D Radiation Pattern:

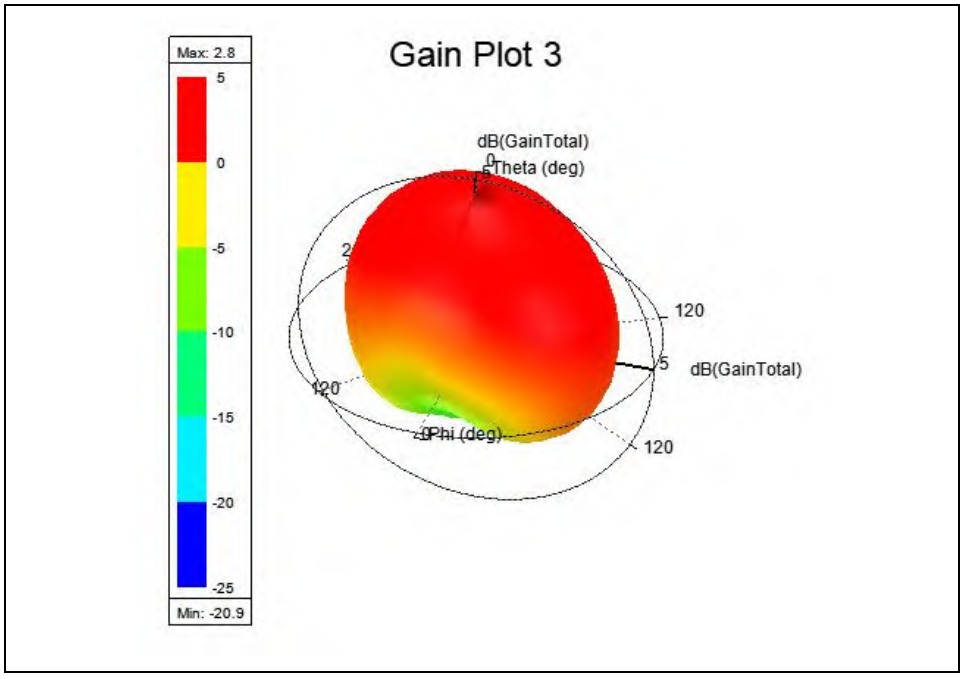
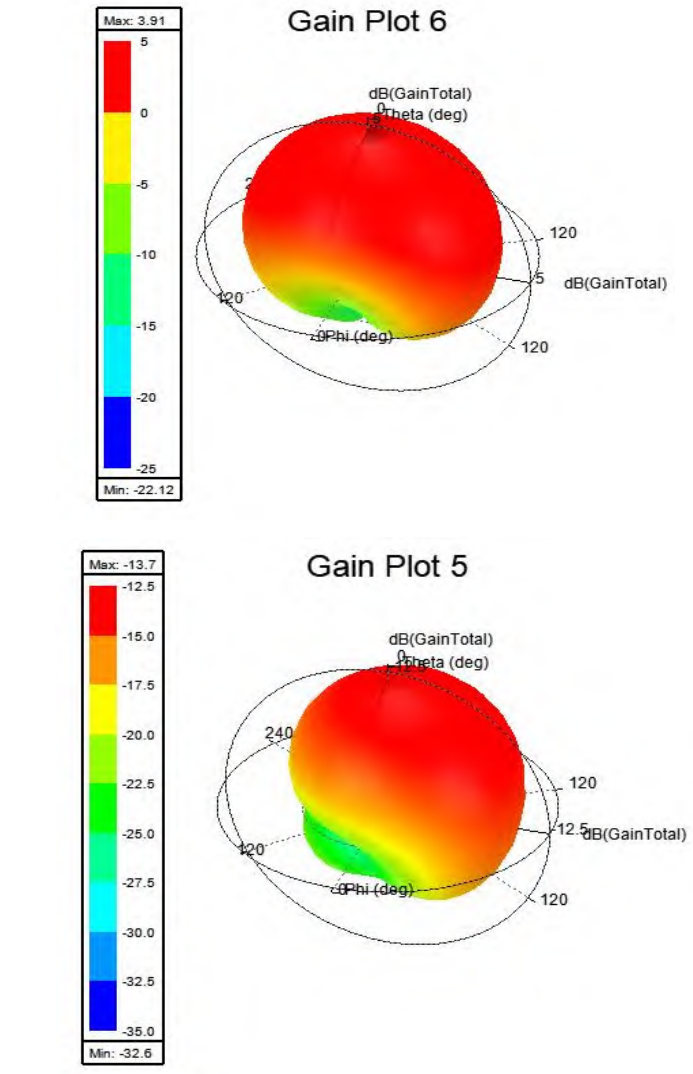


Figure III.17: 3D Radiation Pattern for reconfigurable Antenna (I) in OFFstate.



(a) (b)

Figure III.18:3D Radiation Patterns for the reconfigurable Antenna (I) in ON state: (a) for resonant frequency 1.7236 GHz,(b) for resonant frequency 5.1307 GHz.

FigureIII.17 and Figure III.18 represent the total radiation pattern (gain) of an antenna in two different states: "ON" and "OFF".

In the "OFF" state (Figure III.17), the maximum gain reaches 2.8 dB, with a relatively symmetrical and well-distributed radiation pattern.

In contrast, the "ON" state (Figure III.18) shows a higher maximum gain values of -13.7 dB and 3.91 dB for the frequencies 1.7236 GHz and 5.1307 GHz, respectively, but with

a less uniform radiation pattern.Overall, for the ON and OFF states the antenna offers acceptable gain values.

3.2- Reconfigurable Antenna II from 1 to 3 band

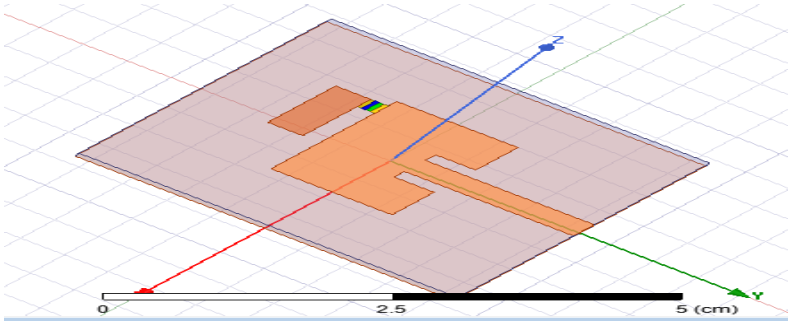


Figure III.19: Reconfigurable Antenna II from 1 to 3 bands: xss=10 mm and yss=4 mm.

By setting the parasitic patch dimensions to Xss=10mm and Yss=-4mm, the antenna exhibits a reconfigurable behavior that allows it to switch between single-band and Triple band operation. This configuration leverages the PIN diode's ON and OFF states to dynamically alter the antenna's resonant frequencies, enabling adaptable performance for different wireless applications.

3.2.1Reflection coefficient :

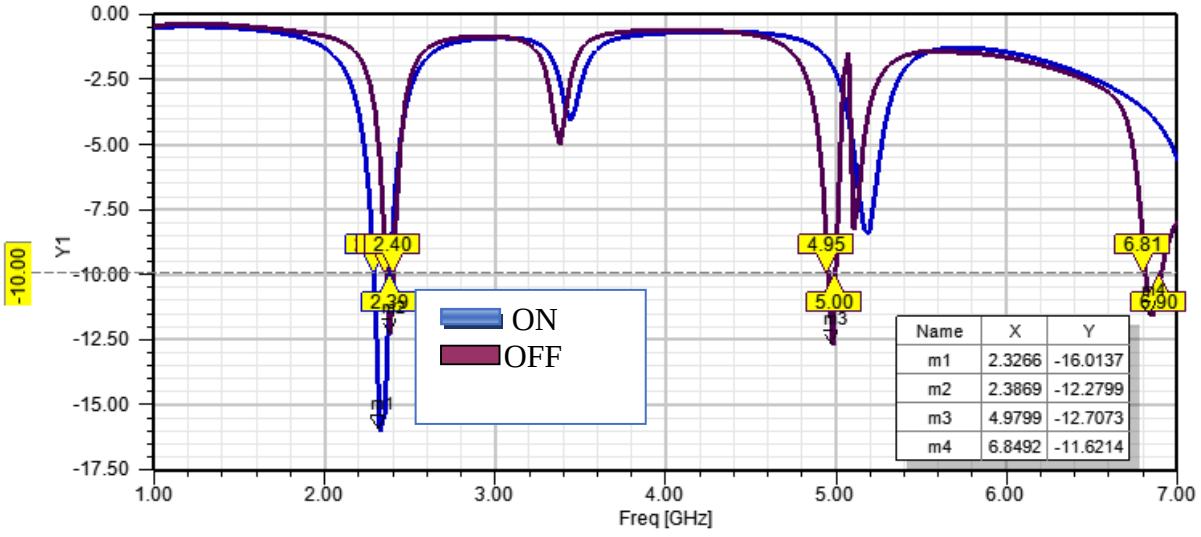


Figure III.20: Reflection coefficient and bandwidth for the reconfigurable antenna (II) for ON and OFF states

Figure III.20 representsthe S11 parameter (in dB) versus frequency (GHz) for two states of PIN diode (ON and OFF) in an RF system.

The purple curve corresponds to the OFF state, exhibiting a clear Triple-band behavior with threeresonant frequencies near 2.3869 GHz and 4.9799 GHz and 6.8492 GHzwith a S11 value of -12.2799 and of -12.7073dB and -11.6214 dB, respectively. The blue curve represents the ON state, showing a single-band behavior with oneresonant frequency near 2.3266 GHz with S11 values of -16.0137dB For both states of the diode (ON and OFF) S11 values indicate efficient signal transmission. The effective bandwidths are approximately [2.29–2.39] GHz for the single band in the ON state, and [2.37–2.40] GHz and [4.95–5.01] GHz and [6.81-6.90] GHz for the triple bands in the OFF state.

3.2.2-Vswr (The Voltage Standing Wave Ratio):

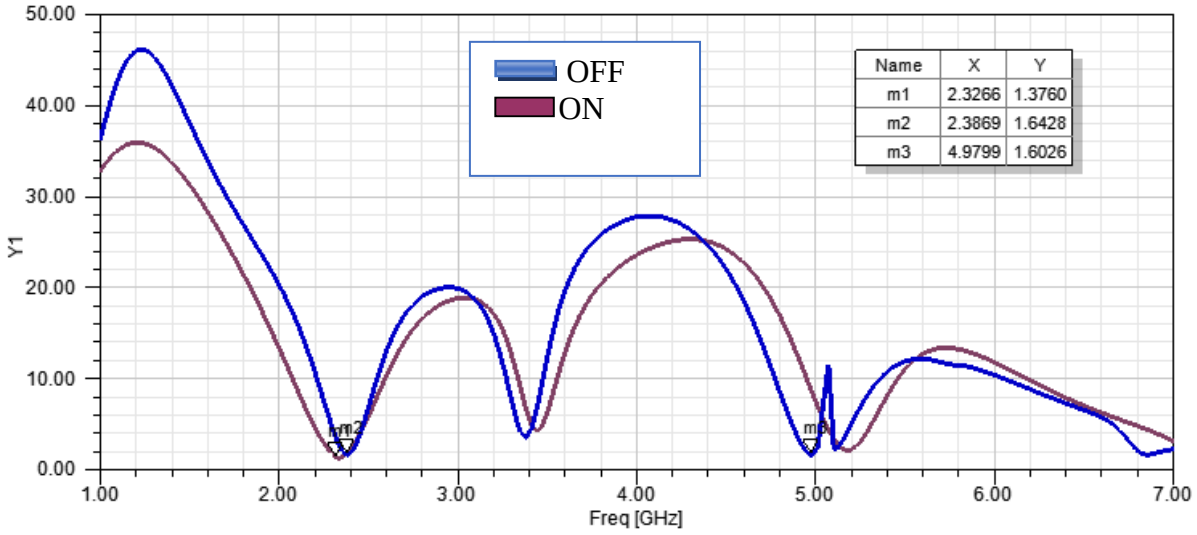


Figure III.21: Vswr for Antenna reconfigurable II from 1 to 3 bandes.

Figure III.21 shows the variation of the Voltage Standing Wave Ratio (VSWR) across the frequency range of 1 to 7 GHz. The purple curve represents the ON state, while the blue curve corresponds to the OFF state of the PIN diode integrated into the antenna design. In the ONstate, a VSWR of 1.3760is observed, indicating good impedance matching. In the OFFstate, VSWR values of 1.6428 and 1.6026 are recorded at the two operating frequencies, also reflecting satisfactory matching conditions.

This behavior confirms that the antenna is frequency-reconfigurable, with its performance varying according to the state of the integrated switching diode. Such a

feature makes the design suitable for multi-band applications or systems requiring dynamic switching between frequency bands.

3.2.32D Radiation Patterns:

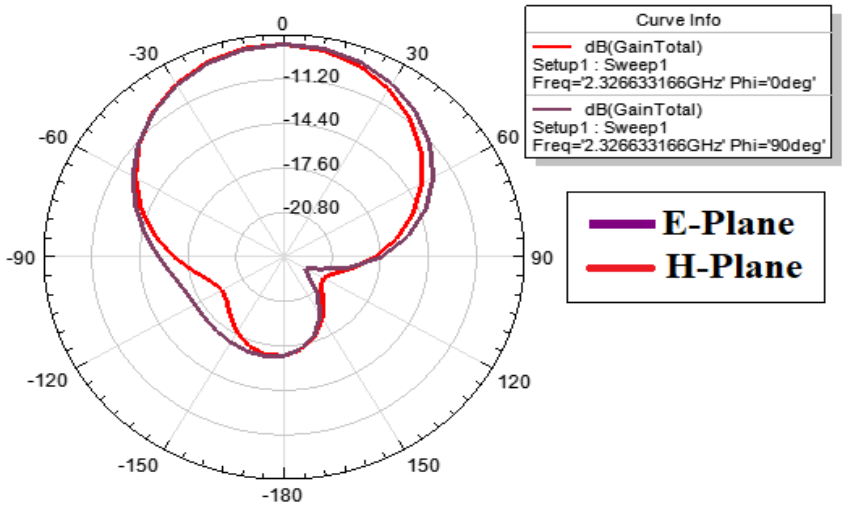
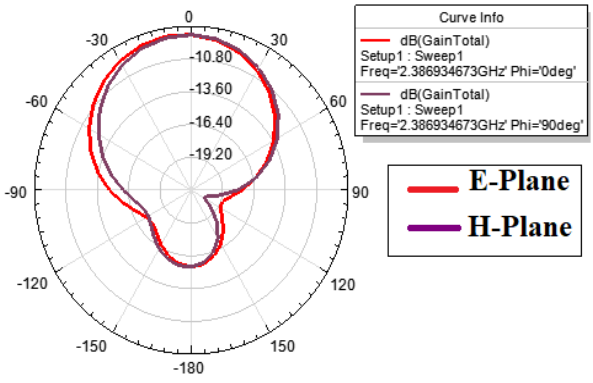
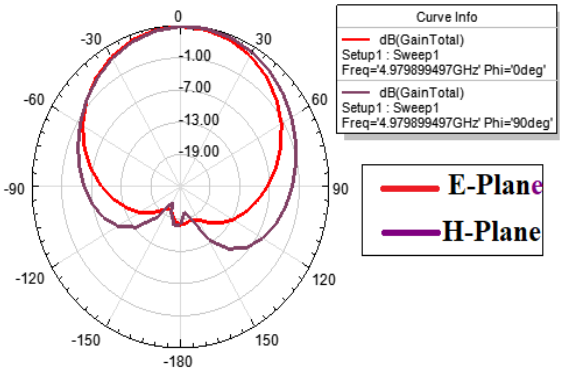


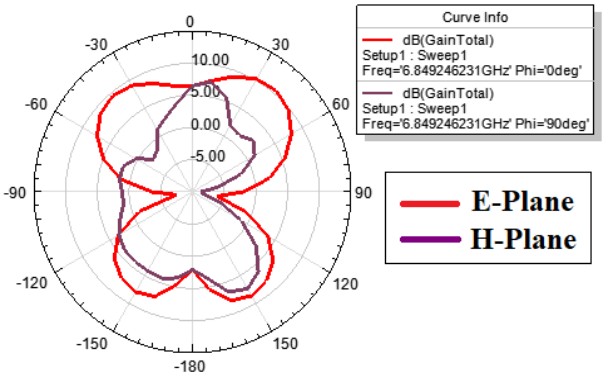
Figure III.22: 2D Radiation Patterns for Antenna reconfigurable II from 1 to 3 bands in ON state for the frequency 2.3266GHz.



(a)



(b)



(c)

Figure III.23: 3D Radiation Patterns for the reconfigurable Antenna (II) in OFF state: (a) for resonant frequency2.3869GHz, (b) for resonant frequency 4.9798GHz,(c) for resonant frequency 6.8492 GHz.

FigureIII.22 and Figure III.23 represent two-dimensional radiation patterns of the proposed antenna (II) displayed in E-plane = 0 deg and H-plane=90 deg.

For the ON state at the frequency of 2.3266GHz, the 2D radiation pattern shows asecondary lobe in the E-plane (θ = -180°) and in the H-plane in the direction (θ = -170°).

For the OFF state, at the frequency of 2.3869 GHz, the 2D radiation pattern exhibits a secondarylobe in the E-plane (θ = 160°) and in the H-plane (θ = -180°). At the second frequency, 4.9798 GHz, the pattern similarly presents a main lobe in both the E-plane (θ = 0°) and H-plane (θ = 90°), indicating consistent directional behavior. However, at the third frequency of 6.8492 GHz, the radiation pattern displays multiple lobes, suggesting more complex radiation characteristics at higher frequencies.

3.2.4 3D Radiation Pattern:

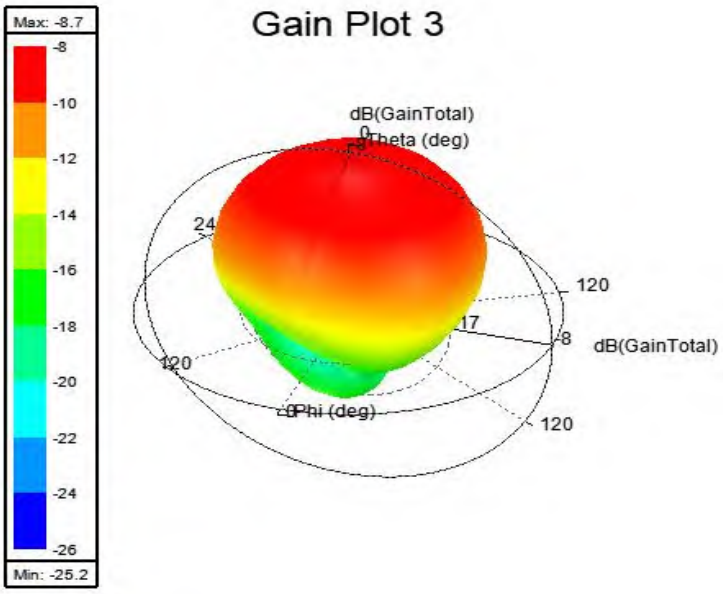
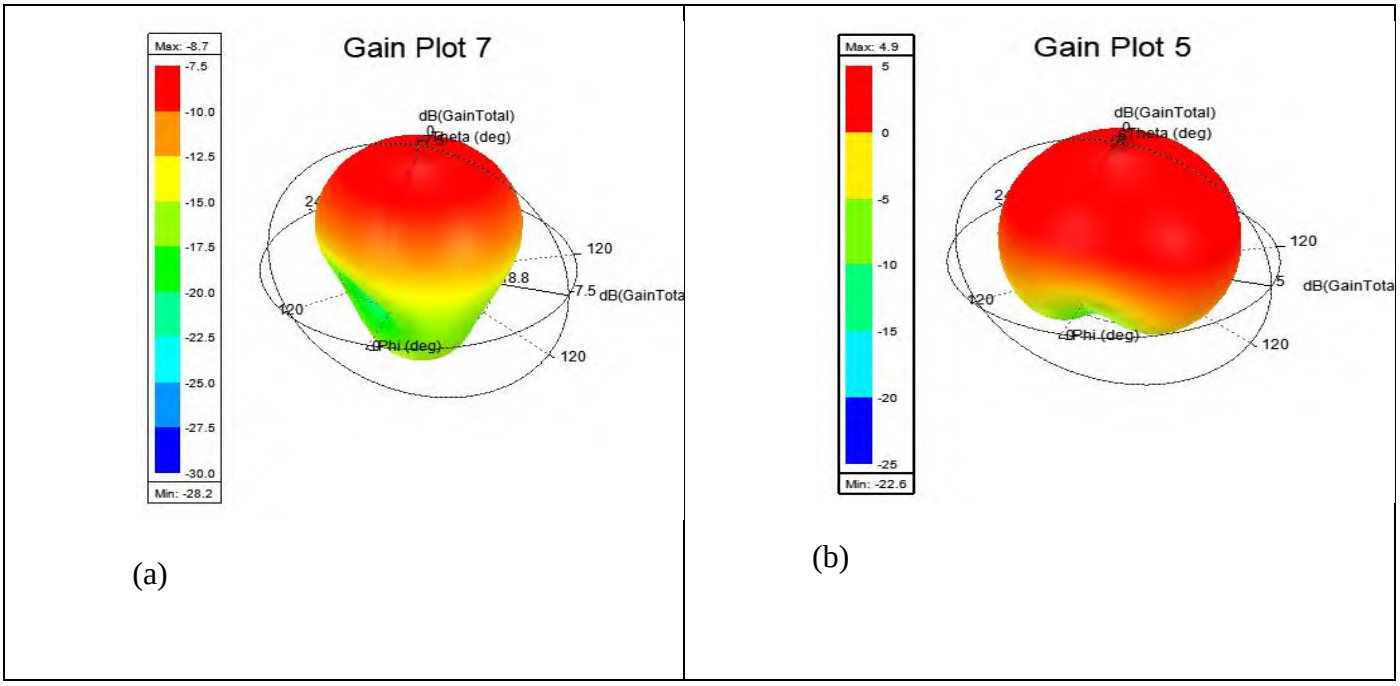
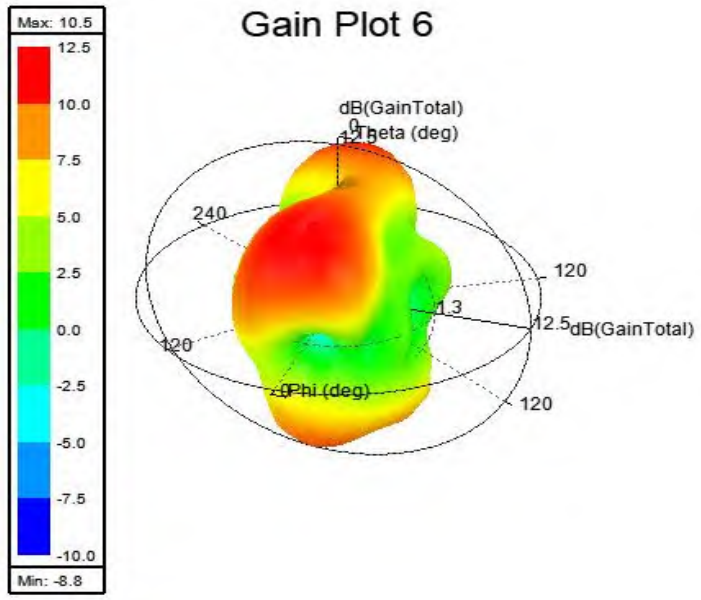


Figure III.24: 3D Radiation Pattern for reconfigurable Antenna (II) in ON state.



(a) (b)



(c)

Figure III.25:3D Radiation Patterns for the reconfigurable Antenna (I) in ON state: (a) for resonant frequency2.3869GHz,(b) for resonant frequency 4.9788 GH,(c) for resonant frequency 6.8492 GHz.

FigureIII.24 and Figure III.25 represent the total radiation pattern (gain) of an antenna in two different states: "ON" and "OFF".

In the "ON" state (Figure III.24), the maximum gain reaches -8.7 dB, with a relatively symmetrical and well-distributed radiation pattern.

In contrast, the "OFF" state (Figure III.25) shows a higher maximum gain values of -8.7 dB and 4.9 dB and 10.5 dB for the frequencies 2.3896 GHz and 4.9788 GHz and 06.8492GHz , respectively, but with a less uniform radiation pattern.Overall, for the ON and OFF states the antenna offers acceptable gain values.

3.3- Reconfigurable Antenna III from 2 to 3 bands:

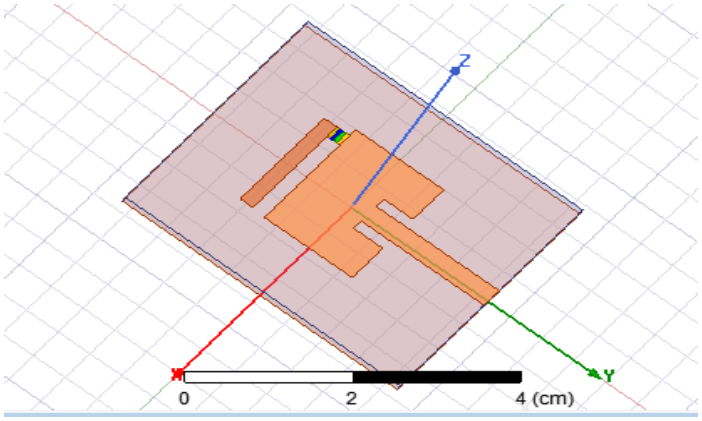


Figure III.26: Reconfigurable Antenna III from 2 to 3 bands: xss=17 mm and yss =2mm.

By configuring the parasitic patch dimensions to Xss = 17 mm and Yss = –2 mm, the antenna demonstrates reconfigurable behavior, enabling it to switch between dual-band and triple-band operation. This adaptability is achieved through the PIN diode, which dynamically alters the resonant frequencies depending on its ON or OFF state, allowing the antenna to meet the requirements of various wireless communication scenarios.

3.3.1-S11(the reflection coefficient):

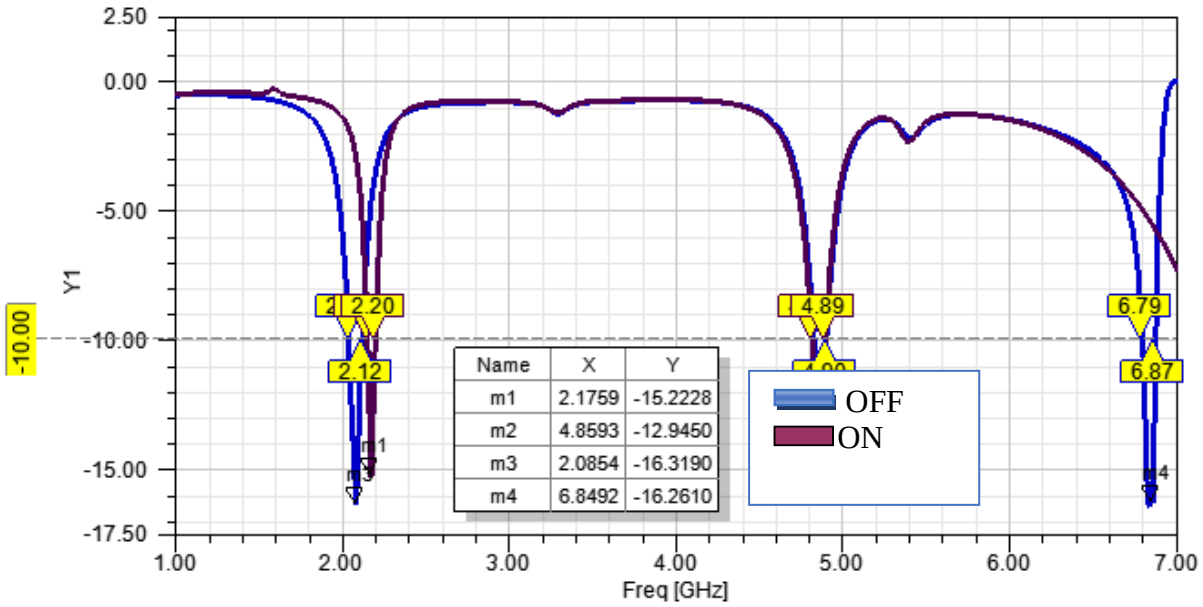


Figure III.27: The reflection coefficient (S11) for Antenna reconfigurable III from 2 to 3 bands.

Figure III.27 illustrates the S11 parameter (in dB) as a function of frequency (GHz) for both ON and OFF states of the PIN diode within the RF system.

The purple curve corresponds to the ON state, exhibiting a clear triple-band behavior with a S11 value of – 16.3190 dB around 2.0854 GHz and -12.5494 dB around 4.8593 GHz and -16.3137 dB around 6.8091 GHz. The blue curve represents the OFF state, showing a dual-band behavior with two resonant frequencies near 2.1759 GHz and 4.8593 GHz with S11 values of -15.2228 dB and of -12.9450 dB, respectively. For both states of the diode (ON and OFF) S11 values indicate efficient signal transmission. The effective bandwidths are approximately [2.04–2.12] GHz and [4.82-4.90] GHz and [6.79-6.87] GHz for the triple band in the ON state, and [2.15–2.20] GHz and [4.81–4.89] GHz for the dual bands in the OFF state.

3.3.2-Vswr (The Voltage Standing Wave Ratio) :

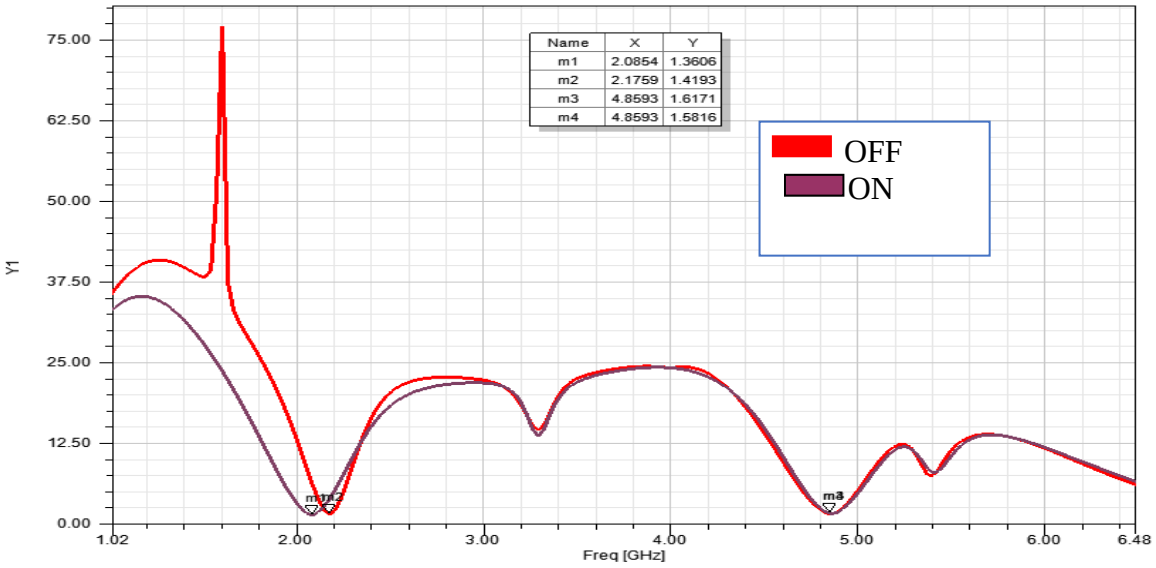
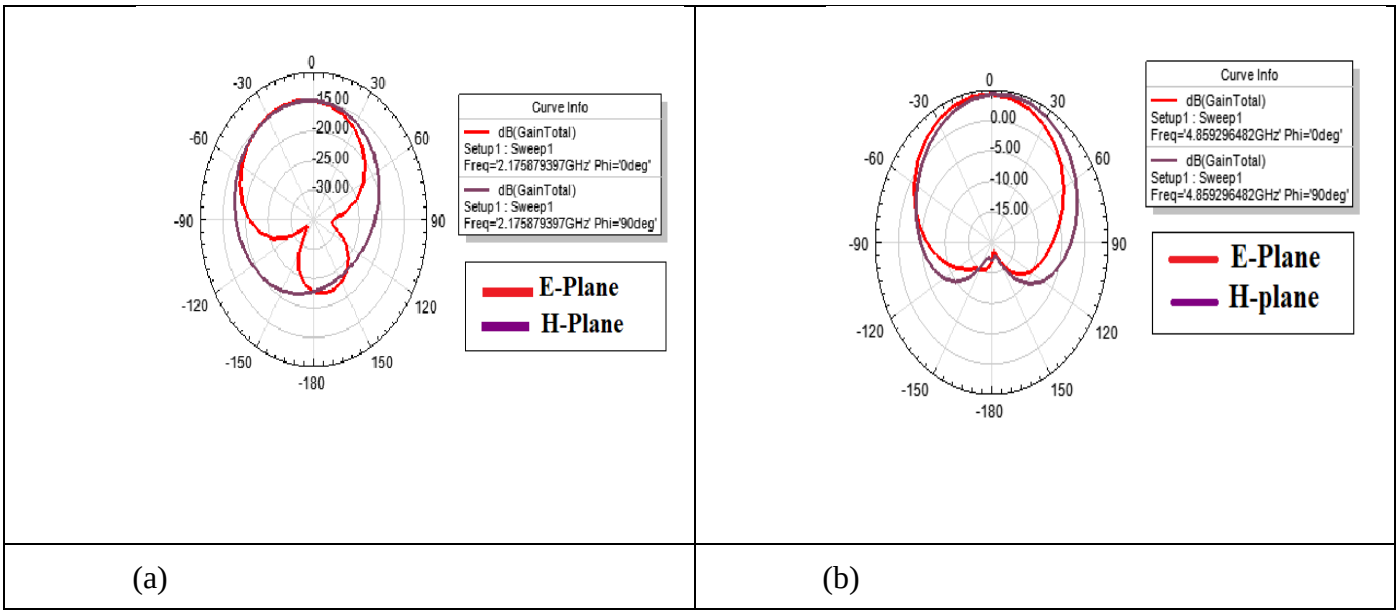


Figure III.28: Vswr for Antenna reconfigurable III from 2 to 3 bandes.

Figure III.28 shows the variation of the Voltage Standing Wave Ratio (VSWR) across the frequency range of 1 to 7 GHz. The purple curve represents the ON state, while the red curve corresponds to the OFF state of the PIN diode integrated into the antenna design. In the ON state, a VSWR of 1.6171and 1.4193 is observed, indicating good impedance matching. In the OFF state, VSWR values of 1.5816 and 1.8171are recorded at the two operating frequencies, also reflecting satisfactory matching conditions.

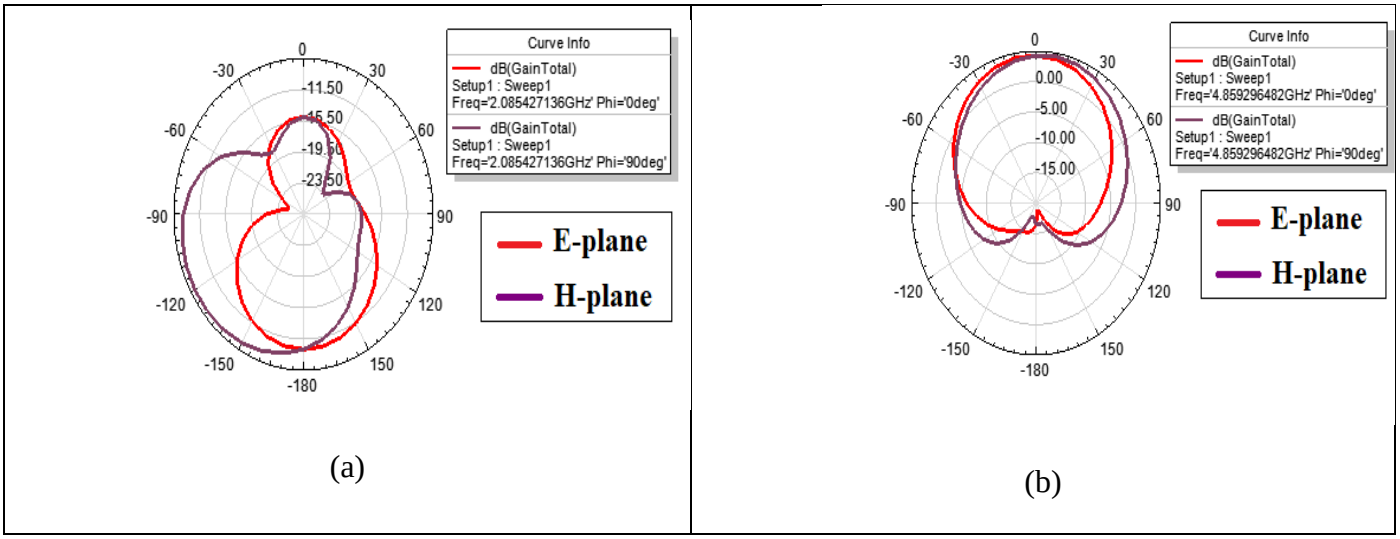
This behavior confirms that the antenna is frequency-reconfigurable, with its performance varying according to the state of the integrated switching diode. Such a feature makes the design suitable for multi-band applications or systems requiring dynamic switching between frequency bands.

3.3.32D Radiation Patterns:

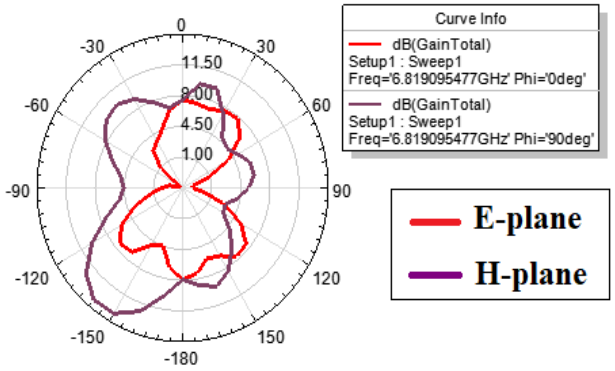


(a) (b)

Figure III.29: 2D Radiation Patterns for Antenna reconfigurable III from 2 to 3 bands in OFF(a) state for the frequency 2.1758GHz,(b) state for the frequency 4.8592GHz.



(a) (b)



(c)

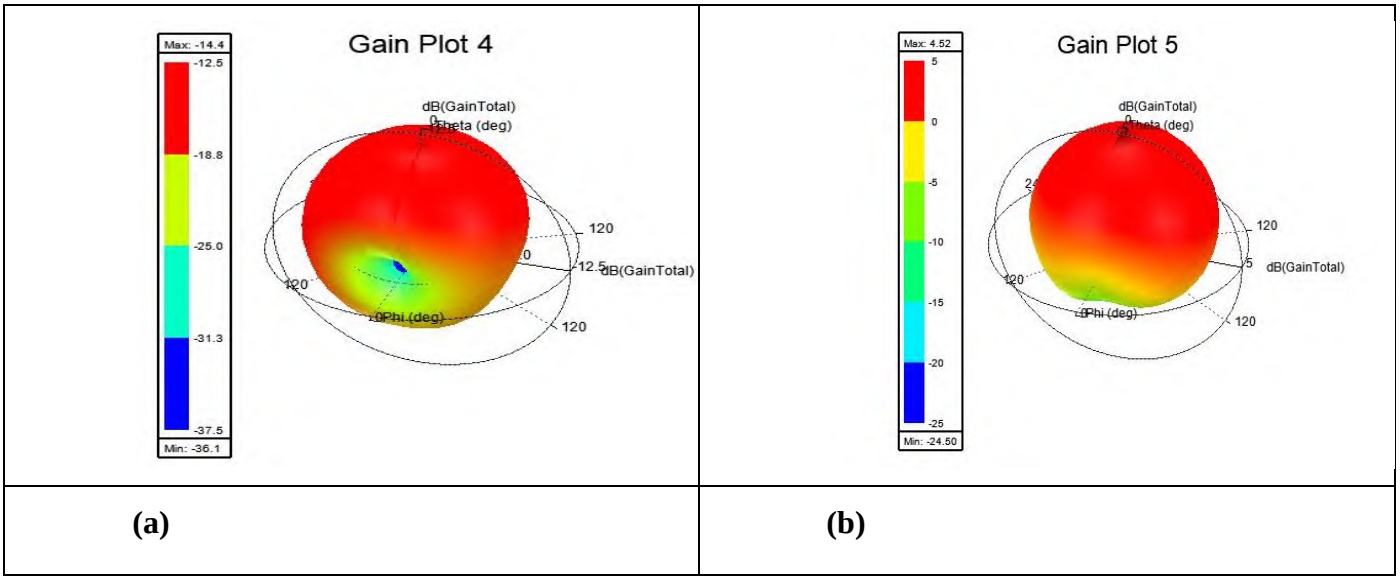
Figure III.30: 3D Radiation Patterns for the reconfigurable Antenna (II) in OFF state: (a) for resonant frequency2.0854GHz, (b) for resonant frequency 4.8592GHz,(c) for resonant frequency 6.8105GHz.

FigureIII.29and Figure III.30represent two-dimensional radiation patterns of an antenna displayed in E-plane = 0 deg and H-plane=90 deg.

For the ON state at the frequency of 2.0854GHz, the 2D radiation pattern shows a secondary lobe in the E-plane (θ = -180°) and in the H-plane in the direction (θ = -120°).For the ON state at the frequency of 4.8592 GHz, the 2D radiation pattern shows a main lobe in the E-plane (θ = 0°) and in the H-plane in the direction (θ = 90°).For the ON state at the frequency of 6.8105GHz, the 2D radiation pattern shows a secondary lobe directed in the E-plane at (θ = 0°and in theH-plane at θ = 90°.

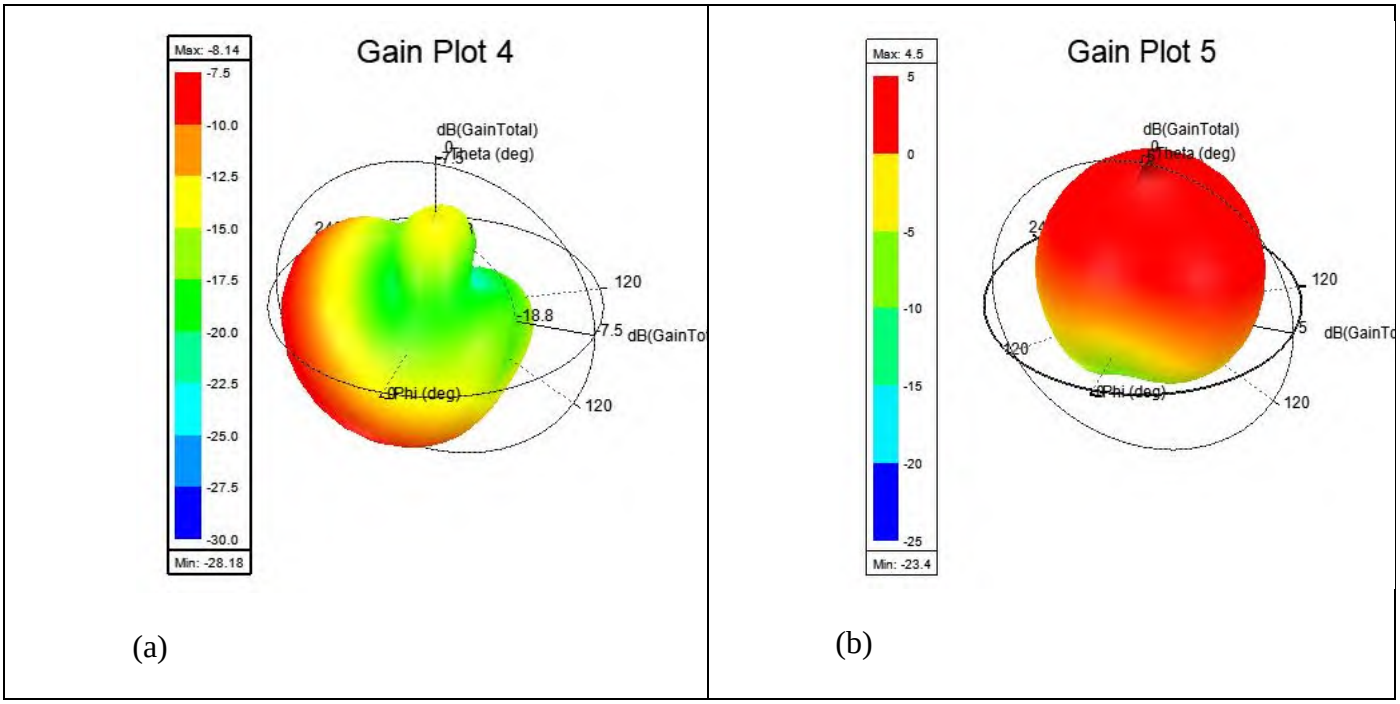
For the OFF state at the frequency of 2.1758GHz, the 2D radiation pattern shows a secondary lobe in the E-plane (θ = -160°) and in the H-plane (θ = 90°). At the second frequency of 4.8592GHz in the OFF state, the radiation pattern similarly exhibits a main lobe in the E-plane (θ = 0°) and the H-plane (θ = 90°), indicating consistent directional behavior.

3.3.4 3D Radiation Pattern:

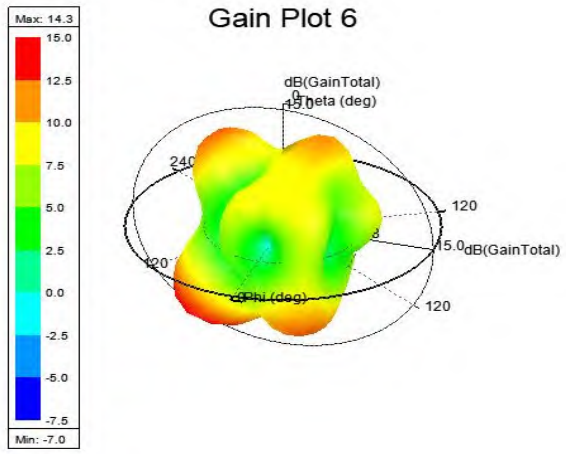


(a) **(b)**

Figure III.31: 3D Radiation Pattern for reconfigurable Antenna (III) in OFF state.



(a) (b)



(c)

Figure III.32:3D Radiation Patterns for the reconfigurable Antenna (I) in ON state: (a) for resonant frequency 2.0854 GHz,(b) for resonant frequency4.8592GHz,(c) for resonant frequency 6.8492 GHz.

FigureIII.31 and Figure III.32 represent the total radiation pattern (gain) of an antenna in two different states: "ON" and "OFF".

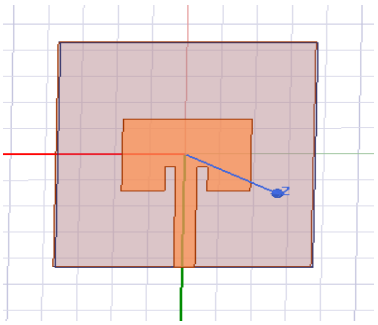
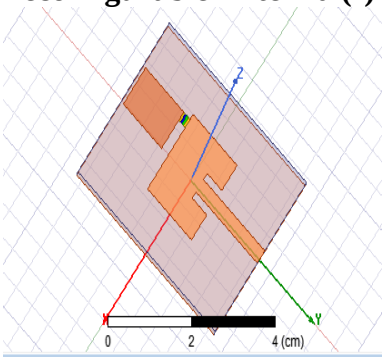
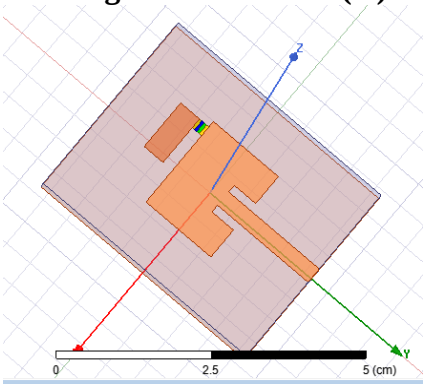
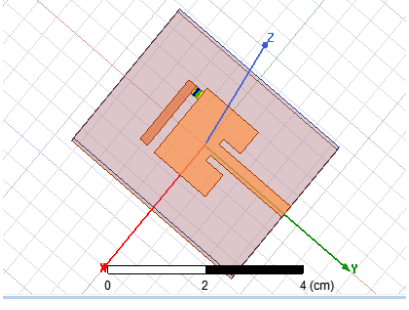
In the "OF" state (Figure III.31), the maximum gain reaches -14.8 dB and 4.5 , with a relatively symmetrical and well-distributed radiation pattern.

In contrast, the "ON" state (Figure III.32) shows a higher maximum gain values of -8.14dB and 4.5 dBand 14.3dB for the frequencies2.0854 GHz and 4.8592 GHz and 6.8492GHz , respectively, but with a less uniform radiation pattern.Overall, for the ON and OFF states the antenna offers acceptable gain values.

4-Comparison between the initial 5GHz antenna and reconfigurable antennas:

TableIII.5 represents a comparison between a conventional 5 GHz antenna and the proposed reconfigurable antennas based on key performance parameters such as reflection coefficient (S11), Voltage Standing Wave Ratio (VSWR), gain, and bandwidth.

Table III.5: Comparison between 5GHz antenna and reconfigurable antennas

Type of antenna	Parameter		
5 GHz Antenna 	**Resonant Frequencies (GHz)**	5	
	S11 (dB)	-12.99	
	VSWR	1.5	
	Gain (dB)	5.2	
	Bandwidth (GHz)	0.10	
Reconfigurable Antenna (I) 	**Parameter**	**Diode ON**	**Diode OFF**
	Resonant Frequencies (GHz)	1.7236 5.1307	5.1307
	S11 (dB)	-24.30 -11.15	-11.75
	VSWR	1.12 1.71	1.71
	gain(dB)	-13.7 3.91	2.8
	Bandwidth (GHz)	0.12 0.04	0.06
Reconfigurable Antenna (II) 	**Resonant Frequencies (GHz)**	2.3266	2.3869 4.9799 6.8442
	S11 (dB)	-16.01	-12.27 -12.70 -11.62
	VSWR	1.37	1.64 1.60
	Gain(dB)	-8.5	-8.5 4.9 10.5
	Bandwidth(GHz)	0.09	0.10 0.03 0.09
Reconfigurable Antenna (III) 	**Resonant Frequencies (GHz)**	2.0854 4.8554 6.8091	2.1759 4.8593
	S11 (dB)	-16.3190 -12.54 -16.3137	-15.22 -12.94
	VSWR	1.41 1.61	1.81 1.58
	Gain(dB)	-8.14	-14.4

		4.5 14.3	4.52
	Bandwidth(GHz)	0.08 0.08et 0.08	0.05 0.08

The 5 GHz reference antenna is designed for single-band operation centered around 5 GHz, with an S11 value of –12.99 dB and a bandwidth of 0.10 GHz. In comparison, the r.econfigurable antennas (I, II, and III) introduce significant enhancements through their multi-band capabilities, enabled by the integration of a PIN diode and a parasitic patch. These .antennas can dynamically switch between dual-band and triple-band modes depending on the diode's state (ON or OFF), offering greater frequency agility. For example, Reconfigurable Antenna I exhibits multiple resonant frequencies in both states with improved S11 values, reaching as low as –24.30 dB in the ON state, indicating excellent impedance matching. Similarly, Antennas II and III show resonances with S11 values better than –12 dB across various frequency bands. Additionally, the bandwidths observed in these reconfigurable designs vary from 0.03 GHz to 0.12 GHz, depending on the configuration, which enables more efficient use of the spectrum and supports a wider range of wireless applications. Overall, these reconfigurable antennas demonstrate superior adaptability and frequency coverage compared to the fixed single-band operation of the original 5 GHz antenna.

5-Comparative Analysis of Reconfigurable Antennas Reported in the Literature:

The comparative analysis presented in the table highlights the advantages of the proposed reconfigurable antenna over existing designs in the literature. While most previous works focus on single or dual-band operation with relatively larger sizes and often require multiple PIN diodes or varactors for reconfiguration, the antenna developed in this work achieves multi-mode functionality—including single, dual, and tri-band operation—using only one PIN diode. With compact dimensions of 33.2 × 47 mm², it effectively covers a wide frequency range from 1.72 GHz to 6.84 GHz, outperforming many existing designs in terms of both frequency agility and hardware simplicity. This makes the proposed antenna a versatile and efficient solution for modern wireless communication systems.

Table III.6: Summary of Reconfigurable Antennas Used in the Literature

Ref.	Dimensions (mm^2)	Operational Mode	Reconfigurable Technique	Frequency Range (GHz)
[68]	100 × 100	Single band	PIN-diode (2)	2.2–3.8
[69]	70 × 70	Single band	Varactor (1)	2.6–3.8
[70]	50 × 50	Single band	Mechanical	2–4.5
[71]	27 × 27	Single band	Varactor (1)	1.4–2
[72]	14 × 36	Single band	PIN-diode (2)	2–2.6
[73]	25 × 27	Single and Dual Band	PIN-diode (2)	2–6
[74]	20 × 16	Single and Dual Band	PIN-diode (2)	2–6
[75]	50 × 45	Dual and Tri Band	PIN-diode (2)	2.5–5
This work	33.2×47	Single and Dual Band	PIN-diode (1)	1.72–5.13
		Single and Tri Band	PIN-diode (1)	2.38–6.84
		Dual and Tri Band	PIN-diode (1)	2.08–6.80

Conclusion:

In this chapter, we presented the design, simulation, and analysis of both a conventional 5 GHz patch antenna and its reconfigurable counterparts. The initial design served as a reference, offering single-band operation with satisfactory S11, VSWR, and gain performance. To introduce frequency agility, we proposed several reconfigurable antennas architecture by integrating a PIN diode and a parasitic patch above the main radiating element.

Through parametric variation of the parasitic patch dimensions and diode state (ON/OFF), several antenna configurations were generated and analyzed using HFSS and MATLAB. The results demonstrated the ability of the reconfigurable antennas to operate over multiple bands (dual and triple bands), while maintaining good impedance matching (S11 < –10 dB) and acceptable bandwidths. These properties make the proposed antennas highly suitable for modern wireless applications requiring dynamic frequency allocation.

In comparison with other reconfigurable antennas reported in the literature, the proposed design stands out by offering multi-band capabilities (from single to triple band) using a single PIN diode, while maintaining a compact size and wide frequency

coverage. This illustrates the effectiveness of the design in meeting the demands of future wireless communication systems.

Ultimately, this chapter highlights the benefits of reconfigurability in antenna design, offering flexibility, compactness, and enhanced spectrum utilization—key characteristics in the development of next-generation communication systems such as 5G and IoT networks.

General Conclusion

GENERAL CONCLUSION

The design and optimization of reconfigurable patch antennas using PIN diodes is an advanced research field aligned with modern trends in intelligent and adaptive wireless communication systems. This study aimed to explore the theoretical foundations and practical implementations of such antennas, with a focus on enhancing their performance by controlling their frequency and radiation characteristics through the integration of actively controllable electronic components. Using HFSS simulation software and MATLAB, several patch antenna models were designed, including conventional and reconfigurable types. In the reconfigurable models, PIN diode was integrated to enable switching between different operational states and frequency bands. This integration significantly improved key antenna parameters such as bandwidth, reflection coefficient, VSWR, and radiation patterns.

Comparative analysis of the proposed models (Conventional antenna, Antenna I, II, and III) showed that incorporating PIN diode enables the antenna to switch between multiple frequency bands, offering the flexibility required to meet diverse application needs. Antenna III achieved the widest bandwidth and best impedance matching, making it a strong candidate for multi-band applications. Antenna II demonstrated the highest gain, making it suitable for long-range communications, while Antenna I provided a balanced performance in terms of gain and reconfigurability. In addition, the proposed antennas are compared with other reconfigurable antenna designs from the literature, underlining their performance advantages and design compactness.

These results highlight the great potential of integrating PIN diodes into patch antenna structures as an effective approach for developing smarter communication systems that can adapt to dynamic frequency environments.

Accordingly, this study underscores the importance of reconfigurable patch antennas as key components in modern wireless systems—especially when enhanced with active electronic elements such as the PIN diode. This work, which combined theoretical analysis with numerical simulation, constitutes a valuable contribution to the development of intelligent antenna systems and paves the way for future innovations in the field.

This work can be further developed through the following avenues:

- Integration of digital control systems for automated PIN diode switching.
- Evaluation of antenna performance within MIMO systems.
- Application of artificial intelligence techniques for automatic environment-based antenna tuning.

ANNEXE

APPENDIX (Presentation of the HFSS Software)

1. Introduction:

HFSS represents a robust solution for 3D electromagnetic (EM) simulation, specifically designed for the accurate and efficient modeling of volumetric passive devices. With a user-friendly interface on Windows, it integrates simulation, visualization, solid modeling, and automation. Thanks to advanced features such as the finite element method and adaptive meshing, HFSS quickly provides accurate solutions for 3D electromagnetic problems. Its high-quality graphics allow for detailed analysis of results, including the calculation of parameters such as S11 parameters, electromagnetic fields, and resonance frequency.

2. Ansoft Term

The Ansoft HFSS window includes various optional panels:

3D Modeler Window

The 3D Modeler window displays the model and its associated tree structure for the active design

A Project Manager

The project manager includes a design tree that presents the complete structure of the project.

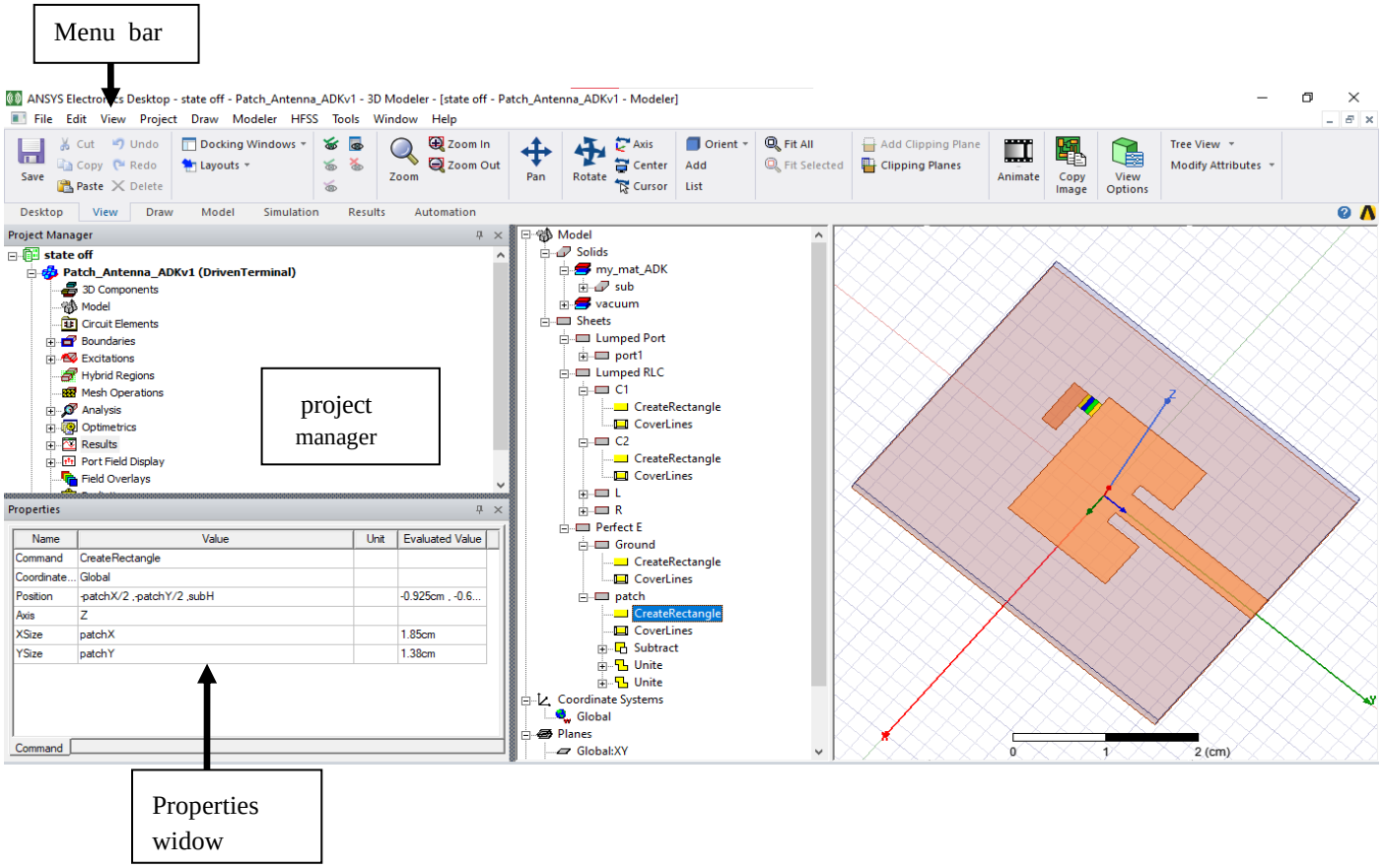


Figure. A.1: Subtraction of objects

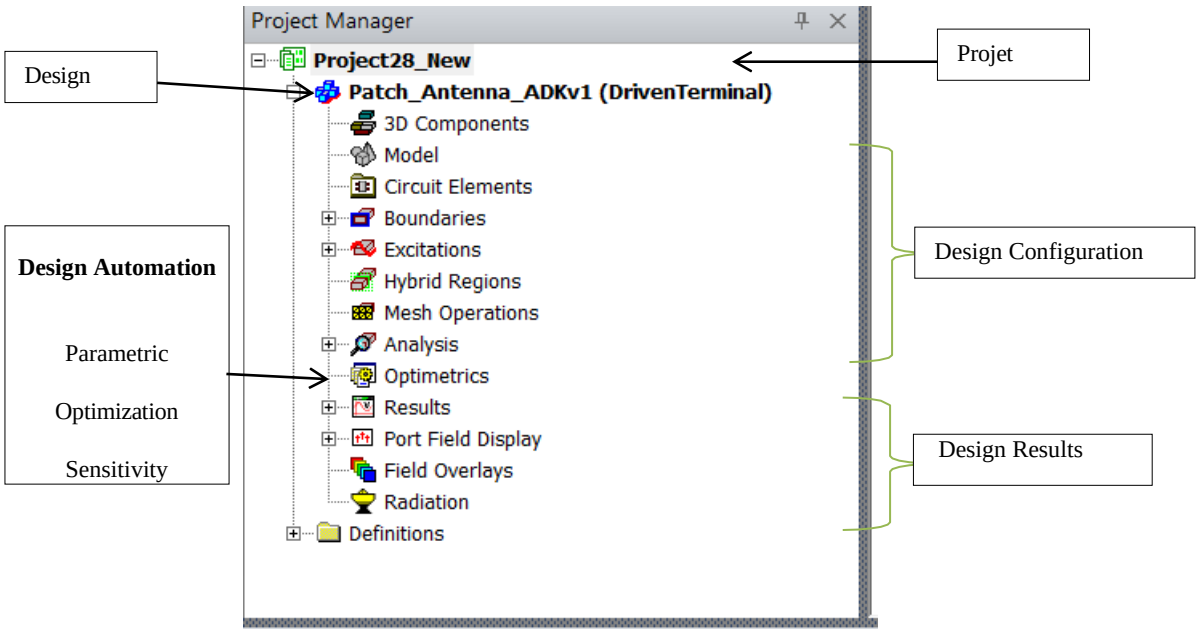


Figure.A.2: Project Manager.

A Message Manager

This allows you to detect errors or warnings before launching a simulation.

Ungestionnairedemessages

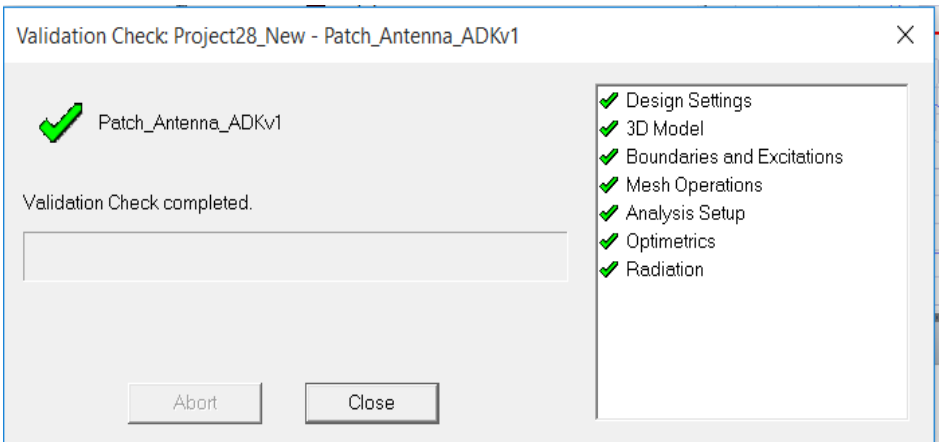


Figure. A.3: Message Manager **Figure.**

A Properties Window

The properties window displays and offers the option to modify the parameters or attributes of the model.

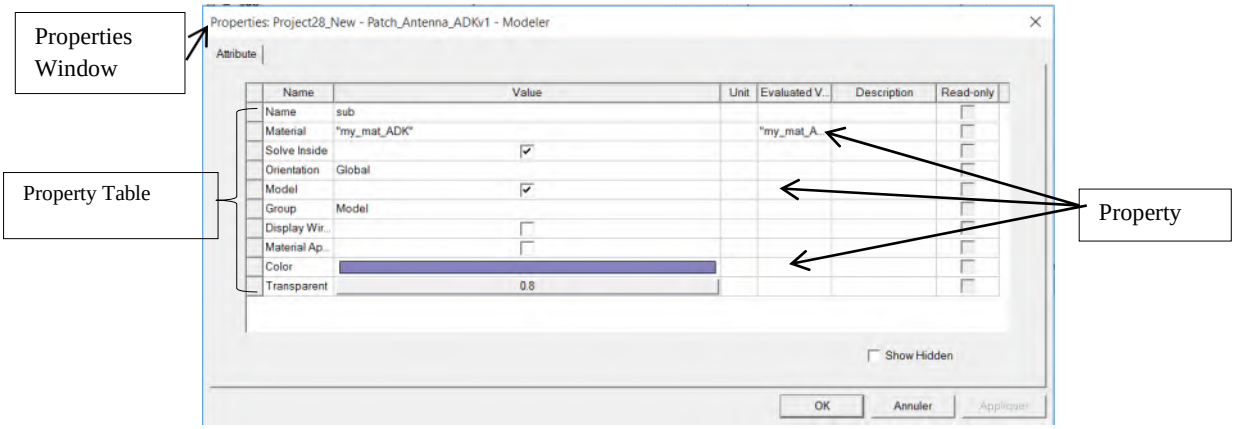


Figure.A.4: Properties Window.

A Progress Window

The progress window shows the status of the resolution process.

3. 3D Modeler Design Tree

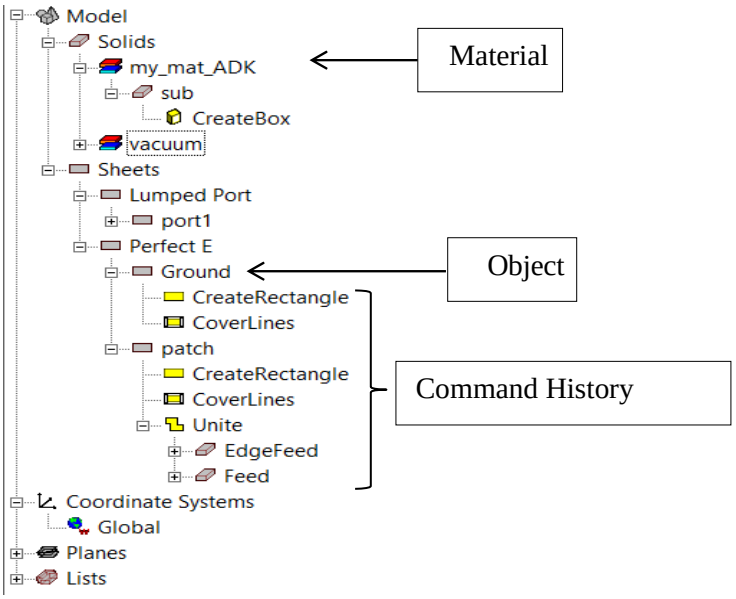


Figure.A.5: Command History.

3. Project Creation

In the "File" menu, select "New" to create a new project. You can specify the project name when saving it using the "Save" or "Save As" options in the "File" menu. To open an already saved project, use the "Open" command in the "File" menu. To design a structure in HFSS, follow this general procedure. It is important to note that while the steps do not need to be executed sequentially after inserting a design, they must be completed before a solution can be generated.

Choose the new units for the model from the selected units dropdown list.

Drawing a Model

To create a 3D structure, simply use the drawing tools provided by the software. Here, we focus on the most complex aspects of this procedure. You can create 3D objects using the drawing commands in HFSS (HFSS > Draw > Commands). The objects are then drawn in the 3D modeler window (see figure A.6).

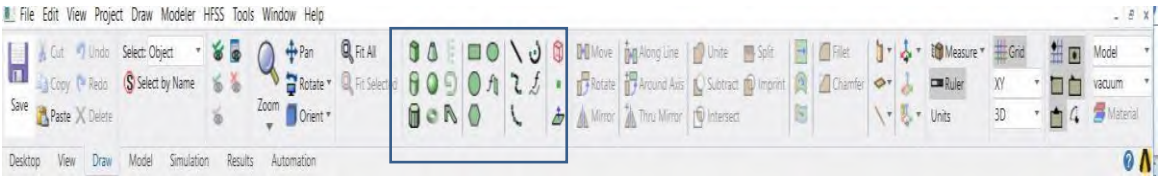


Figure. A.6: Drawing a Mode.

Using Project Variables

In HFSS, we have the ability to define variables and associate them with various parameters of the structure, such as dimensions or material properties (see figure A.7).

Using variables to link dimensions simplifies the management of potential future changes. For example, to modify the dimensions and excitations of an element, such as a pin in our case, you only need to change the value of the corresponding variable.

To define a variable, go to **Project > Project Variables** and enter its name, value, and unit. Once a variable is defined, its name can be used in place of its value. HFSS also allows the use of mathematical functions on defined variables

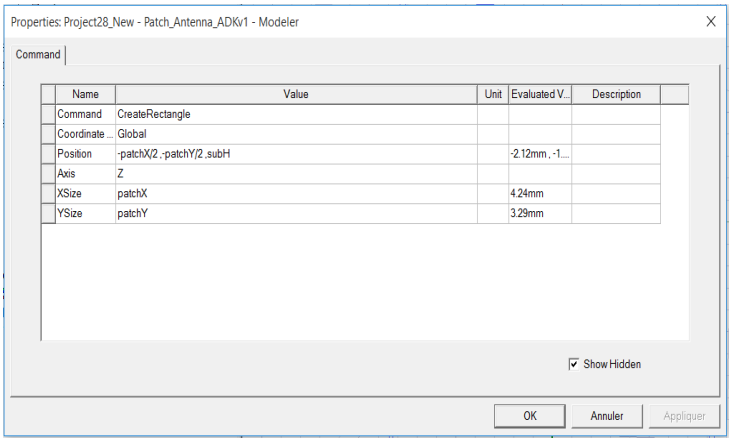


Figure A.7: Using Project Variables

Subtraction of Objects

It is common to need to eliminate certain parts of an object.

- Start by drawing the main object along with the objects to subtract from it.
- Select the main object.
- While holding down the CTRL key, select the objects to subtract.
- Click on "Subtract." 
- The objects listed in the "Tool Parts" section will be subtracted from the objects listed under "Empty Parts."
- If you want HFSS to keep a copy of the subtracted objects, check the "Clone tool objects before subtracting" option.
- Press OK to validate.

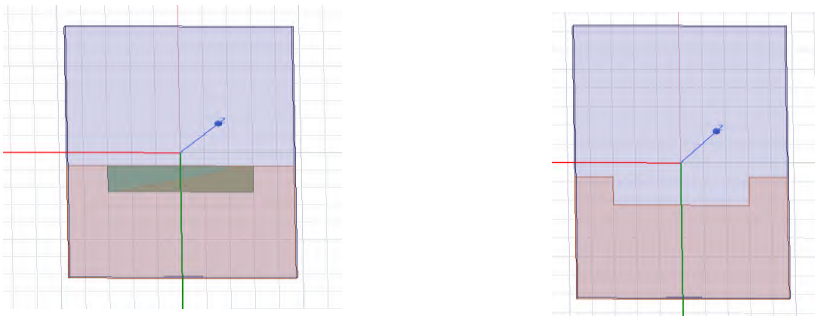


Figure.A.8: Subtraction of Objects.

Toolbars

The toolbar buttons provide shortcuts to the most commonly used commands. Although most toolbars are displayed in the initial Ansoft HFSS screen illustration, your Ansoft HFSS window may be configured differently. You have the option to customize the display of your toolbars according to your preferences. Some toolbars are always visible, while others appear automatically when you select a corresponding document. For example, when you choose a 2D report in the project tree, the 2D state toolbar will appear.



Figure.A.9: Toolbars.

Boundaries

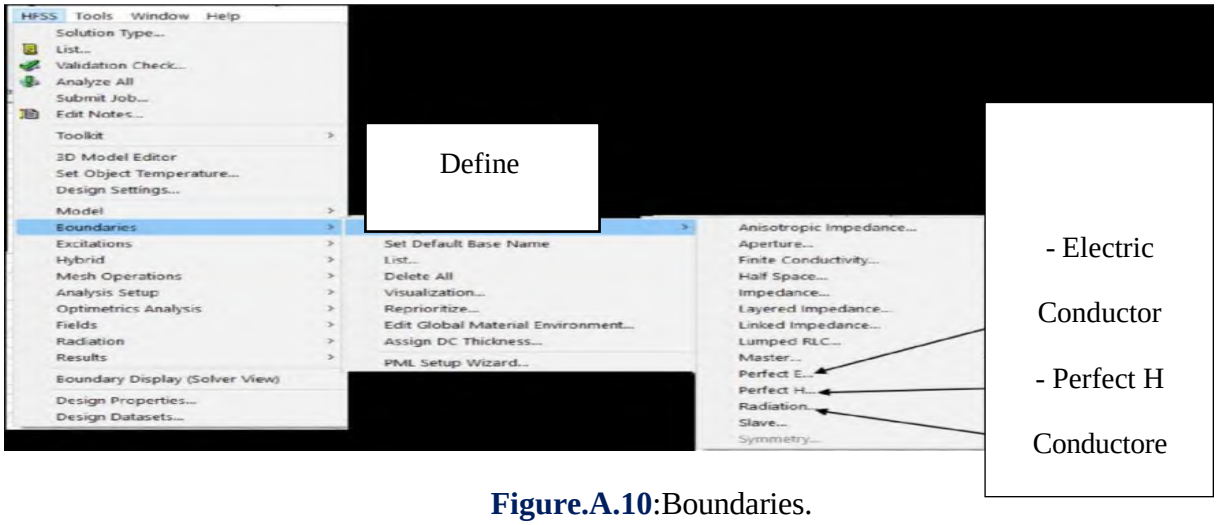


Figure.A.10:Boundaries.

- **PerfectE:**

his type of boundary is often referred to as a **"Perfect Electric Conductor (PEC)"**. In this case, the electric field is **perpendicular** to the surface. Two automatic criteria define a conductor as perfectly conductive:

✓ When a surface of the object comes into contact with a substrate, it is automatically categorized as a perfectly conducting boundary and designated as an outer boundary condition.

✓ When an object is assigned a PEC (Perfect Electric Conductor) material, it is automatically subjected to a perfect electric boundary condition.

- **PerfectH:**

If a material is a Perfect Magnetic Conductor (PMC)**,** the magnetic field is tangential to its surface.

Analyze Setup

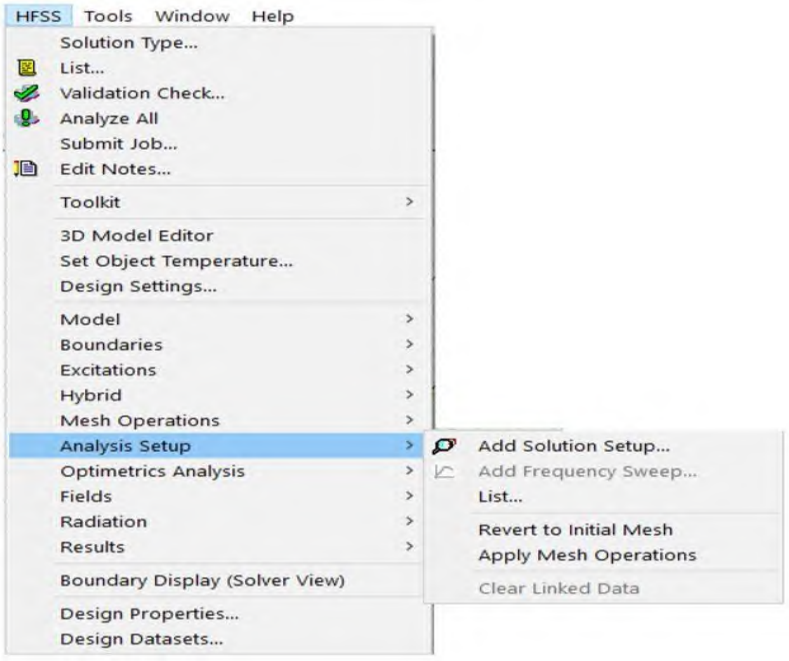


Figure.A.11: Analyze Setup.

3. PIN diode:

The first step is to click on the Capacitance

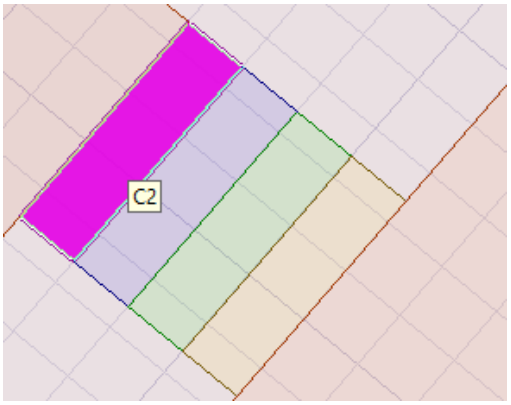


Figure A.12: PIN diode.

Step 2: Assigning the Lumped RLC Boundary

Right-click on the surface representing the location of the component, then select:

Assign Boundary → Lumped RLC

In the window that appears (**Lumped RLC Boundary**), enable the **Capacitance** option only, and enter the appropriate value (0.5 µF). Ensure that the Current Flow Line is set to Defined**.** After configuring the values, click OK to apply the settings

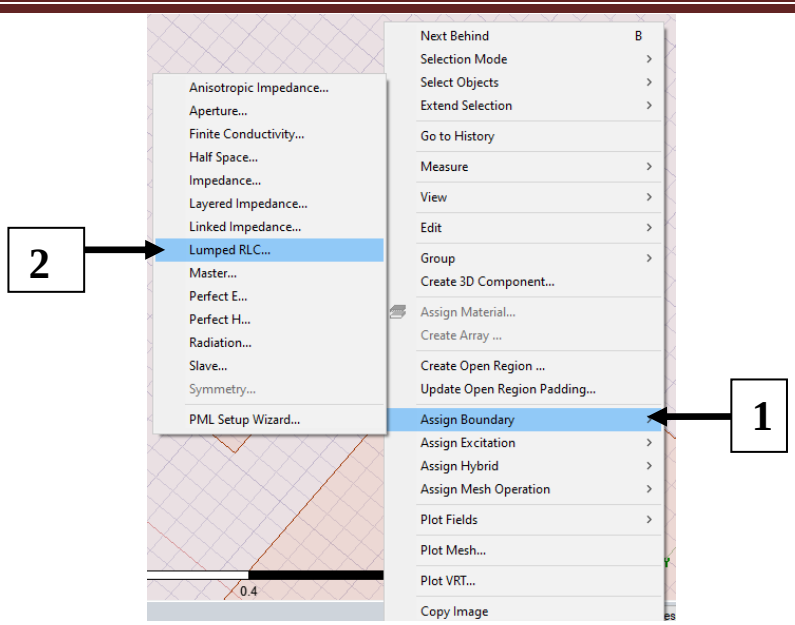
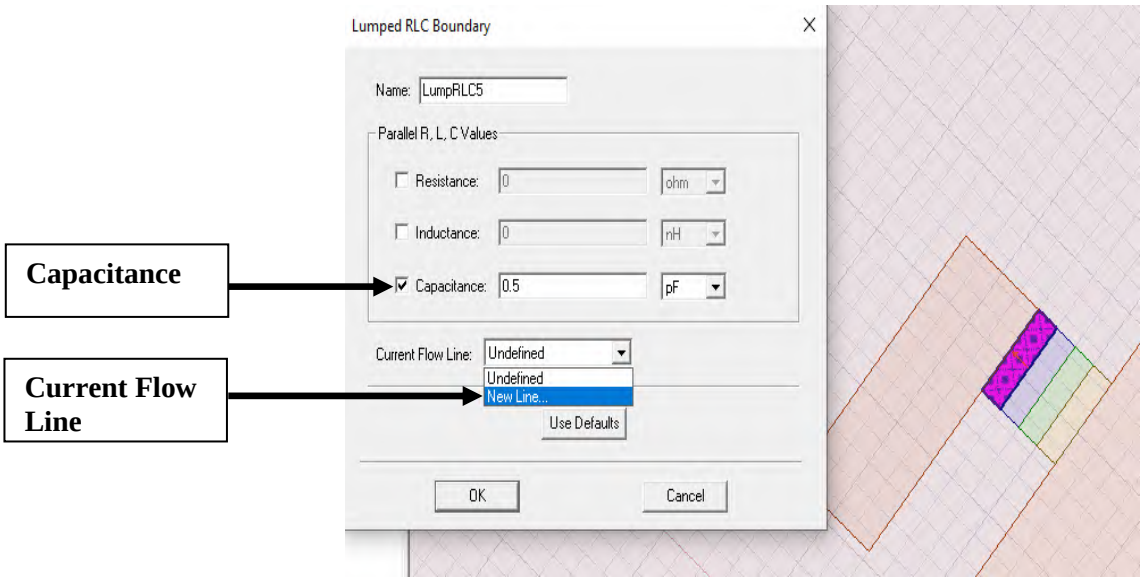
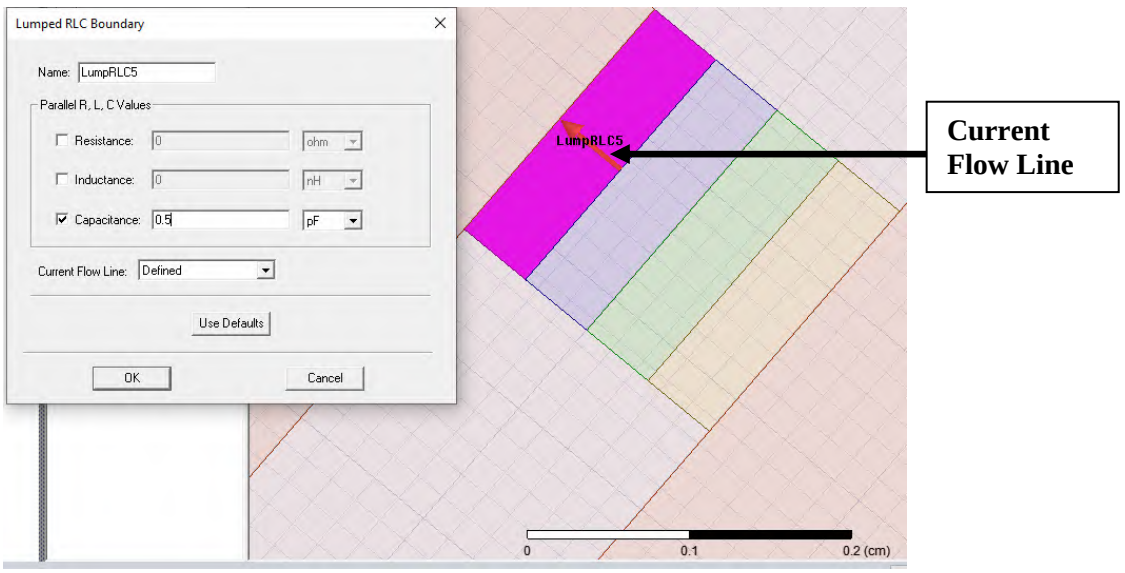


Figure A.13: Lumped RLC Boundary Condition



figureA.14: Configuration of a Lumped RLC Boundary with a Capacitance of 0.5 pF



figureA.15: Defined Current Flow Line for the Lumped Capacitance

Using the same style for the other components of the PIN diode, when incorporating the resistance (Resistance) and inductance (bobine) values, along with specifying the current flow path

4. **Plotting S11 and VSWR:**

   First, we access the Project Manager**,** then for the results, we display a list that includes the creation of a solution data report and a rectangular plot**.** We select the unit in decibels (dB)**.**

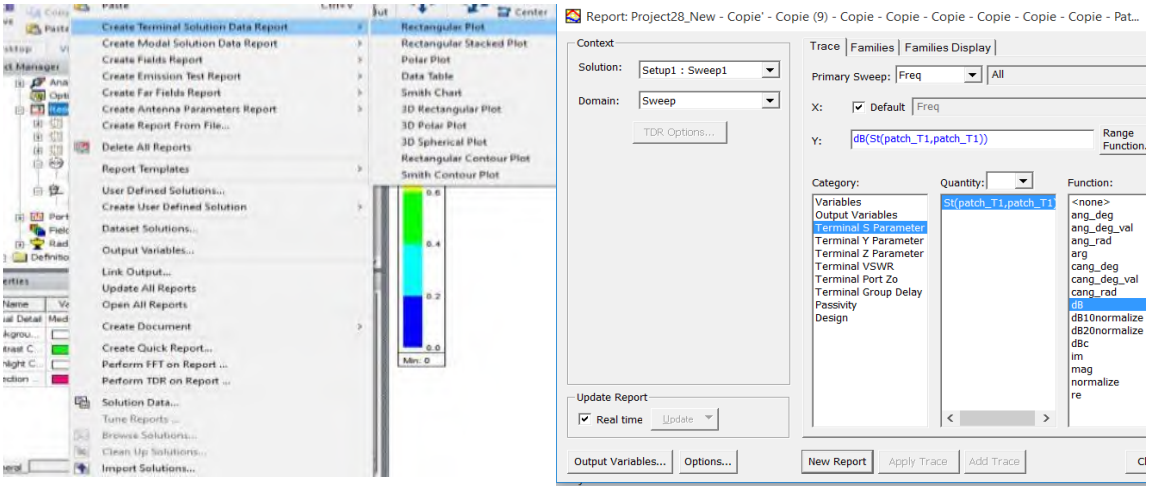
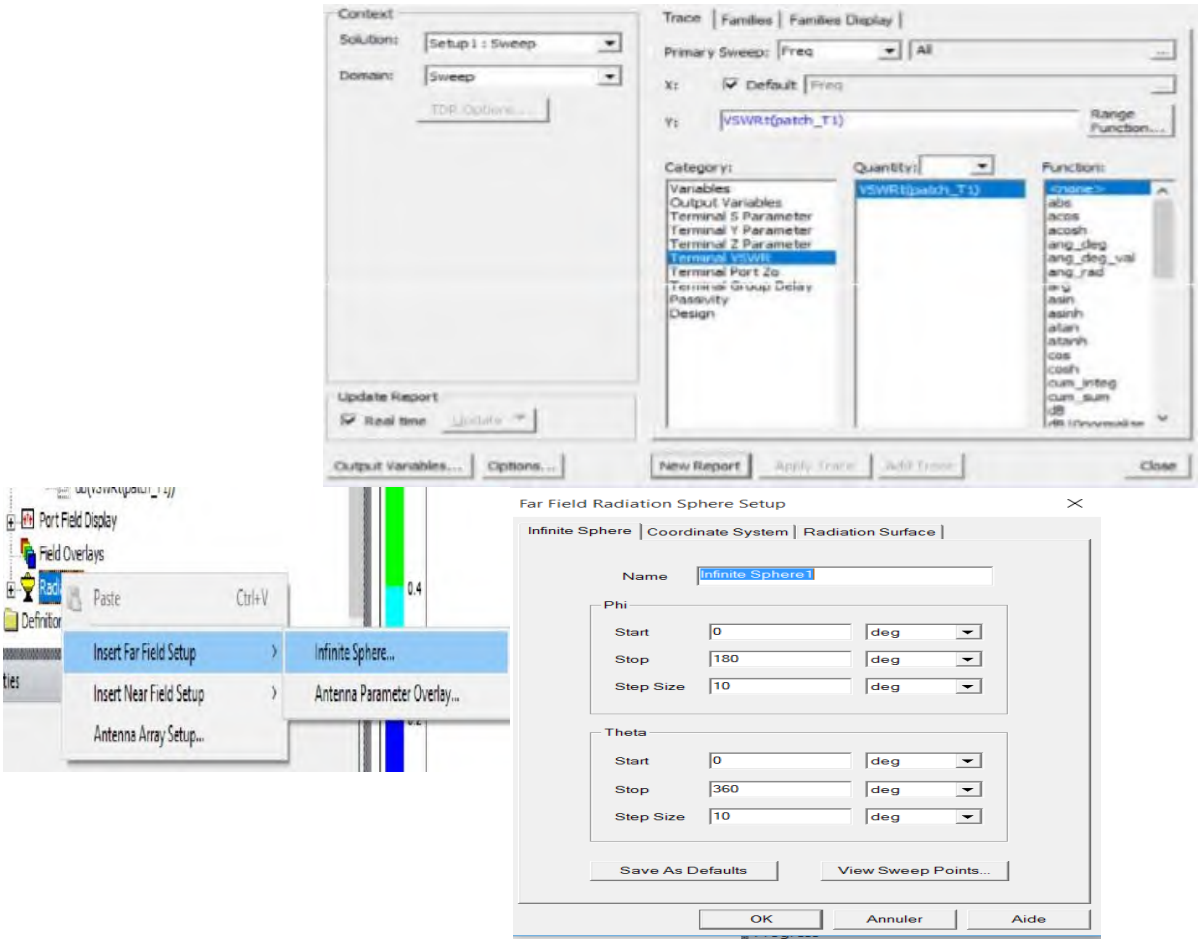
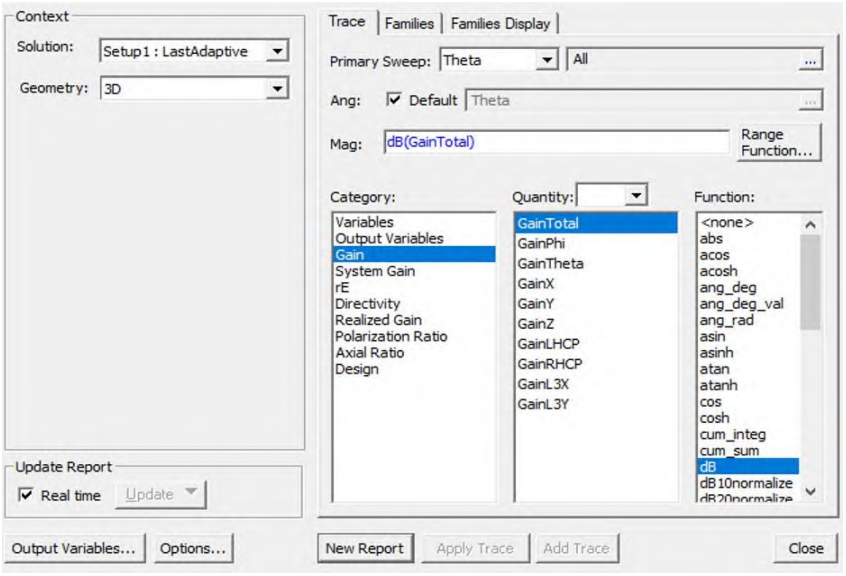


Figure.A.12:S11 and VSWR.

1. **Radiation Pattern**:
   First, we access the Project Manager, then we click on "Insert Far Field Setup" (infinite sphere) and adjust the parameters.

ANEXE


Context
Solution:
Setup 1 : Sweep
Domain:
Sweep
Trace
Families
Families Display
Primary Sweep:
Freq
All
X:
Default
Freq
Y:
VSWR1(patch_T1)
Range Function...
Category:
Quantity:
Function:
Variables
Output Variables
Terminal S Parameter
Terminal Y Parameter
Terminal Z Parameter
Terminal VSWR
Terminal Port Zo
Passivity
Design
abs
acos
acosh
ang_deg
ang_deg_val
ang_rad
asin
asinh
atan
atanh
cos
cosh
cum_integ
cum_sum
Update Report
Real time
Update
Output Variables...
Options...
New Report
Apply Trace
Add Trace
Close
Port Field Display
Field Overlays
Paste
Ctrl+V
Insert Far Field Setup
Insert Near Field Setup
Antenna Array Setup...
Infinite Sphere...
Antenna Parameter Overlay...
0.4
Far Field Radiation Sphere Setup
Infinite Sphere
Coordinate System
Radiation Surface
Name
Infinite Sphere1
Phi
Start
0
deg
Stop
180
deg
Step Size
10
deg
Theta
Start
0
deg
Stop
360
deg
Step Size
10
deg
Save As Defaults
View Sweep Points...
OK
Annuler
Aide



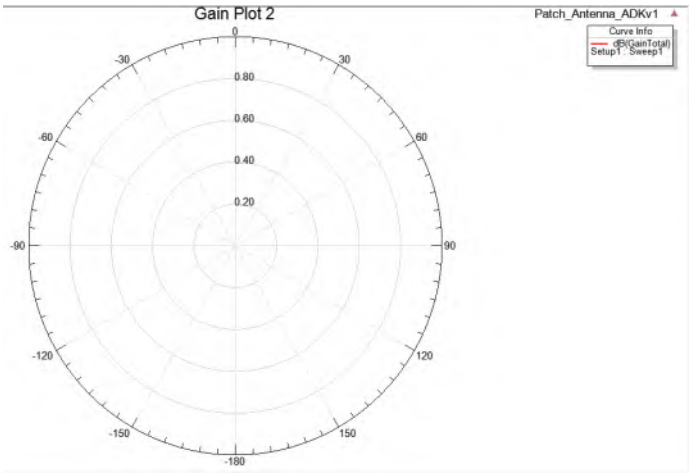


Figure.A.13: Radiation Pattern**.**

5. Conclusion :

In this additional appendix, we present and detail the essential steps for designing an HFSS project. We exemplify this process using a rectangular patch antenna excited by microstrip lines. HFSS is an electromagnetic simulation software that allows for the analysis of structures by creating 3D models and2d

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