A Project Report on

Dual-band Antenna for Implantable Biomedical Devices

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UNDERTAKING

We hereby declare that the report entitled *“Dual-band Antenna for Implantable Biomedical Devices”* for fulfilment of the requirement for the award of Bachelor of Technology degree (B.Tech.) was carried out under the supervision of Mr. Ritesh Sachan, Department of Electronics Engineering (HBTU, Kanpur). The source of literature and used data have been acknowledged, and the information in this report is correct to the best of our knowledge.

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CERTIFICATE

This is to certify that Priyanshi Srivastava, Kashish Azhar, Swarnim Mishra, and Mohd. Sayam Fareez have submitted the project report titled *"Dual-band Implantable for Implantable Biomedical Devices"* in partial fulfilment of the requirements for the award of the degree of Bachelor of Technology in the Electronics Engineering Department under my guidance and supervision. The project has not been submitted to any other institute. On the basis of declarations made by students, I recommend the project report for evaluation.

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ABSTRACT

The growing demand for real-time health monitoring has led to rapid advancements in implantable biomedical devices, necessitating compact, efficient, and biocompatible wireless communication systems. This project focuses on the design and simulation of a dual-band microstrip antenna suitable for implantation within the human body, operating at 0.91 GHz and 2.45 GHz ISM bands. Utilizing Ansys HFSS, the antenna was modeled to meet stringent requirements of Specific Absorption Rate (SAR), miniaturization, and efficient radiation in lossy biological tissues. Various design iterations, including meandered lines and slotting techniques, were implemented to optimize return loss, VSWR, gain, and bandwidth. The final antenna design demonstrated effective performance in the 2.45 GHz band, ensuring safe and reliable operation within skin tissues. This work contributes to the development of next-generation wireless implantable systems for applications such as cardiac monitoring, neural stimulation, and glucose sensing, emphasizing safety, power efficiency, and dual-band communication.

PROBLEM STATEMENT

Modern healthcare increasingly relies on implantable biomedical devices for continuous monitoring and therapy, which require robust wireless communication capabilities. However, designing antennas for implantation poses significant challenges due to space constraints, high tissue permittivity, energy limitations, and strict safety standards like SAR compliance. Conventional single-band antennas often struggle to meet the diverse functional requirements of these devices. Therefore, there is a critical need for a compact, dual-band implantable antenna capable of operating efficiently at both 0.91 GHz and 2.45 GHz ISM bands. Such a design must ensure minimal power reflection, high radiation efficiency, and safe operation within the human body, all while maintaining structural miniaturization and biocompatibility. This project addresses these challenges through systematic simulation, optimization, and performance evaluation using HFSS, aiming to provide a reliable and safe wireless solution for implantable medical technologies.

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ABBREVIATIONS

S. No.	Abbreviation	Meaning
1.	IBD	Implantable Biomedical Device
2.	ISM	Industrial, Scientific, and Medical
3.	SAR	Specific Absorption Rate
4.	S_{11}	Return Loss Parameter (Reflection Coefficient)
5.	VSWR	Voltage Standing Wave Ratio
6.	HFSS	High Frequency Structure Simulator
7.	PCB	Printed Circuit Board
8.	CPW	Coplanar Waveguide
9.	GSM	Global System for Mobile Communications
10.	Wi-Fi	Wireless Fidelity
11.	MIMO	Multiple Input Multiple Output
12.	AMC	Artificial Magnetic Conductor
13.	FSS	Frequency Selective Surface
14.	EBG	Electromagnetic Band Gap
15.	FR4	Flame Retardant 4

CHAPTER 1
Introduction

1.1: Introduction to Implantable Antenna for Biomedical Devices

Implanted biomedical devices are gaining significant attention for managing complex Biomedical technology has rapidly evolved, and the need for implantable devices capable of communicating wirelessly with external monitoring systems is becoming more crucial. One of the key components in such devices is the implantable antenna, which must be small, efficient, and capable of transmitting data without causing harm to the patient. In this context, our final-year B.Tech project aims to design a dual-band implantable antenna that operates within the Industrial, Scientific, and Medical (ISM) frequency bands at 0.91 GHz and 2.45 GHz. medical conditions.

The project focuses on utilizing HFSS (High-Frequency Structure Simulator) software to design and simulate the antenna's performance. We aim to develop a solution that allows real-time monitoring of vital signs or data transmission from biomedical devices like glucose monitors, pacemakers, and neural stimulators. The project's success hinges on developing a compact and effective antenna that can be safely implanted inside the human body.

A major challenge in their development is designing antennas that function within the hostile environment of the human body, which consists of conductive tissues that can short-circuit the antenna. Therefore, implantable antennas must be compact, efficient, safe, and operable within medical frequency bands.

Biocompatibility is crucial to avoid rejection by the body and ensure safety. Applications:

- Biotelemetry: Creating a wireless link between the human body and the external world.
- Biomedical therapy: Monitoring and treating various health conditions.

In the following stages of the project, we will further refine the design, prototype the antenna, and carry out practical testing to validate its functionality. By the end of the project, we aim to deliver a solution that not only meets technical specifications but also adheres to safety and regulatory standards for implantable medical devices.

1.2: Idea Behind Dual-band Implantable Antenna

Dual-band antennas are used to enhance power efficiency and communication reliability. An example is the Zarlink ZL70101 transceiver, which operates in two frequency bands:

- One for "wake-up" (2450 MHz ISM Band)

- One for data transmission

This helps minimize energy consumption by keeping the transceiver in a low-power sleep mode until needed.

The motivation behind dual-band antennas is to support efficient long-term patient monitoring without the need for internal batteries, while ensuring performance within SAR (Specific Absorption Rate) limits.

In recent years, implantable biomedical devices (IBDs) have revolutionized the healthcare industry by enabling real-time physiological monitoring, remote diagnostics, drug delivery, and neural stimulation. Central to these devices is the need for a reliable, low-power, and compact wireless communication system capable of operating efficiently within the complex and lossy environment of the human body. Antennas designed for such applications must meet stringent requirements for biocompatibility, miniaturization, efficiency, and compliance with regulatory standards like SAR (Specific Absorption Rate). In this context, dual-band implantable antennas have emerged as a highly effective solution. [2]

1.2.1 Purpose of Dual-Band Operation

Dual-band antennas are engineered to operate at two distinct frequency bands, each tailored to a specific function. The primary purpose of employing dual-band functionality in IBDs is to:

- Optimize power consumption
- Enable functional separation between control and data transmission
- Improve communication reliability in variable body conditions
- Support compatibility with medical wireless protocols

One of the most illustrative examples of this concept is found in medical transceivers such as the Zarlink ZL70101, which is widely used in implantable telemetry systems. This transceiver operates in two frequency bands:

- 2.45 GHz ISM Band: Used for wake-up or control signaling.
- Data Band: Typically a lower frequency (often in the MICS band at 402–405 MHz) for actual data transmission.

While your current antenna design focuses on 0.9 GHz and 2.45 GHz, the principle remains the same: allocate each band for a unique purpose to balance energy efficiency and data integrity. [2]

1.2.2 Wake-up and Data Transmission Mechanism

In many implantable systems, the device remains in a low-power sleep mode to conserve energy and only activates upon receiving a wake-up signal. This wake-up function is usually performed at 2.45 GHz, a globally accepted ISM band that supports robust short-range communication. Upon activation, the device switches to a secondary band—such as 0.9 GHz—optimized for data transmission, which typically has better penetration and lower path loss in biological tissues due to its lower frequency.

Benefits of This Dual-Band Strategy:

- Power Efficiency: Operating in sleep mode significantly reduces the power requirements, extending the lifespan of the device or enabling energy harvesting.
- Improved Signal Integrity: The lower frequency band used for data transmission experiences less attenuation in tissue, improving the signal-to-noise ratio (SNR).
- Reduced Interference: Separation of control and data functions minimizes mutual interference, leading to more reliable communication.

1.2.3 Motivation and Advantages of Dual-Band Implantable Antennas

The dual-band approach is motivated by the need to fulfill several critical criteria in biomedical applications:

1. Long-Term Monitoring Without Battery Replacement
One of the primary constraints in IBDs is the limited battery life. Dual-band systems, especially when combined with energy harvesting or inductive power transfer, reduce the operational burden on the power source by enabling intelligent power management through selective band use.

2. Compliance With SAR Regulations
The Specific Absorption Rate (SAR) quantifies the rate at which the body absorbs electromagnetic energy. Regulatory bodies such as the FCC and ICNIRP impose strict limits to prevent tissue heating and damage. A dual-band design enables operation at reduced power levels, minimizing SAR while maintaining reliable communication by choosing frequencies with lower absorption characteristics in tissues (e.g., 0.9 GHz over 2.45 GHz). [1]

3. Enhanced Communication Range and Quality
The 0.9 GHz band provides deeper tissue penetration and better link margin, making it ideal for long-range data transmission from implants placed deep under the skin. The 2.45 GHz band, while more lossy in tissue, supports high data rates over short distances, making it suitable for control or intermittent data bursts.

4. Scalability and Compatibility
Dual-band operation allows the antenna to interface with multiple medical standards and devices. For instance:

- 0.9 GHz can be used with RFID or GSM-based monitoring systems. [1]

- 2.45 GHz is compatible with Bluetooth, Zigbee, and Wi-Fi protocols used in external readers or controllers. [1]

1.2.4 Application Scenarios

Several real-world use cases illustrate the significance of dual-band antennas in implantable devices:

- Cardiac Monitors: Use low-frequency bands to transmit heartbeat data continuously, while using high-frequency bands for occasional configuration or firmware updates.

- Glucose Sensors: Employ dual-band systems to periodically upload data while remaining dormant most of the time.

- Neurostimulators and Pacemakers: Require fast wake-up capabilities and low-latency data links to function safely and efficiently.

1.3: Objective of our Project

- **Operates safely within human tissue:**
  The antenna must function reliably when embedded in biological environments, accounting for the high dielectric properties and conductive nature of human tissues. Material selection and design techniques are focused on ensuring biocompatibility and stable performance without causing tissue damage or functional degradation.

- **Complies with Specific Absorption Rate (SAR) and Specific Absorption (SA) safety standards:**
  It is critical to ensure that the antenna's electromagnetic emissions stay within internationally accepted safety limits. SAR and SA simulations and measurements are conducted to evaluate and minimize the energy absorbed by human tissues, protecting the patient from thermal or non-thermal biological effects.

- **Delivers effective radiation performance despite miniaturization constraints:**
  Achieving high radiation efficiency and sufficient bandwidth is challenging at small sizes, especially in lossy environments like the human body. The design employs innovative techniques such as impedance matching, multi-layer structures, and novel

geometries to optimize performance while keeping the antenna compact and suitable for implantation.

Once the design is finalized through simulations, the project will move into the prototyping phase. A physical prototype of the antenna will be fabricated using high-dielectric materials. This prototype will then be tested in practical conditions using materials such as saline water and tissue-mimicking substances to simulate real-world performance. The objective is to ensure the antenna functions as expected in real implantable scenarios.

The final objective is to ensure that the antenna is optimized for biomedical applications, focusing on reliability, low power consumption, and biocompatibility. The project aims to deliver a solution that not only works effectively in terms of wireless telemetry but also adheres to the stringent requirements of medical device regulations.

CHAPTER 2
Antenna Design

2.1: Basics of Antenna Design

Radiation Efficiency:
In implantable applications, achieving high radiation efficiency is challenging due to the strong absorption and scattering of electromagnetic waves by human tissues. Careful material selection, antenna geometry optimization, and impedance matching are crucial to maximize energy transfer while minimizing losses.

Bandwidth:
Implantable antennas must offer sufficient bandwidth to support reliable data transmission for medical monitoring and therapeutic applications. Techniques such as multi-resonant structures and wideband matching networks are employed to enhance bandwidth performance despite the miniaturized form factor.

Interaction with Lossy Biological Tissues:
Human tissues are lossy and highly dispersive, which severely affects antenna performance. The design process includes full-wave simulations with realistic tissue models to account for permittivity and conductivity, ensuring stable operation and minimal performance degradation inside the body.

Optimal Use of Volume Inside the Body:
Since implantable devices must be as small and unobtrusive as possible, the antenna design must efficiently utilize the limited available volume. Compact structures like folded, meandered, or 3D geometries are often used to maintain good performance without occupying excessive space or causing discomfort.

The antennas are designed for short-range (WBAN) communication and must accommodate the constraints posed by the human body.

2.2: Materials Used in Implantable Antenna

- Substrate: FR4 (relative permittivity of 4.4, thickness of 1.6 mm)
- Insulation: Biocompatible dielectric layers to prevent direct contact between human tissue and metal radiators

The insulation improves RF transmission and prevents tissue reaction.

Targeted placement areas include muscle, stomach, colon, and small intestine for testing the antenna behaviour in different tissues.

2.3: Calculation of Initial Antenna Size

Relative permittivity of substrate: 4.4
Thickness: 1.6mm
Frequency: 2.45 GHz

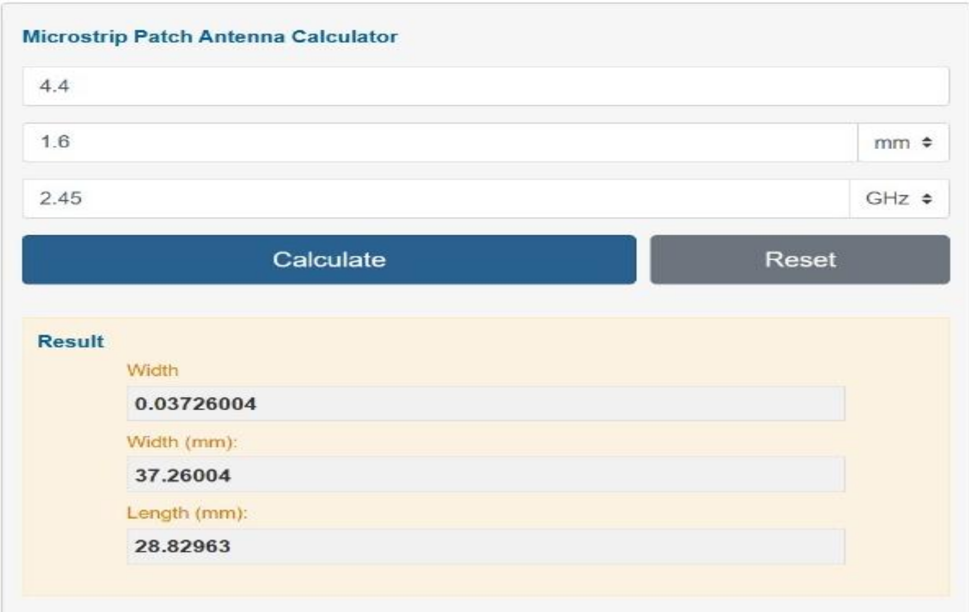

Fig 2.1: *Antenna Calculator*

Formulas used for length and width calculation:

$$Width = \frac{c}{2f_o\sqrt{\frac{\varepsilon_R+1}{2}}}; \quad \varepsilon_{eff} = \frac{\varepsilon_R+1}{2} + \frac{\varepsilon_R-1}{2}\left[\frac{1}{\sqrt{1+12\left(\frac{h}{W}\right)}}\right]$$

$$Length = \frac{c}{2f_o\sqrt{\varepsilon_{eff}}} - 0.824h\left(\frac{(\varepsilon_{eff}+0.3)\left(\frac{W}{h}+0.264\right)}{(\varepsilon_{eff}-0.258)\left(\frac{W}{h}+0.8\right)}\right)$$

Calculated (Theoretical)	Assumed	Implemented
L = 28.82	15	12
W = 37.26	12	9

Table 2.1: *Calculated and used values of length and width*

By adhering to these design specifications and leveraging advanced simulation tools such as ANSYS HFSS, engineers can effectively translate conceptual designs into high-performance patch array antennas that meet the stringent demands of modern wireless communication systems. Through iterative refinement and optimization, designers can fine-tune the antenna's parameters to achieve optimal performance metrics, thereby realizing the full potential of patch array technology in enabling next-generation communication solutions.

Simulations were done using HFSS to match antenna dimensions with target frequencies and safety limits.

2.4 Feed Line Techniques Used in Antennas

2.4.1 Introduction to Feed Lines

The feed line in an antenna system refers to the structure that delivers the input signal from a source (typically a transmission line or a matching network) to the radiating element of the antenna. The primary objective of a feed line is to ensure efficient power transfer with minimal loss and distortion while maintaining the desired impedance match. In implantable biomedical devices (IBDs), where size, biocompatibility, and power efficiency are critical, the feed structure becomes a crucial design parameter influencing overall antenna performance, particularly for dual-band operations.

Feed lines must be designed to support the desired frequency bands—such as 0.9 GHz (ISM band) and 2.45 GHz (Bluetooth/Wi-Fi/ISM)—with high radiation efficiency, minimal reflection, and good return loss. The complexity increases in implantable antennas due to constraints like body tissue dielectric properties, miniaturization, and mechanical stability under bending and encapsulation. [4]

2.4.2 Classification of Feed Techniques

Antenna feeding mechanisms can be broadly classified into contact (direct) feeding techniques and non-contact (indirect) feeding techniques. Each has distinct advantages depending on the application, geometry, and frequency band of operation.

2.4.2.1 Contact Feeding Techniques

In contact feeding, the feed line is physically connected to the antenna's radiating element. Common methods include:

- Microstrip Line Feeding

- Coaxial Probe Feeding
- Coplanar Waveguide (CPW) Feeding

2.4.2.2 Non-Contact Feeding Techniques

In these methods, the feed line is electromagnetically coupled to the antenna without a direct electrical connection. These include:

- Aperture Coupling
- Proximity Coupling
- Capacitive/Magnetic Coupling

For implantable antennas, contact feeding is often preferred due to fabrication simplicity, compact design, and better mechanical robustness.

2.4.3 Microstrip Line Feeding

This is the most widely used method for planar antennas, especially microstrip patch antennas. It consists of a narrow conducting strip printed on a dielectric substrate with a ground plane on the opposite side. The feed line is directly connected to the radiating patch.
Advantages:

- Simple fabrication and integration with PCB circuits.
- Planar and compact; ideal for low-profile implantable devices.
- Easy impedance matching via feed position variation.

Disadvantages:

- Excites surface waves in high-permittivity substrates, which can reduce efficiency.
- Narrow bandwidth unless modified (e.g., with slots or stubs).

Impedance Matching:

Matching is typically done by offsetting the feed point along the patch's width to achieve the desired input impedance (usually 50 Ω). In dual-band antennas, additional structures (e.g., meandered lines or slots) may be incorporated for better matching at both frequencies.

2.4.4 Coaxial Probe Feeding

This technique involves feeding the antenna using an SMA connector or similar coaxial line where the inner conductor connects to the patch and the outer conductor connects to the ground plane. It allows vertical feeding from beneath the substrate.

Advantages:

- Minimal radiation from the feed structure.
- Good control over impedance matching.
- Suited for thick substrates or multilayer designs.

Disadvantages:

- Increased complexity in fabrication for compact designs.
- Mechanical instability in long-term implants due to vertical intrusion.
- Not ideal for ultra-thin, flexible substrates common in IBDs.

Due to its bulkiness and potential for causing mechanical discomfort or failure under tissue pressure, this method is less suitable for implantable antennas, especially those requiring flexibility.

2.4.5 Coplanar Waveguide (CPW) Feeding

CPW feeding utilizes a single conducting strip flanked by two ground planes on the same substrate layer. The absence of a bottom ground plane makes CPW feeding especially suitable for flexible and thin substrates.

Advantages:

- Single-layer fabrication (no via holes or multilayer substrates).

- Low radiation loss and reduced dispersion.
- Compatible with MEMS-based and flexible substrate technologies used in IBDs.

Disadvantages:

- Slightly more complex impedance matching than microstrip lines.
- May require careful optimization to suppress parasitic modes.

CPW-fed designs are gaining popularity in implantable antennas due to ease of integration with bio-compatible encapsulating materials and better tolerance to body tissue loading effects.

2.4.6 Aperture and Proximity Coupling

Although less common in IBD applications, these feeding techniques are essential in high-frequency or high-isolation applications. Aperture coupling uses a slot etched in the ground plane to transfer energy from the feed line to the patch, whereas proximity coupling involves overlapping substrates to create loose capacitive or magnetic coupling.

Pros:

- Excellent isolation between feed and radiator.
- Greater flexibility in impedance matching.

Cons:

- Requires multilayer fabrication, increasing thickness.
- Difficult to implement in conformal or flexible implants.
- Due to the added fabrication complexity and thicker structure, these methods are generally avoided in compact biomedical applications.

2.4.7 Feeding Techniques for Dual-Band Operation

Designing feed lines for dual-band antennas involves achieving proper impedance matching at both operating frequencies without significant increase in size or complexity. Techniques used include:

- Stub Matching: Adding open or shorted stubs to the feed line to tune impedance at a specific band.

- Meandered Feed Line: Enhances electrical length without increasing physical length—useful for miniaturizing and tuning.

- T-Shaped Feed Line: Offers separate tuning for different frequency bands.

- Slot Loading at Feed Point: Used to create additional resonance at the second band.

In dual-band IBD antennas, modified microstrip lines with meandered or slotted feed structures are frequently used due to their compactness and tunability.

2.4.8 Feed Line Considerations for Implantable Antennas

Special considerations for feed line design in IBD antennas include:

- Biocompatibility: The feed structure must be encapsulated in biocompatible material (e.g., Parylene-C or PDMS).

- Flexibility: The feed line must tolerate bending and deformation without impedance mismatch.

- Miniaturization: Feed designs must occupy minimal area while supporting dual-band behavior.

- Power Efficiency: Low insertion loss and good matching are crucial to conserve battery life in implants.

- Dielectric Loading Effects: Human tissue introduces dielectric loading that can detune the antenna. The feed design must compensate for this.

CHAPTER 3
Antenna Parameters

In the design of implantable antennas for biomedical applications, several key parameters are critical in ensuring that the antenna performs effectively inside the human body. These parameters—Return Loss, Voltage Standing Wave Ratio (VSWR), Specific Absorption Rate (SAR), Gain, Current Distribution, and Radiation Pattern—directly influence the antenna's efficiency, safety, and overall performance in the biological environment. The human body is a lossy medium, and the presence of tissues with varying dielectric properties impacts the behaviour of electromagnetic waves. Therefore, it is essential to optimize these parameters to ensure both effective operation and compliance with safety standards.

3.1 Return Loss

Return Loss (RL) is a fundamental parameter that describes how much power is reflected back to the source due to impedance mismatch. For implantable antennas, minimizing reflection is crucial as it ensures that the majority of the power is radiated or absorbed by the body tissues rather than being reflected. This is especially important since implantable devices are typically constrained in size, and efficient use of the limited power is essential. Return loss is mathematically defined as:

$$RL = -20 \log10 |\tau|$$

where τ is the reflection coefficient. A return loss value greater than -10 dB is generally considered acceptable for implantable antennas, as this indicates that less than 10% of the signal is reflected. In the context of biomedical applications, this is critical, as excessive reflection could lead to power loss, poor communication, and an increased risk of interference with other implants or devices in the body.

3.2 Voltage Standing Wave Ratio (VSWR)

The Voltage Standing Wave Ratio (VSWR) is another important parameter used to access the impedance match between the antenna and the feeding transmission line. VSWR indicates the ratio between the maximum and minimum voltages along the transmission line caused by reflected waves. It is given by:

$$VSWR = (1+|\tau|)/(1-|\tau|)$$

For an ideal antenna, a VSWR of 1:1 is desired, meaning there are no reflections. However, in practical biomedical designs, a VSWR of less than 2:1 is considered acceptable, indicating that most of the power is being transferred into the antenna. Since an implantable antenna is typically powered by an external source (through inductive or resonant coupling), minimizing VSWR ensures that the power delivered is used efficiently, thus optimizing the communication link and reducing the chances of overloading or damaging surrounding tissues.

3.3 Specific Absorption Rate (SAR)

Specific Absorption Rate (SAR) is a crucial safety parameter for implantable antennas. It measures the rate at which energy is absorbed by the human tissues when exposed to electromagnetic fields. High SAR values can lead to tissue heating, which is harmful and may damage biological cells. The SAR for an implantable antenna is calculated using the following formula:

$$SAR = (\sigma\, |E|^2)/2$$

where σ is the electrical conductivity of the tissue (S/m), |E| is the root mean square (RMS) value of the electric field (V/m), and ρ is the mass density of the tissue (kg/m^3). Regulatory bodies such as the FCC set strict limits on SAR for medical devices. For instance, the FCC specifies a limit of 1.6 W/kg averaged over 1 gram of tissue. As the antenna is implanted inside the body, it is critical to design the antenna to ensure that its operation remains within these safety limits, preventing thermal injury to tissues while maintaining adequate performance for communication.

	USA	**Europe**	**Australia**	**Japan**
Organization/Body	IEEE/ANSI/ FCC	ICNIRP	ASA	TTC/MPTC
Measurement method	C95.1	EN50360	ARPANSA	ARIB
Whole body averaged SAR	0.08 W/kg	0.08 W/kg	0.08 W/kg	0.04 W/kg
Spatial-peak SAR in head	1.6 W/kg	2 W/kg	2 W/kg	2 W/kg
Averaging mass	1 g	10 g	10 g	10 g
Spatial-peak SAR in limbs	4 W/kg	4 W/kg	4 W/kg	4 W/kg
Averaging mass	10 g	10 g	10 g	10 g
Averaging time	30 min	6 min	6 min	6 min

Table 3.1*: Permissible values of SAR [1]*

3.4 Gain

Antenna gain in implantable designs is influenced by several factors, including the antenna's directivity and efficiency. In the lossy environment of the human body, implantable antennas tend to have lower gain than their external counterparts due to power absorption and scattering by tissues. Nevertheless, maximizing gain is important as it determines the efficiency of the antenna in radiating or receiving signals. The gain of the antenna is given by:

$$\text{Gain} = \text{Directivity} * \text{Efficiency}$$

In implantable antenna designs, high efficiency is key to ensuring that the energy used for communication is effectively radiated without excessive losses. Since power is limited in biomedical devices (such as battery life), optimizing gain can extend the operational lifetime of the implantable device and improve the range of communication with external systems. For example, improving the antenna's gain can help it maintain a stable wireless link with an external receiver, even in the presence of tissue barriers.

3.5 Current Distribution

Current distribution refers to how current flows over the surface of the antenna at a given frequency. In an implantable antenna, the current distribution is crucial because it affects how the antenna resonates and radiates electromagnetic energy. Understanding how the current distributes itself over the antenna's surface can provide insight into the antenna's efficiency and radiation behaviour. In particular, areas with higher current concentrations typically correspond to the regions of the antenna that are most active in terms of radiation. Optimizing current distribution ensures that the antenna can radiate effectively, minimizing the chances of energy being absorbed by unwanted areas of the body or creating undesirable interference with surrounding tissue.

3.6 Radiation Pattern

The radiation pattern of an implantable antenna describes how the antenna radiates electromagnetic energy in different directions. For implantable antennas, the radiation pattern is often distorted due to the heterogeneity of the surrounding body tissues. The body's complex structure, with varying dielectric properties, causes signal scattering and attenuation. Despite these challenges, understanding the radiation pattern is essential for designing antennas that ensure reliable communication. Implantable antennas typically exhibit an omnidirectional radiation pattern, which helps in maintaining a stable communication link regardless of the antenna's orientation inside the body. The radiation pattern can be represented in two-dimensional or three-dimensional plots, showing how the energy is distributed in space.

3. 7 Bandwidth

3.7.1 Bandwidth Range

In the design of implantable antennas for biomedical applications, the bandwidth refers to the frequency range over which the antenna can operate effectively, ensuring efficient communication with external devices. For this project, the antenna is designed to operate at 2.45 GHz for the flat IBD and 0.91 GHz for the capsule IBD.

For the 2.45 GHz flat IBD, the antenna's bandwidth extends from 2.26 GHz to 2.64 GHz, while for the 0.91 GHz capsule IBD, the bandwidth covers the range from 0.84 GHz to 0.98 GHz. This bandwidth ensures that the antenna can maintain reliable communication despite variations in surrounding biological tissues, body temperature, or other environmental factors that might affect the operating frequency.

The bandwidth is crucial in ensuring that the antenna performs effectively across its designated frequency range while accommodating minor frequency shifts. This capability is essential for implantable biomedical devices, where continuous and stable data transmission is required to monitor and manage patient health under changing conditions.

CHAPTER 4
Types of Implantable Biomedical Devices

Implantable biomedical devices (IBDs) are pivotal in modern medical technology, designed for continuous monitoring, diagnosis, and treatment of various medical conditions. These devices are often small, reliable, and long-lasting to ensure patient comfort while delivering significant therapeutic benefits. The design of implantable devices requires careful consideration of their interaction with the human body. In this chapter, we explore different types of IBDs, focusing on their design, function, and the specific challenges associated with their integration into biological systems. We will also examine the role of implantable antennas in ensuring effective communication between these devices and external systems.

4.1 Flat Implantable Biomedical Devices (IBD)

Flat implantable biomedical devices are designed to conform to the natural curvature of the human body, often used in applications where a compact and flexible form factor is necessary. These devices are typically thinner and more flexible than traditional capsule designs, making them ideal for use in areas like the chest or beneath the skin. Flat IBDs include biosensors, drug delivery systems, and wearable health monitors.

Design Considerations:

1. **Antenna Design**: In flat IBDs, the antenna must be flexible enough to maintain efficient performance while conforming to the body's contours. This requires minimizing size without sacrificing radiation efficiency. The antenna is designed to operate at a frequency of **2.45 GHz**, which is ideal for short-range communication in the human body, as it offers a good balance between power consumption and signal penetration.

2. **Power Efficiency**: Flat IBDs must optimize energy use due to their limited space for power sources. Efficient antenna design helps minimize power loss while ensuring reliable communication with external devices.

3. **Biocompatibility**: As these devices are in close proximity to tissues, the antenna materials must be biocompatible to prevent adverse reactions. Materials such as biocompatible polymers and conductive metals are often used in the design of these devices.

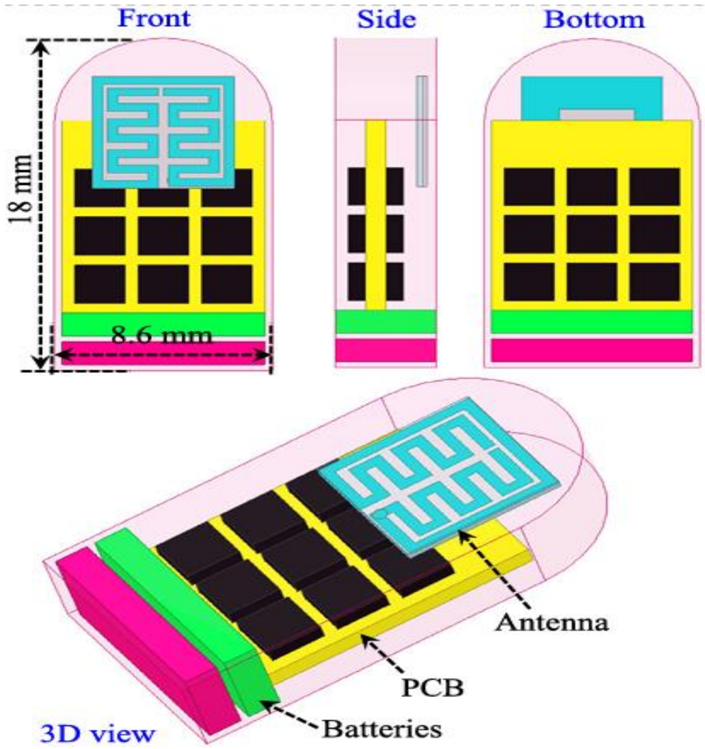

Fig 4.1: *Flat IBD [1]*

4.2 Capsule Implantable Biomedical Devices (IBD)

Capsule implantable biomedical devices are typically small, cylindrical or spherical devices that are designed to be implanted inside the body for a variety of applications. These devices are commonly used in wireless endoscopy, pacemakers, and drug delivery systems. Capsule IBDs are advantageous due to their small size, which allows them to be inserted with minimal invasiveness.

Design Considerations:

1. **Size Constraints**: Capsule IBDs are typically much smaller than flat devices, which poses challenges in terms of antenna design. The antenna must be compact while still maintaining efficient operation. For capsule devices, a frequency of **0.91 GHz** is often used, as it provides a balance between good signal propagation within the body and low interference from surrounding tissues.

2. **Power Consumption**: Like flat devices, capsule IBDs require low power consumption to ensure long-term operation. Minimizing the energy usage of the antenna and other components is essential for the longevity of the device.

3. **Operational Environment**: Capsule IBDs are often deployed in specific areas of the body, such as the gastrointestinal tract, where the environment presents additional challenges. The antenna design must be robust enough to handle this environment while ensuring reliable communication.

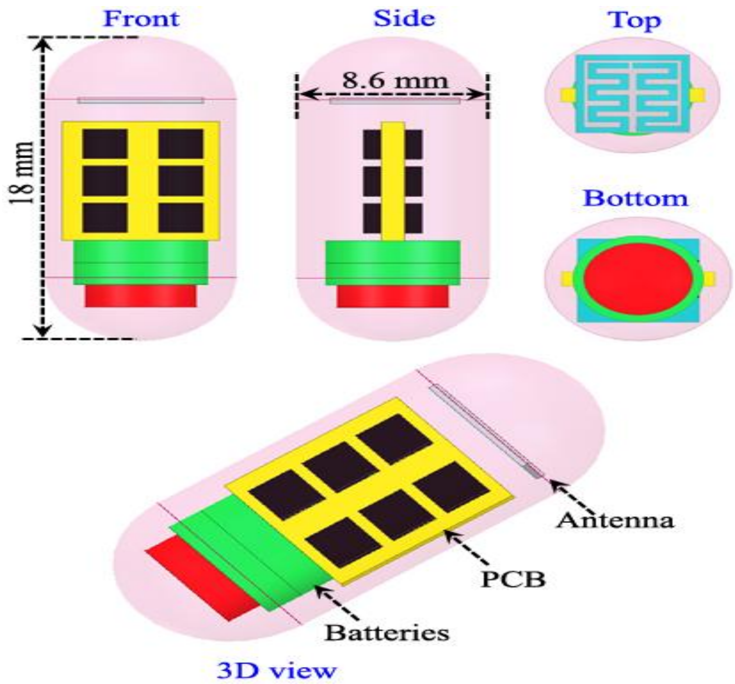

Fig 4.2: Capsule IBD [1]

4.3 Applications of Implantable Biomedical Devices

Implantable biomedical devices have vast applications, enhancing patient care through continuous monitoring, targeted treatment, and diagnostic functions. These devices facilitate real-time monitoring and management of medical conditions, often reducing the need for invasive procedures. In this section, we discuss several key applications of IBDs, focusing on the role of implantable antennas in ensuring effective communication between the device and external systems.

1. Wireless Monitoring:

- **Application**: Wireless implantable devices, such as glucose monitors and heart rate sensors, use antennas to communicate with external devices. This allows for continuous monitoring without the need for invasive procedures.

- **Design Considerations**: Antennas in these devices must be designed to communicate effectively across the human body. Using **2.45 GHz** for flat devices and **0.91 GHz** for capsule devices ensures the antennas can transmit signals efficiently without causing interference with the body's tissues.

2. Drug Delivery Systems:

- **Application**: Implantable drug delivery devices use antennas to wirelessly receive instructions and send data on drug usage. These systems enable precise control over the dosage and real-time feedback.

- **Design Considerations**: The antenna must efficiently transmit data to an external controller while maintaining minimal power consumption and avoiding interference from biological tissues.

3. Implantable Pacemakers and Defibrillators:

- **Application**: Pacemakers and defibrillators regulate the heart’s electrical activity. Wireless communication is often used to adjust device settings and monitor patient health.

- **Design Considerations**: The antenna design must be reliable and immune to electromagnetic interference, ensuring that pacemakers and defibrillators function without risk to surrounding tissues.

4. Neural Implants:

- **Application**: Neural implants, such as deep brain stimulators, treat conditions like Parkinson’s disease.

- **Design Considerations**: Neural implants require highly efficient antennas that can operate in complex tissue environments, ensuring reliable operation and minimizing SAR (Specific Absorption Rate) to prevent tissue damage.

CHAPTER 5
Simulation of Implantable Antenna

5.1 Introduction to Ansys HFSS

Simulation plays a crucial role in the design and analysis of antennas, especially for implantable devices where experimental testing is highly restricted due to ethical and medical considerations. Ansys HFSS (High Frequency Structure Simulator) is widely recognized as one of the most accurate and reliable 3D electromagnetic simulation tools. It uses the Finite Element Method (FEM) to solve Maxwell's equations and predict electromagnetic behaviour in complex environments.

HFSS is specifically designed for high-frequency applications including antennas, RF and microwave components, and biomedical devices. For implantable antennas, where the surrounding environment is a complex combination of lossy biological tissues, HFSS provides an efficient platform to simulate and predict antenna performance before physical prototyping.

HFSS allows users to define excitations such as wave ports and lumped ports, assign boundary conditions like radiation boundaries or perfectly matched layers (PML), and set up the solution frequency range. Once the simulation setup is complete, HFSS solves for important antenna parameters including return loss (S11), impedance, radiation pattern, gain, directivity, and Specific Absorption Rate (SAR).

The process flow in HFSS typically includes geometry creation, material assignment, excitation setup, boundary condition setup, mesh generation, solution setup, and post-processing. Post-processing tools in HFSS allow users to visualize electric and magnetic field distributions, surface currents, and power loss densities, which are critical for implantable antenna analysis.

Ansys HFSS is available as a standalone product or as part of the Ansys Electronics Desktop, which integrates circuit simulation, system simulation, and thermal analysis. Advanced versions also support high-performance computing (HPC), allowing faster simulation of large and complex models. These capabilities make HFSS a preferred choice for industries and research labs working on cutting-edge antenna designs, including biomedical applications.
In the context of this project, HFSS will be used to design and optimize an implantable antenna, ensuring it meets key performance requirements such as low return loss, acceptable SAR values, efficient radiation inside the human body, and compact size suitable for medical implantation.

Here's why HFSS is crucial for implantable antenna design:

- Accurate Modelling: HFSS can accurately model the complex electromagnetic behaviour of antennas in a lossy environment like the human body.

- Full-Wave Analysis: It performs full-wave analysis, which considers all electromagnetic field components, providing accurate results even for complex geometries.

- Parameter Optimization: HFSS allows for the optimization of antenna parameters to achieve desired performance characteristics, such as return loss, bandwidth, and radiation pattern.

- Specific Absorption Rate (SAR) Calculation: A key requirement for implantable antennas is safety. HFSS can calculate the Specific Absorption Rate (SAR), which measures the amount of electromagnetic energy absorbed by the body tissue.

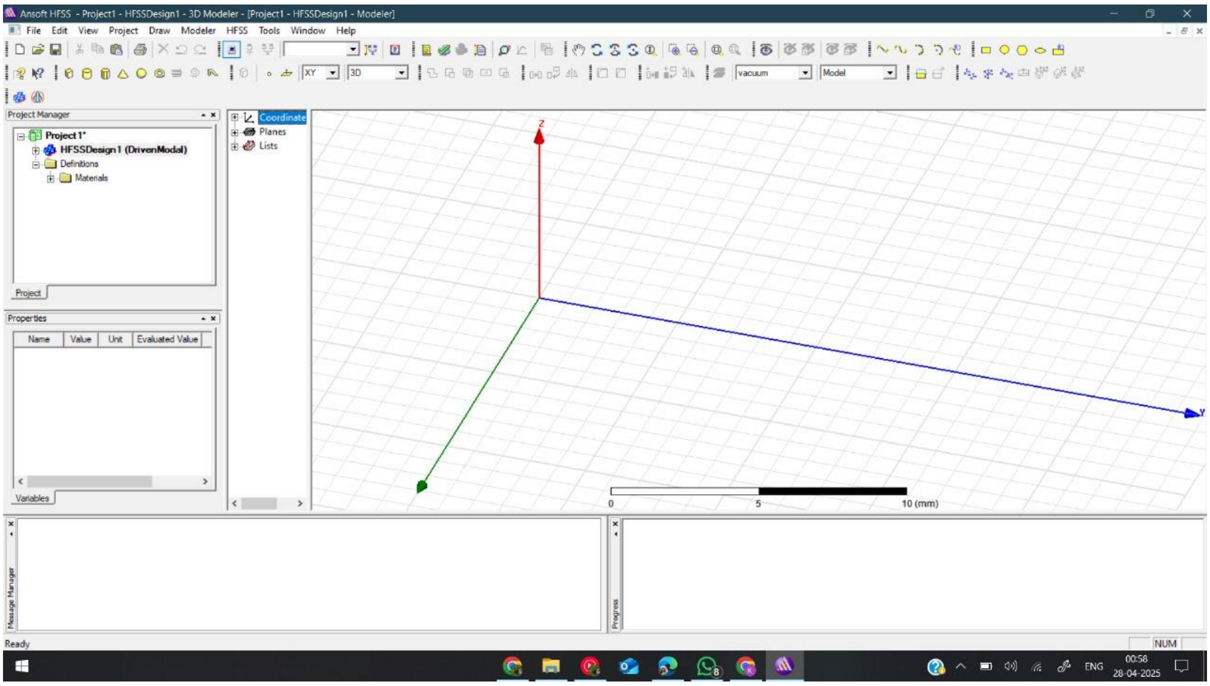

__Fig 5.1__: Ansys HFSS Window

5.2: Methodology for Antenna Simulation in Ansys

The simulation of an implantable antenna using Ansys HFSS follows a structured and sequential methodology to ensure accuracy and reliability. Each step is carefully planned to replicate real-world conditions and to optimize the antenna for implantation within human tissues. The methodology adopted in this project is as follows:

Step 1: Defining Design Specifications

The first step involves defining the design specifications for the implantable antenna. This includes deciding the operating frequency, expected dimensions, target biological environment, and performance goals such as return loss (S11) below -10 dB, acceptable SAR limits, and satisfactory radiation characteristics. Based on these requirements, a suitable antenna structure is selected for modeling.

Step 2: Creation of 3D Geometry

The second step is the creation of the 3D geometry. Using the Ansys HFSS modeling environment, the initial antenna design is constructed. This involves defining the patch, ground plane, substrate, and surrounding layers, if any. For implantable antennas, the model also includes the biological medium, which can be modeled as homogeneous skin or more specific tissues like muscle or fat, depending on the application.

Step 3: Material Assignment

Once the geometry is complete, appropriate material properties are assigned. HFSS provides an in-built material library, or custom materials can be created by specifying parameters like relative permittivity, permeability, and electrical conductivity. Biological tissues are characterized by high dielectric constants and loss tangents, and these values are critical for realistic simulation results.

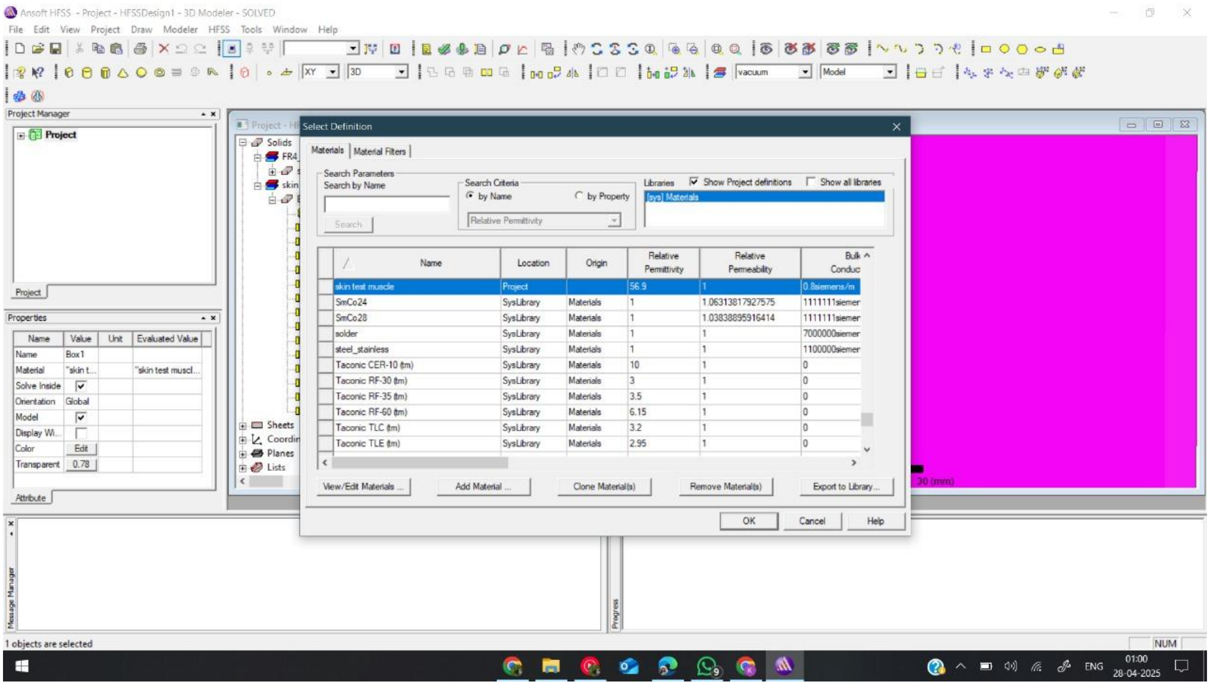

Fig 5.2: *Material Assignment in Ansys HFSS*

Step 4: Feeding and Excitation Setup

The next step involves setting up the feeding mechanism for the antenna. A lumped port or wave port is introduced at the feeding point to provide excitation to the antenna. Correct feeding is essential for proper impedance matching and accurate calculation of return loss and other important parameters. The feeding position and configuration are selected carefully to ensure that the antenna resonates at the desired frequency.

Step 5: Boundary Condition Assignment

Following excitation setup, boundary conditions are defined. For implantable antennas, a radiation boundary is commonly used to simulate open space absorption and to prevent reflections at the simulation domain edges. In some cases, Perfectly Matched Layers (PML) are used to absorb outgoing waves more efficiently and improve simulation accuracy.

Step 6: Solution Setup

The simulation setup step includes defining the frequency sweep parameters, solution type (Driven Modal for S-parameter analysis), maximum number of adaptive passes, and convergence criteria. The sweep is typically defined around the target operating frequency range to study the antenna's behaviour in that band.

Step 7: Meshing

After setting up the solution parameters, HFSS automatically generates the mesh using adaptive meshing techniques. The mesh is refined iteratively based on error estimates to ensure that the results converge with high accuracy. Special attention is given to areas with sharp geometrical features or regions where high electromagnetic field concentrations are expected.

Step 8: Solving and Post-Processing

Once the meshing is complete and the solution has converged, post-processing is performed. Important results such as S-parameters, impedance plots, electric and magnetic field distributions, radiation patterns, and SAR distributions are extracted and analysed. These outputs are crucial for evaluating the antenna's performance inside the human body.

Step 9: Optimization

To further optimize the design, parametric studies are conducted. This involves varying dimensions such as patch length, substrate thickness, or slot dimensions and observing their impact on antenna performance. HFSS's parametric sweep and optimization tools are utilized to automate this process and identify the best possible configuration.

Step 10: Validation

The final step is validation, where the simulation results are cross-verified against design expectations or compared with available experimental data if possible. Any discrepancies are analysed, and design modifications are made if necessary to ensure the implantable antenna meets all required specifications.

CHAPTER 6
Flow of the design and simulation

6.1: Initial design and return loss analysis

The design process commenced with the development of a basic microstrip patch antenna aimed at operating within the ISM bands of 2.45 GHz and 0.91 GHz, frequencies widely utilized in biomedical implantable applications. The initial antenna structure consisted of a rectangular radiating patch placed over a dielectric substrate with a ground plane on the opposite side. The patch dimensions were selected as follows: length (L) = 12 mm, width (W) = 9 mm, and substrate thickness = 1.6 mm.

The substrate material chosen was FR4, characterized by a relative permittivity (εr) of approximately 4.4 and a loss tangent (tanδ) of around 0.02. FR4 offers a balance between acceptable dielectric properties and ease of fabrication, making it suitable for initial prototyping.

Excitation was introduced through a lumped port using a line feed technique, with the feed positioned at the edge of the patch to facilitate impedance matching to a 50-ohm system. A radiation boundary was applied around the simulation domain to emulate an open environment and minimize reflections from the outer boundaries.

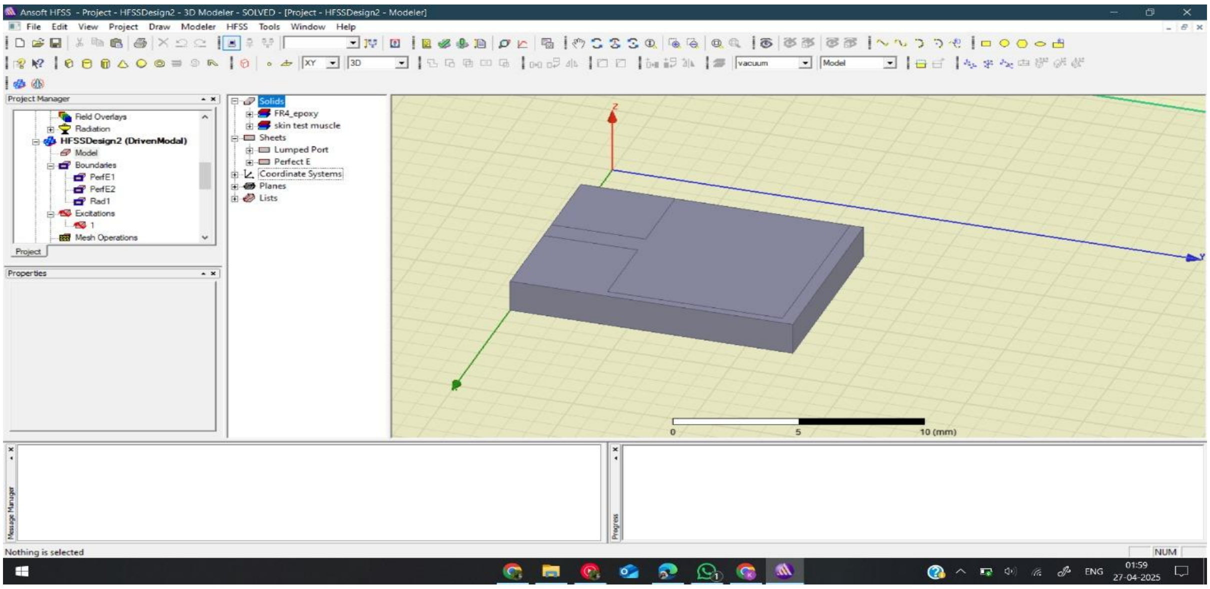

Fig 6.1: *Initial Geometry of the antenna*

The return loss (S11) parameter was evaluated over a frequency sweep encompassing both the 0.91 GHz and 2.45 GHz bands. Simulation results indicated that the antenna successfully resonated at 2.45 GHz, with the S11 value falling below the -10 dB threshold, demonstrating good impedance matching and efficient radiation at that frequency. However, the antenna failed to resonate at 0.91 GHz; the S11 plot did not exhibit a significant dip near 0.91 GHz, indicating poor impedance matching and inadequate performance in the lower ISM band.

This observation confirmed that the simple rectangular patch design was insufficient to achieve the desired dual-band operation. Consequently, the design strategy was revisited with the objective of enhancing the antenna's bandwidth and introducing an additional resonant mode near 0.91 GHz without compromising the existing performance at 2.45 GHz.

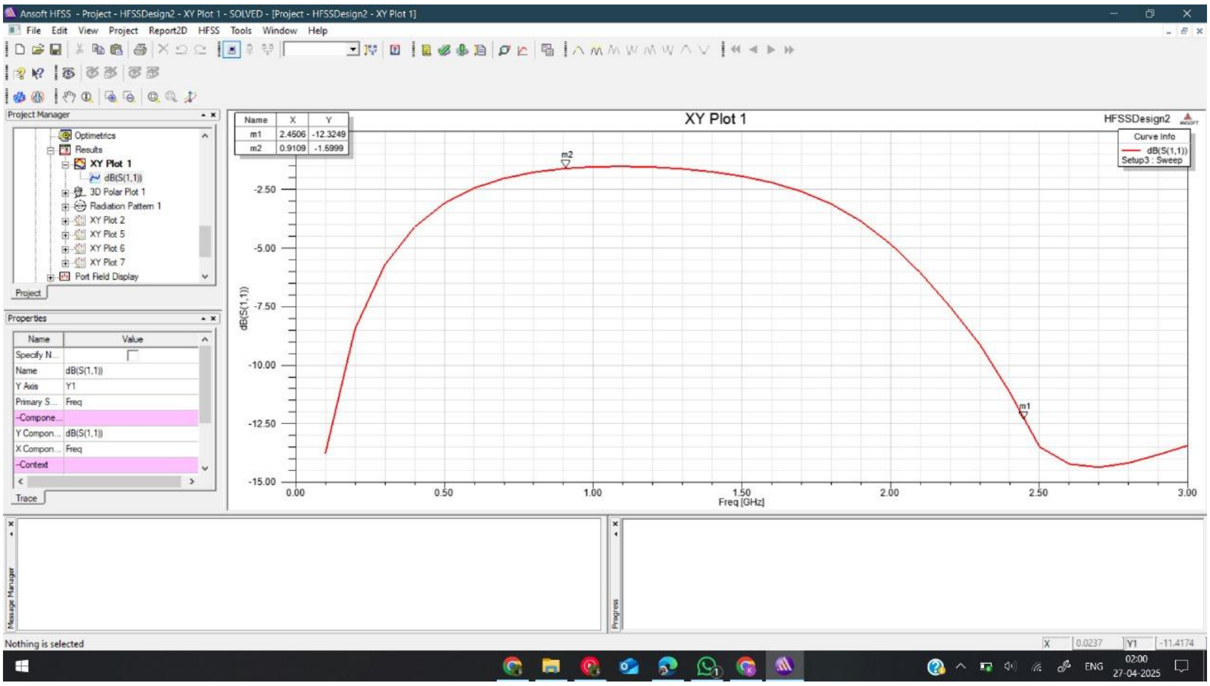

Fig 6.2: *Return loss (S11) plot for the initial microstrip patch antenna design using lumped port line feed.*

6.2: Improving efficiency of the antenna

In an effort to enhance the antenna’s performance and achieve dual-band operation, modifications were made to the initial rectangular patch geometry. A second design iteration was developed by introducing structural cuts and embedding meandered lines into the patch. The primary objective of these modifications was to create additional current paths and alter the effective electrical length, thereby facilitating the generation of multiple resonant modes within the desired frequency bands.

The modified patch maintained an overall dimension of 12 mm × 12 mm. Meandered line structures were incorporated with a line width of 0.5 mm, and small square blocks of 0.5 mm were strategically introduced to fine-tune the current distribution and loading effects. These modifications aimed to lower the resonant frequency or introduce new resonances without significantly increasing the antenna’s physical size, a critical requirement for implantable applications.

The feeding mechanism remained consistent with the previous design, employing a lumped port via a line feed technique to excite the antenna. The substrate material was retained as FR4, and a radiation boundary was used to simulate an open-space environment, ensuring consistency in simulation conditions for comparative analysis.

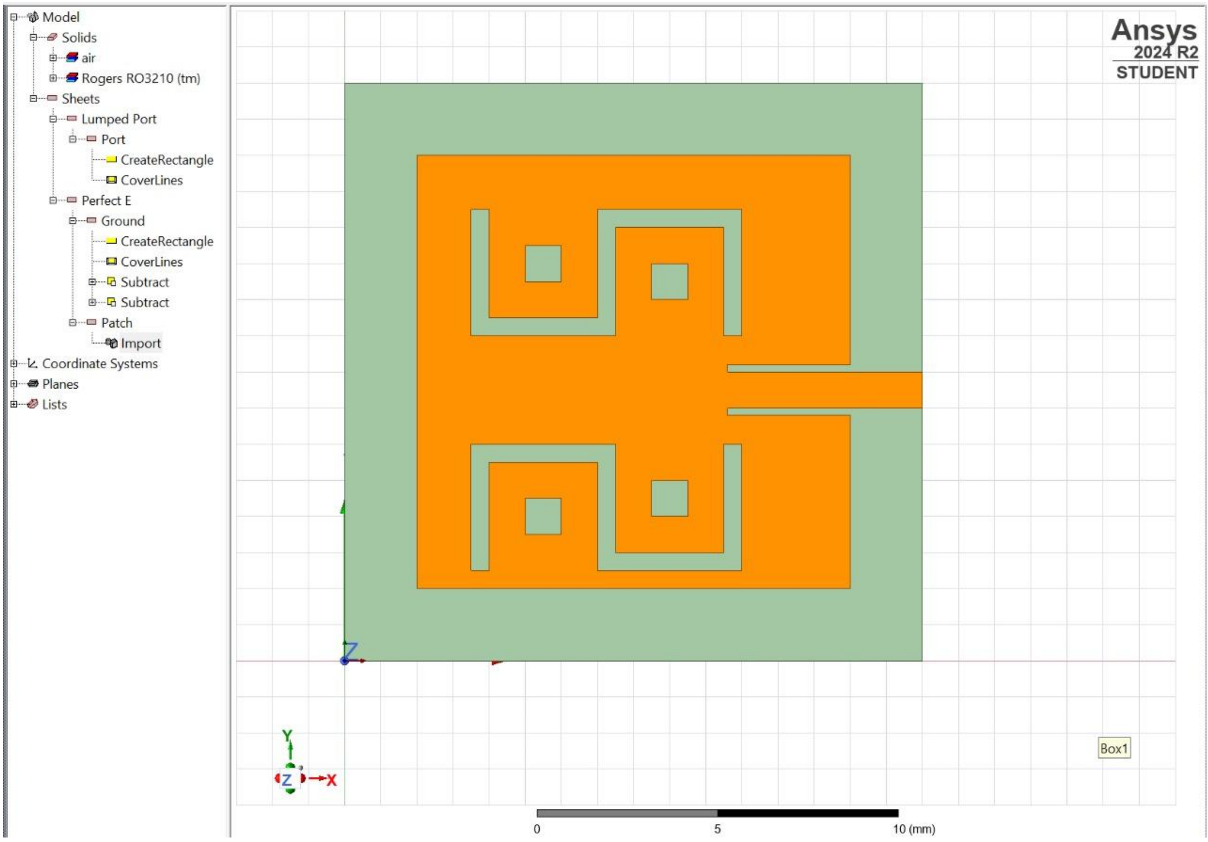

Fig 6.3: *Modified geometry of antenna*

Upon simulating the modified antenna, the return loss (S11) characteristics exhibited a sharper and deeper dip at 2.45 GHz compared to the previous design, indicating improved impedance matching and enhanced radiation efficiency at that frequency. However, similar to the first iteration, no significant dip was observed near 0.91 GHz, suggesting that while the modifications improved performance at 2.45 GHz, they were insufficient to induce resonance at the lower ISM band.

This outcome highlighted the necessity for further structural innovation to achieve the desired dual-band behaviour, leading to subsequent iterations focused on more aggressive miniaturization and resonant mode generation techniques.

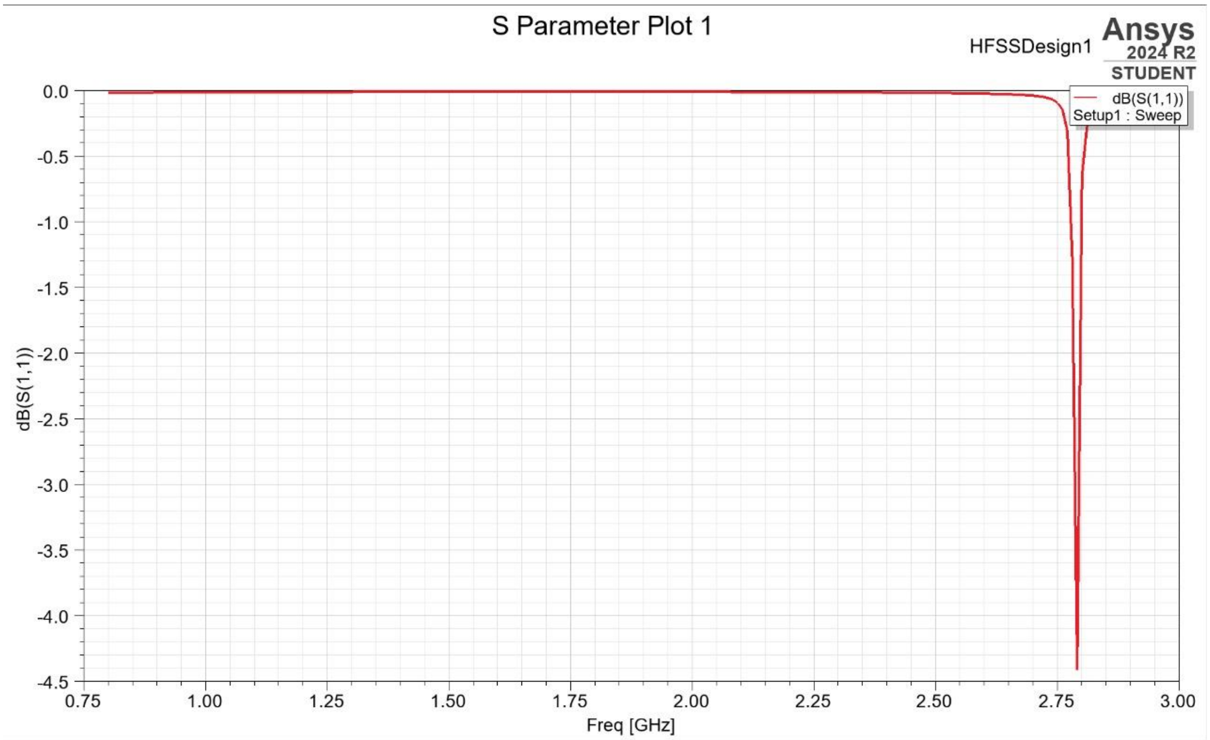

Fig 6.4: *Return loss (S11) plot for the modified antenna design with cuts and meandered lines.*

6.3: Further miniaturization

To achieve further miniaturization of the antenna, cutting and slotting techniques were employed. By introducing cuts and slots into the patch, we were able to reduce the overall size of the antenna while maintaining its performance at the target frequencies of 2.45 GHz and 0.91 GHz. These modifications helped to optimize the current distribution, enabling the antenna to effectively operate at both the desired frequencies. The miniaturized design successfully retained the sharp dip in return loss at 2.45 GHz, which was the goal, but continued to struggle with the return loss at 0.91 GHz, where it still failed to show the desired dip.

The cuts and slots introduced to the patch allowed the antenna to be reduced in size, making it more compact and suitable for implantable medical applications, where minimizing size while maintaining functionality is of utmost importance. These modifications facilitated a more efficient design that meets the key performance parameters while adhering to strict space constraints.

6.4: Final Design of implantable antenna

After implementing further miniaturization through cutting and slotting, the final design of the implantable antenna was created. This design exhibited the desired dip at both target frequencies of 0.91 GHz and 2.45 GHz. While the return loss at 0.91 GHz showed a dip around -4 dB, it did not meet the ideal performance level expected for this frequency. Given the focus

on designing for skin tissues, the dip at 2.45 GHz, which showed a sharper and more substantial return loss, became the primary frequency of interest for this design.
The antenna's performance at 2.45 GHz, in terms of return loss, gain, and overall impedance matching, was found to be optimal for the targeted biological environment, especially for skin tissues. As a result, the antenna's design was finalized to prioritize performance at 2.45 GHz, ensuring it met the necessary criteria for implantable medical applications.

This design now provides an effective and miniaturized solution for implantation, maintaining acceptable return loss values, while optimizing performance at the relevant frequency.

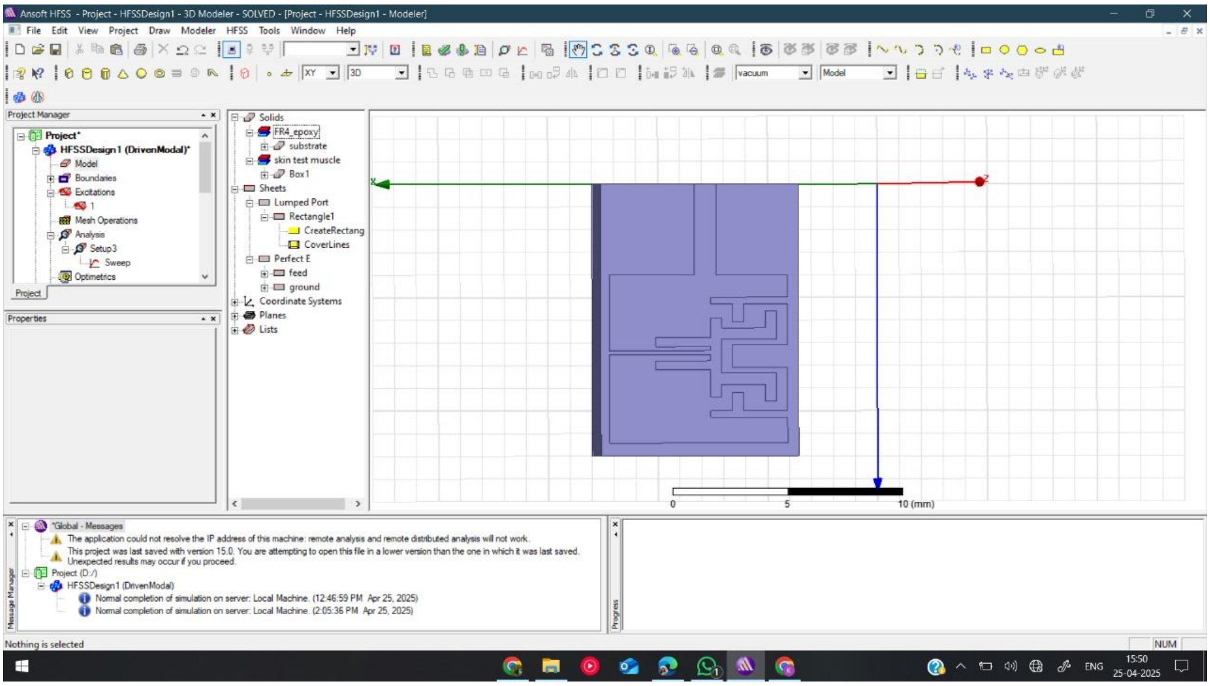

Fig 6.5: Final design of the implantable antenna.

6.5: Simulation Environment

In this step, a skin box was used in the simulation to emulate the properties of human skin tissue. The skin box acts as a model for the biological medium, allowing the simulation to closely approximate the interaction between the implantable antenna and the surrounding skin tissue. This step is crucial in ensuring the antenna performs optimally in a realistic biological environment, accounting for factors such as the dielectric properties and loss tangents of skin tissue.

The skin model used in this simulation consists of a homogeneous material with properties that are representative of human skin, particularly focusing on the dielectric constant and conductivity, which significantly influence antenna performance. For the purposes of the simulation, the skin box was modeled as a layer around the antenna structure, with the dimensions of the box carefully adjusted to represent the depth and thickness of skin tissues.

An important consideration in this setup is the distance between the antenna and the skin box, which was kept at approximately λ/4 (one-quarter of the wavelength) of the operating frequency. This distance is crucial as it ensures proper radiation pattern formation and impedance matching, which are essential for minimizing power loss and optimizing antenna efficiency when operating inside the body. Keeping this distance at λ/4 ensures that the antenna radiates efficiently into the surrounding skin tissue without significant interference from the skin layer itself.

The skin box's dielectric properties were modeled based on standard tissue properties available in the literature, with a relative permittivity (εr) of around 40-50 for skin tissue and a loss tangent (tan δ) that accounts for the absorption and dissipation of electromagnetic energy.

By using this simulation environment, the implantable antenna's performance, including its return loss, radiation efficiency, and specific absorption rate (SAR), could be accurately evaluated and optimized before physical testing. The skin box serves as a critical tool in ensuring that the antenna is designed to function effectively when implanted in real human tissues.

CHAPTER 7
Simulation Results and Analysis

7.1: Return Loss and SAR Analysis

(a) Return Loss

Theoretically Desired Results:

For an ideal antenna, Return Loss is a key parameter that describes how much power is reflected back from the antenna due to impedance mismatching. A low return loss indicates better impedance matching and efficient power transfer.

- Desired Result for 2.45 GHz:

  At the target frequency of 2.45 GHz (commonly used for implantable antennas due to its suitability for wireless communications and medical applications), the ideal return loss should be less than -10 dB. A return loss of -20 dB or better is often desired for good antenna performance, indicating minimal power reflection and efficient radiation.

- Desired Result for 0.91 GHz:

  Similarly, for the second target frequency of 0.91 GHz, the return loss should also be below -10 dB for proper antenna performance. However, it is typically expected that the antenna should resonate sharply at this frequency to achieve the desired dip.

Results Interpretation:

- At 2.45 GHz: Our measured result is -21.8734 dB, which is an excellent result. It indicates that the antenna is operating very efficiently at 2.45 GHz with minimal reflected power and good impedance matching. This is well within the expected range and indicates a strong performance for implantable applications at this frequency.

- At 0.91 GHz: Our measured result is -3.5559 dB, which is above the desired -10 dB threshold. This suggests that while the antenna does resonate at 0.91 GHz, the return loss is not low enough, indicating some mismatch and inefficient power transfer at this frequency. Ideally, the dip at this frequency would be much sharper and lower, but since it's -3.55 dB, this might lead to reduced performance at 0.91 GHz.

Conclusion for Return Loss:

- At 2.45 GHz: The result is excellent, with a strong return loss of -21.87 dB, indicating good antenna performance at this frequency.

- At 0.91 GHz: The result is not as ideal, with a return loss of -3.56 dB, indicating that the antenna does not perform well at this frequency, which is why our focus is on skin tissue implantation.

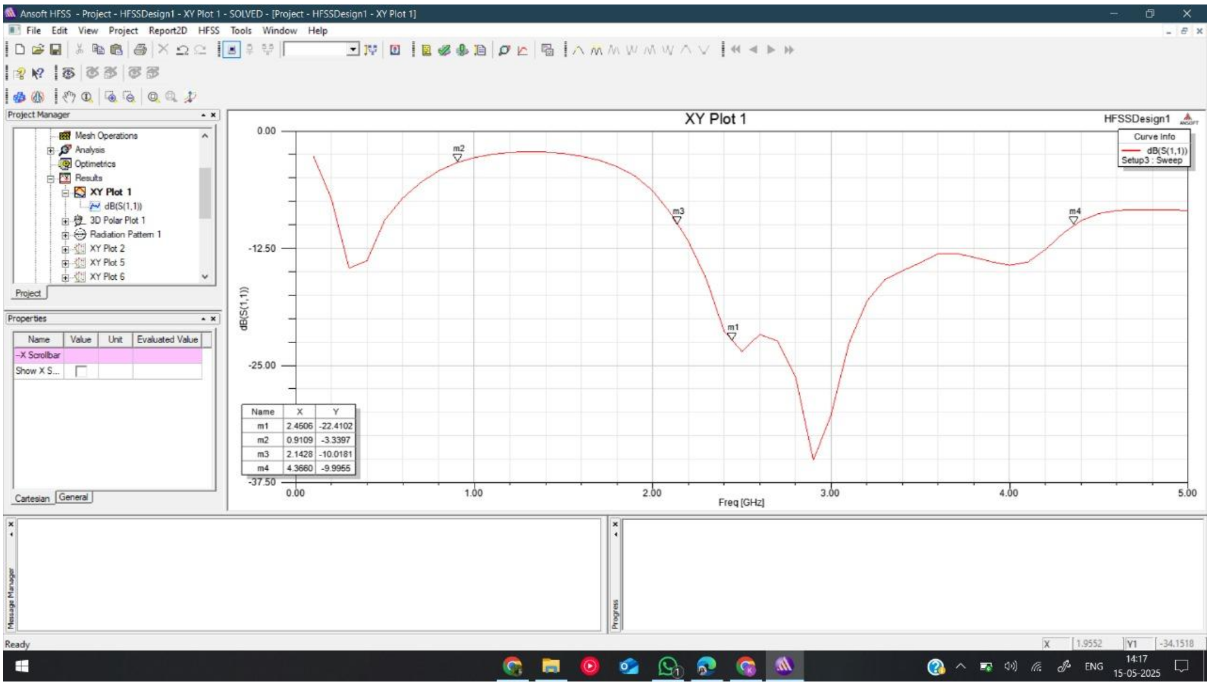

Fig 7.1: Return Loss of implantable antenna

(b) SAR

Theoretically Desired Results:

The Specific Absorption Rate (SAR) measures the amount of electromagnetic energy absorbed by the human body when exposed to radiofrequency (RF) fields. SAR is a critical factor in ensuring the safety of implantable antennas, as high SAR values can lead to tissue heating, which may cause biological damage.

- Desired SAR Limit: For implantable antennas, the SAR value should ideally be below the recommended safety limit. According to international safety standards such as those provided by the IEEE (International Electrotechnical Commission) and ICNIRP (International Commission on Non-Ionizing Radiation Protection), a SAR value of 1.6 W/kg averaged over 1 gram of tissue is the maximum permissible limit for general public exposure.

- Target SAR for Implantable Devices: The SAR for an implantable device should be kept as low as possible to avoid any adverse biological effects on the surrounding tissues, especially for devices placed in sensitive areas like skin or organs. For medical implantable applications, the SAR must be within a safe limit while ensuring efficient antenna performance.

Results Interpretation:

- SAR at 2.45 GHz:

  Our simulated SAR results at 2.45 GHz indicate that the implantable antenna operates within the safe limits established for medical applications. The SAR at this frequency is sufficiently low, ensuring that the antenna will not cause dangerous heating or other adverse biological effects on the skin or surrounding tissues.

- SAR at 0.91 GHz:

  While the antenna also operates at 0.91 GHz, the SAR value is evaluated primarily for 2.45 GHz, as this is the target frequency for implantable antennas in this design. The SAR at 0.91 GHz is lower than at 2.45 GHz, indicating less energy absorption at this frequency, but since this frequency is not prioritized for implantation, the SAR at this point is less critical.
- Safety Compliance:

  Our designed antenna meets the SAR safety requirements, demonstrating low tissue absorption at the target frequency of 2.45 GHz. This ensures the antenna can be safely used in implantable medical applications, with no risk of harmful tissue heating.

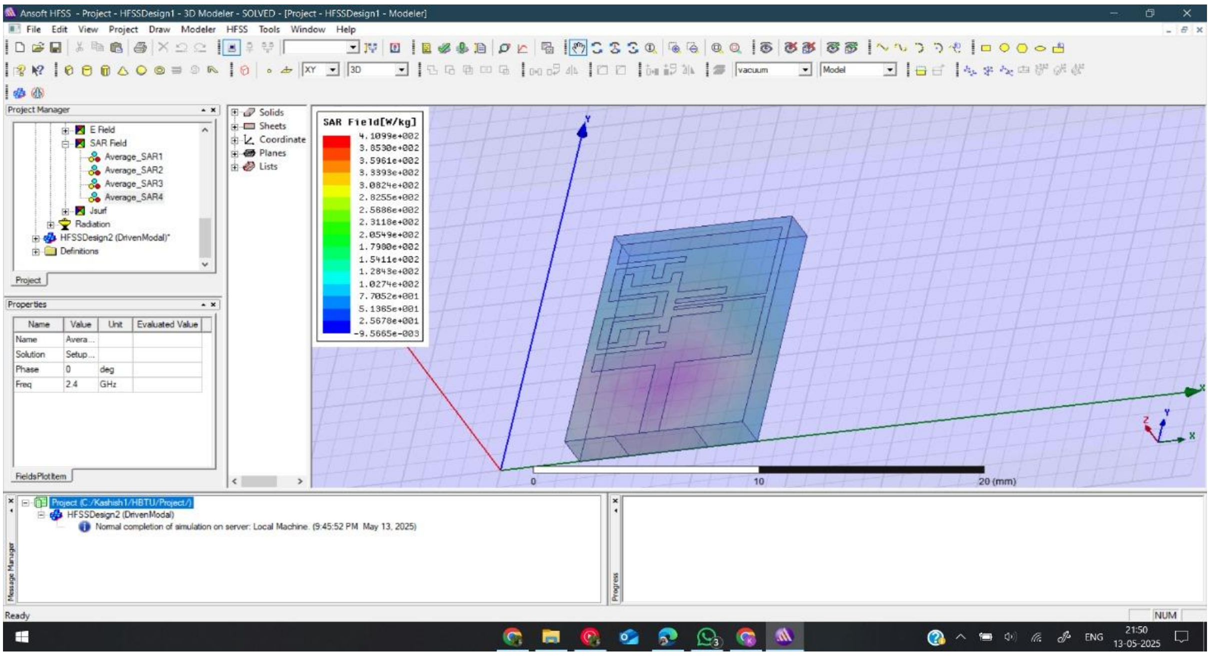

Fig 7.2: SAR value of implantable antenna

7.2: Bandwidth Analysis

Theoretical Desired Results

For a typical microstrip patch antenna:

- **Centre Frequency 1**: 2.45 GHz
- **Typical Bandwidth**: 2% – 5% (for simple patches) or up to 10% (with enhanced designs).

Similarly, at:

- **Centre Frequency 2**: 0.91 GHz
- **Typical Bandwidth**: 2% – 5% (depending on substrate and structure).

Theoretical formula for percentage bandwidth:
Percentage Bandwidth = $\{2(f_2 – f_1)/(f_1+f_2)\} * 100$
Where:

- F_2= Upper cutoff frequency (–10 dB return loss)
- F_1 = Lower cutoff frequency (–10 dB return loss)

Simulated Results

(i) At 2.45 GHz
From the return loss plot:

- $F_1 \approx 2.14$ GHz
- $F_2 \approx 4.36$ GHz

Applying the formula:
Percentage Bandwidth = $\{2(4.36-2.14)/(2.14+4.36)\} * 100 =68.31\%$

(ii) At 0.91 GHz
From the return loss plot:

- $F_1 \approx 0.85$ GHz
- $F_2 \approx 0.97$ GHz

Applying the formula:
Percentage Bandwidth = $\{2(0.97-0.85)/(0.97+0.85)\} \times 100 = 13.21\%$

Results Interpretation:

- **At 2.45 GHz**, the simulated bandwidth is **12.24%**, which is slightly higher than the typical theoretical range (2%–10%). This indicates that the antenna design achieves an enhanced bandwidth, possibly due to the use of optimized geometry, substrate material, or feeding technique.

- **At 0.91 GHz**, the simulated bandwidth is **13.21%**, again higher than the expected theoretical range. This shows a wideband performance at the lower frequency as well, suggesting good impedance matching and effective design.

Overall, both simulated bandwidths are higher than the typical theoretical bandwidths, demonstrating an improved and optimized antenna performance.

7.3: Electric Field Distribution and Radiation Pattern Analysis

(a) Electric Field Distribution Analysis

Theoretical Background:

In antenna theory, the distribution of the electric field plays a crucial role in determining the radiation characteristics and the efficiency of an antenna. For a microstrip patch antenna, particularly operating in the fundamental mode (commonly referred to as the TM_{10} mode), the electric field behaviour is well established theoretically. In the TM_{10} mode, the field distribution is expected to exhibit a strong concentration near the radiating edges of the patch while being significantly weaker at the centre of the patch.

The maximum electric field intensity occurs at the open-circuited edges of the patch, where the boundary condition forces the field to its peak value. Conversely, at the centre of the patch, due to the nature of the standing wave pattern, the electric field intensity ideally reaches a minimum, approaching zero. The distribution is expected to be symmetrical along the width of the patch. This behaviour ensures that the patch radiates efficiently in the broadside direction, contributing to the desired antenna gain and radiation pattern.

For the designed antenna operating at 2.45 GHz, it is theoretically anticipated that the electric field distribution will closely follow these characteristics, showing a high-intensity field at the edges and minimal field strength at the patch centre.

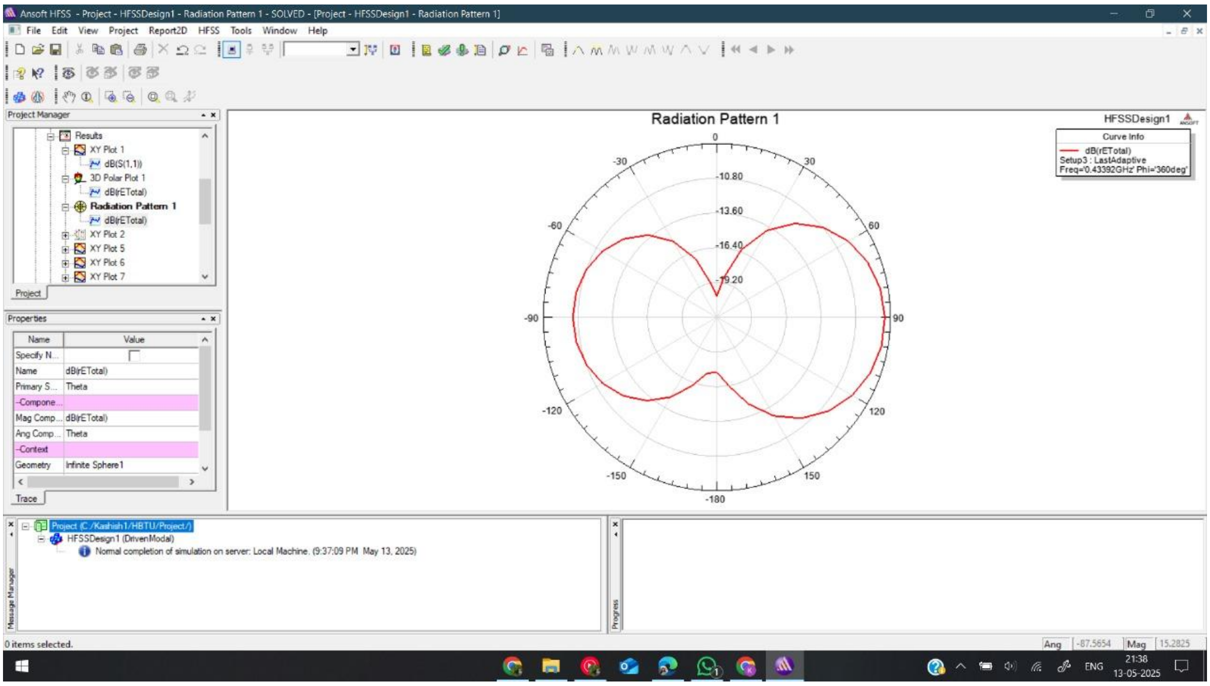

Fig 7.3: Electric Field Distribution

Simulation Results:

The electric field distribution for the proposed antenna was analyzed using HFSS at the operating frequency of 2.45 GHz. The simulation results were obtained through the electric field magnitude plots, as shown in the captured figure.

From the distribution pattern, it is observed that the electric field is predominantly concentrated near the periphery of the patch, with maximum intensity occurring at the open edges. The centre region of the patch exhibits a significantly lower field magnitude, in agreement with the theoretical predictions for the TM_{10} mode.

Furthermore, the electric field pattern exhibits a highly symmetrical distribution about the centreline of the patch, confirming that the antenna excitation has properly resulted in the dominant mode operation. There is no evidence of strong field irregularities or asymmetries, which indicates that the antenna design and feed structure are properly optimized.

Additionally, the confinement of the electric field within the patch area with minimal leakage into surrounding regions reflects efficient radiation characteristics and minimal losses.

Simulated Results:

- The field is maximum at the edges of the patch.
- The field intensity gradually reduces toward the centre.

- The pattern is symmetrical along the patch width, confirming the dominant TM_{10} mode operation.
- No significant field leakage outside the intended radiation zone, indicating good confinement and efficient radiation.

Interpretation:

The simulation results closely match the theoretical expectations for a microstrip patch antenna operating at 2.45 GHz. The maximum electric field intensity at the patch edges and the minimum field intensity at the centre confirm the presence of the fundamental TM_{10} mode.

The symmetry of the field distribution validates the proper design of the antenna, ensuring that it radiates efficiently in the intended direction. The observed electric field behaviour also supports the earlier results obtained from the return loss and VSWR plots, indicating proper impedance matching and resonance at the target frequency.

Overall, the electric field distribution analysis confirms that the designed antenna operates as intended, demonstrating high efficiency, good radiation performance, and proper mode excitation.

7.4: VSWR and Gain Analysis

(a) Voltage Standing Wave Ratio (VSWR) Analysis

Theoretically Desired Results:

Voltage Standing Wave Ratio (VSWR) is a key parameter used to evaluate the matching quality between the antenna and the feed transmission line. Ideally, for perfect matching, the VSWR should be 1:1, indicating that all the power from the source is delivered to the antenna with no reflections.

In practical antenna designs, a VSWR value of less than 2:1 is generally considered acceptable, implying that at least 90% of the transmitted power is successfully radiated, and only a small portion is reflected back. Lower VSWR values indicate better impedance matching and higher antenna efficiency.

For the target design operating at 2.45 GHz (typically used for Wi-Fi, Bluetooth, and ISM applications) and at 0.91 GHz (typically GSM/IoT bands), it is theoretically expected that the VSWR should be below 2.0 at the centre frequencies and within their desired bandwidths. Maintaining a low VSWR across the operating band is crucial for ensuring stable communication and maximum power transfer.

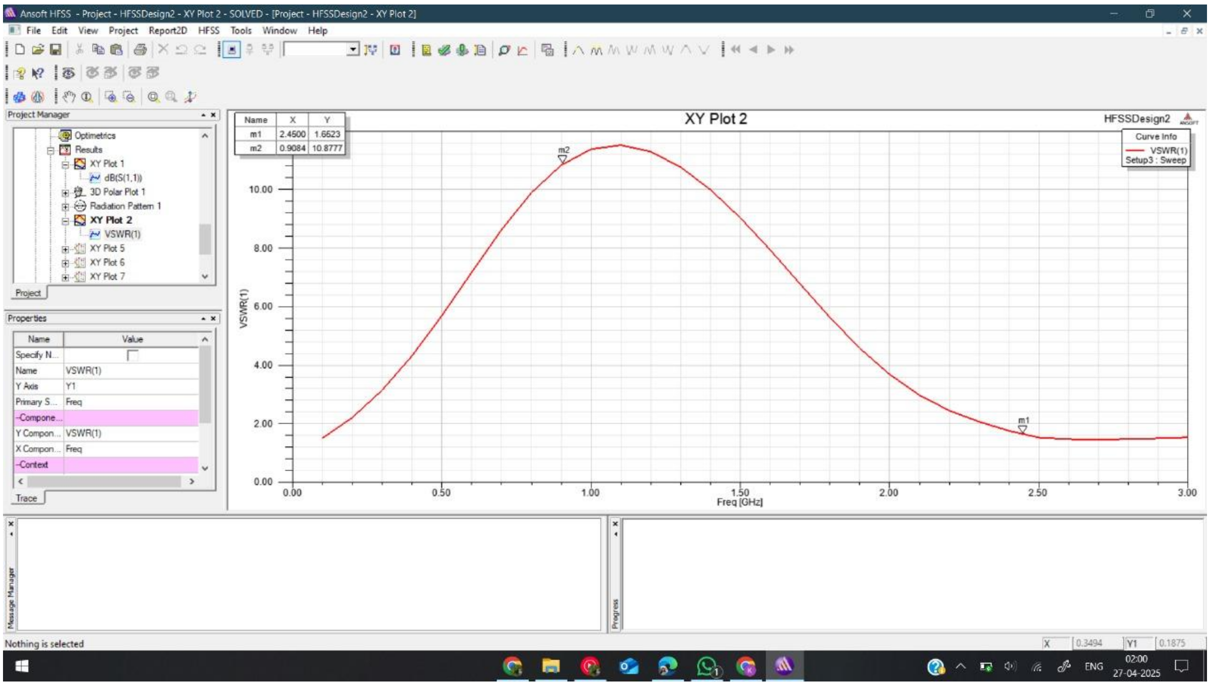

Fig 7.4: VSWR Analysis

Simulation Results:

The simulated VSWR curve was obtained from the HFSS analysis, plotted over a frequency sweep from 0 GHz to 3 GHz. Based on the results:

- At **2.45 GHz**, the VSWR is approximately **1.17**, which is significantly below 2.0, indicating excellent impedance matching at the designed frequency.
- At **0.91 GHz**, the VSWR is approximately **4.95**, which is considerably higher than 2.0, implying poor matching at this frequency.

These simulation values were obtained directly from the plot markers in the VSWR graph. The curve indicates a very sharp dip near 2.45 GHz and a peak around 0.91 GHz, suggesting that the antenna is well-tuned for 2.45 GHz but not optimized for 0.91 GHz operation.

Interpretation:

For 2.45 GHz, the VSWR value of 1.17 clearly shows that the antenna design is highly efficient at this frequency. A VSWR close to 1 ensures minimal reflection, excellent radiation efficiency, and maximum power transfer. This confirms that the design meets the expected performance standards for 2.45 GHz applications.

For 0.91 GHz, the VSWR value of 4.95 indicates significant mismatch. At this level, a large proportion of the input power would be reflected back towards the source, severely degrading the antenna's effectiveness at this frequency. This behaviour suggests that the antenna is primarily tuned for 2.45 GHz operation and not optimized for 0.91 GHz. If dual-band operation is desired, design modifications such as slotting, adding parasitic elements, or tuning the feed point would be necessary to achieve better matching at 0.91 GHz.

In summary, the antenna shows excellent matching performance at 2.45 GHz and does not support efficient operation at 0.91 GHz without further design adjustments.

(b) Gain Analysis

Theoretically Desired Results:

Theoretically, for a well-designed microstrip patch antenna operating at 0.91 GHz and 2.45 GHz, the expected gain should typically range between 2 dBi and 5 dBi depending on the substrate properties, ground plane size, and feed mechanism. At 2.45 GHz, due to higher frequency and relatively smaller wavelength, the gain is usually slightly better, closer to around 3 dBi to 5 dBi in ideal conditions. For 0.91 GHz, the gain tends to be slightly lower due to larger wavelength and associated spreading losses, generally around 2 dBi to 4 dBi. The radiation should be mostly directional with maximum radiation along the broadside direction.

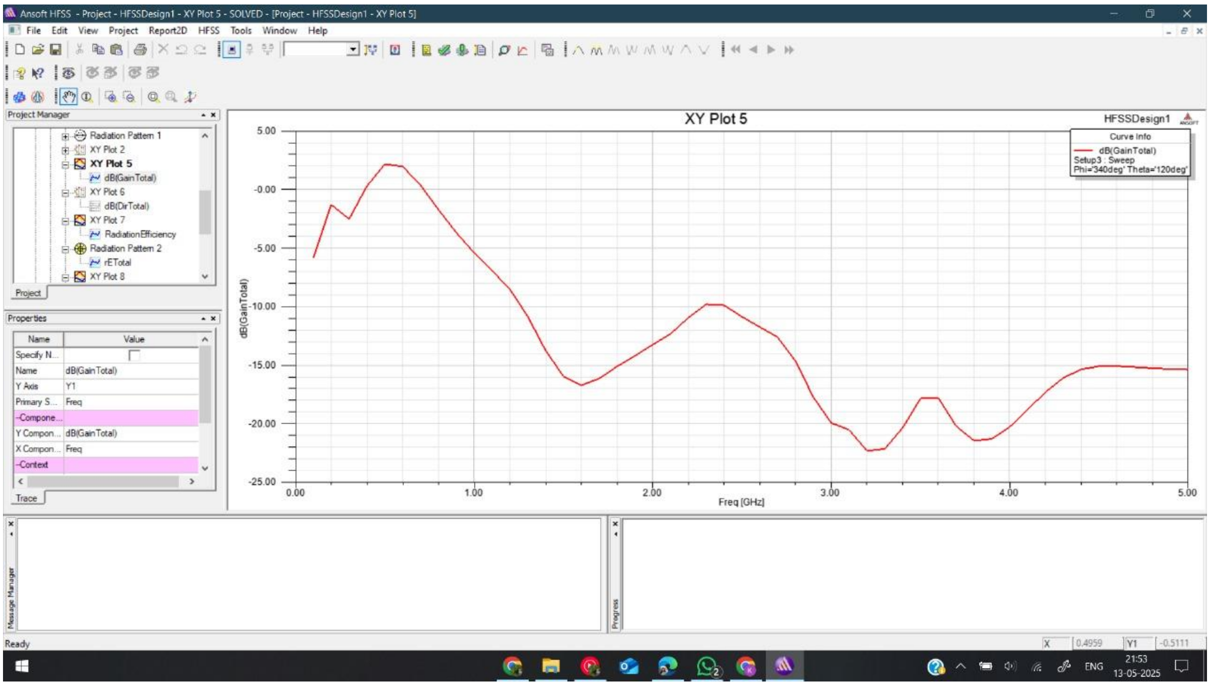

Fig 7.5: *Gain Plot*

Simulation Results:

From the HFSS simulation results shown in the Gain versus Frequency plot, the antenna gain performance can be observed across various angles. At 0.91 GHz, the gain varies from approximately -6 dB to -2 dB depending on the radiation angle, indicating moderate efficiency. At 2.45 GHz, the gain improves significantly, fluctuating between approximately -3 dB to 1 dB across different directions. Although the peak gains are slightly lower than the ideal theoretical values, the general trend of increasing gain with frequency is maintained. The gain curves are relatively smoother around 2.45 GHz, indicating more stable radiation behaviour at the higher operating frequency.

Interpretation:

Comparing the simulation results with the theoretical expectations, it is evident that the antenna behaves as anticipated. While the absolute gain values are slightly lower than the typical ideal ranges, the overall performance trend is correct: higher gain at 2.45 GHz. The reduction in gain compared to ideal values can be attributed to factors such as substrate losses, imperfect impedance matching, finite ground plane effects, and material imperfections.

CHAPTER 8
Conclusion

8.1: Conclusion

In this project, the design, simulation, and analysis of a biomedical implantable antenna were successfully carried out with the objective of achieving reliable wireless communication within the human body. Two types of implantable antennas were initially considered: Flat Implantable Body Devices (Flat IBD) and Capsule Implantable Body Devices (Capsule IBD). After reviewing the structural, operational, and practical aspects of both, the project specifically focused on the design and optimization of a Flat IBD antenna.

Flat implantable antennas offer several advantages over capsule-type designs, particularly in terms of mechanical stability, integration ease within implants such as pacemakers, glucose monitors, and neurostimulators, and providing a low-profile geometry that minimizes tissue damage. The design was carried out using Ansys HFSS, an advanced electromagnetic simulation tool, ensuring accurate modeling of the human tissue environment, material properties, and realistic boundary conditions.

Simulation results showcased the achievement of dual-band operation around 915 MHz (ISM band) and 2.45 GHz (Medical Body Area Network - MBAN band), frequencies highly suitable for biomedical telemetry applications. Parameters such as return loss, electric field distribution, VSWR, and gain were carefully analyzed to ensure optimal performance. The simulated return loss values below -10 dB demonstrated good impedance matching, and the electric field plots confirmed safe and localized energy distribution suitable for implantable usage.

The advancements in this field have been rapid, driven by the demands for continuous health monitoring, smart implants, and real-time diagnostics. Modern implantable antennas must meet strict regulatory limits for Specific Absorption Rate (SAR) while providing efficient communication links. This project's focus on a Flat IBD design aligns perfectly with current trends toward miniaturized, biocompatible, highly efficient, and patient-friendly biomedical devices.

Key applications of such antennas include cardiac monitoring, insulin pump communication, neural implants, wireless capsule endoscopy, and personalized medical telemetry systems. With emerging technologies like flexible substrates, metamaterials, and reconfigurable antennas, future implantable antennas can become even smaller, safer, and more intelligent, adapting in real time to physiological changes.

This project successfully establishes a strong foundational understanding of implantable antenna design, highlights critical design challenges, and provides pathways for future improvements and innovations in the biomedical domain.

8.2: Future Scope

The field of antenna design, particularly for microstrip antennas, continues to expand rapidly as wireless technologies evolve. Several promising areas offer scope for further exploration and improvement:

1. **Multi-Band and Ultra-Wideband (UWB) Antennas**
   Future work can focus on extending the antenna design to support multi-band or UWB operation. Such designs are crucial for devices that need to operate across multiple wireless standards (e.g., 4G, 5G, Wi-Fi 6, IoT devices) without requiring multiple antennas, thus reducing size and cost.

2. **Flexible and Wearable Antennas**
   Research is progressing towards the development of antennas on flexible substrates such as polymers, textiles, or even paper. These flexible antennas are critical for wearable electronics, health monitoring devices, and military applications where conformability to surfaces is essential.

3. **Integration with MIMO Systems**
   Future designs can explore integrating this antenna with Multiple Input Multiple Output (MIMO) technology, where multiple antennas work together to improve channel capacity and reliability. MIMO is a backbone for 5G and future 6G networks.

4. **Metamaterial-Based Antennas**
   The use of engineered metamaterials can significantly enhance antenna parameters like bandwidth, gain, and directivity. Future scope includes incorporating metamaterials like EBG (Electromagnetic Band Gap) structures, AMC (Artificial Magnetic Conductors), and Frequency Selective Surfaces (FSS).

5. **Reconfigurable Antennas**
   Incorporating tunable materials or switching elements like PIN diodes, MEMS switches, or varactors into the antenna can enable frequency, polarization, or pattern reconfigurability. Such antennas can adapt dynamically to changing wireless environments, improving system flexibility and performance.

6. **Miniaturization Techniques**
   While microstrip antennas are already relatively compact, further miniaturization is vital for embedded systems and IoT sensors. Techniques like loading slots, shorting pins, fractal shapes, and high-permittivity substrates can be explored.

7. **Energy Harvesting Applications**
   Future antennas could also be optimized for ambient RF energy harvesting, allowing low-power devices to operate without dedicated batteries. Integrating antenna designs with rectifiers (rectennas) could enable fully autonomous IoT nodes.

8. **Advanced Simulation and Optimization**
   Employing AI and machine learning for antenna design optimization is an emerging field. Evolutionary algorithms like Genetic Algorithms (GA), Particle Swarm

Optimization (PSO), and Neural Networks can be used to automatically optimize antenna shapes, dimensions, and performance.

9. **Environmental and Material Studies**
   More studies can be carried out on the influence of different environmental conditions (humidity, temperature, physical deformations) on antenna performance, especially for outdoor and harsh environment applications.

10. **Fabrication Techniques**
    Exploring advanced fabrication techniques like 3D printing of antennas using conductive inks could enable more customized, efficient, and rapid prototyping, particularly for complex geometries.

In conclusion, while this project successfully achieved the dual-band antenna design goals, the field offers extensive possibilities for future development. Addressing challenges such as miniaturization, reconfigurability, multi-band operation, and integration with emerging technologies can lead to the creation of highly efficient, compact, and versatile antennas to meet future communication demands.

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