DESIGN AND ANALYSIS OF A CIRCULARLY POLARIZED IMPLANTABLE PATCH ANTENNA FOR ADVANCED WIRELESS COMMUNICATION APPLICATIONS

A Project Report Submitted in the partial fulfillment of the requirements for the award of the degree of

BACHELOR OF TECHNOLOGY IN ELECTRONICS

AND COMMUNICATION ENGINEERING

Submitted by

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RAGHU ENGINEERING COLLEGE

(Autonomous)

(Affiliated to JNTU Gurajada, Approved by AICTE, Accredited by NBA, Accredited by NAAC with A+ grade)

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DEPARTMENT OF ELECTRONICS AND COMMUNICATION ENGINEERING

CERTIFICATE

This is to certify that the project entitled "**DESIGN AND ANALYSIS OF A CIRCULARLY POLARIZED IMPLANTABLE PATCH ANTENNA FOR ADVANCED WIRELESS COMMUNICATION APPLICATIONS**" is the bonafide record of project work carried out by A. GIREESH NAIDU(21981A0402), D. KARTEEK(21981A0459), A. ROHIT (21981A0409), and D.HEMANTH(21981A0458) submitted in the partial fulfillment of the requirements for the award of the degree of **Bachelors of Technology** in **Electronics and Communications Engineering** during the academic year 2024-2025.

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Visakhapatnam.	Visakhapatnam.

External Examiner

DISSERTATION APPROVAL SHEET

This is to certify that the dissertation titled

Design and Analysis of a Circularly Polarized Implantable Patch Antenna for Advanced Wireless Communication Applications

By

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DECLARATION

This is to certify that this project titled **"Design and Analysis of a Circularly Polarized Implantable Patch Antenna for Advanced Wireless Communication Applications"** is Bonafide work done by my team, in partial fulfillment of the requirements for the award of the degree Bachelor of Technology and submitted to the Department of Electronics and Communications Engineering, Raghu Engineering College (A), Dakamarri, Visakhapatnam.

We also declare that this project is a result of my own effort and that has not been copied from any one and I have taken only citations from the sources which are mentioned in the references.

This work was not submitted earlier at any other University or Institute for the award of any degree.

DATE:

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ABSTRACT

This research presents the design and development of a compact circularly polarized implantable patch antenna optimized for wireless biomedical telemetry and advanced communication applications. The proposed antenna addresses key challenges associated with implantable antennas, including signal attenuation, impedance mismatching, and polarization sensitivity in biological environments. The substrate material chosen for the antenna is silicone, with dimensions of 20 mm × 18 mm × 1.5 mm. The design underwent four iterative modifications to achieve optimal performance, refining the patch and ground plane structure to enhance radiation efficiency and circular polarization. In the final iteration, a crescent-shaped patch structure was implemented by subtracting a 3 mm circular section (R4) from an existing circular cut (R3), positioned 1.2 mm apart. Additionally, the ground plane was modified with a reverse T-shaped slot and a 2 mm × 5 mm rectangular stub, significantly improving impedance matching, bandwidth, and radiation efficiency. The optimized antenna operates at four distinct resonant frequencies—3.6 GHz, 4.4 GHz, 5.3 GHz, and 7.5 GHz—with return losses of -25.2 dB, -16.6 dB, -21.2 dB, and -12.3 dB, respectively. It achieves circular polarization at these bands, with axial ratio values of 1.5 dB at 3.6 GHz, 1.6 dB at 4.4 GHz, and 1.8 dB at 5.3 GHz, ensuring robust and stable wireless communication. The antenna's multi-band functionality enables its application in C-band communications, 5G networks, ISM-band wireless systems, military communications, and satellite-based radar systems. Designed using biocompatible silicone, the antenna ensures safe and long-term implantation, making it ideal for medical telemetry, neural interfaces, biosensors, and wireless body area networks (WBANs). The proposed design provides a low-power, energy-efficient, and high-performance solution for next-generation implantable medical devices, contributing to advancements in wireless healthcare monitoring and biomedical communication technologies

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LIST OF ABBREVIATIONS

Abbreviation	Definition
1. CRT	Cardiac Resynchronization Therapy
2. ICD	Implantable Cardioverter-Defibrillators
3. LVAD	Left Ventricular Assist Devices
4. PP	Polypropylene
5. PLA	Poly Lactic Acid
6. PCB	Printed Circuit Board
7. FDA	Food and Drug Administration
8. EMA	European Medicines Agency
9. HFSS	High-Frequency Structure Simulator
10. FEM	Finite Element Method
11. EMC	Electromagnetic Compatibility
12. FEA	Finite Element Analysis
13. ANSYS	Analysis System
14. IE	Integral Equation Solver
15. AMD	Advanced Micro Devices
16. RAM	Random Access Memory
17. MOM	Hybrid Method of Moments

CHAPTER-1

INTRODUCTION

Implantability refers to the quality or capability of a device, material, or substance to be safely and effectively implanted into the body for a specific purpose. It involves the ability of the implant to integrate with the surrounding tissues or organs without causing harm or adverse reactions and to perform its intended function over the desired duration. It encompasses various factors, including biocompatibility, mechanical compatibility, stability, functionality, and safety, all of which are essential for the successful integration and performance of the implant within the body.

1.1 *Implantable devices*

Implantable devices refer to medical devices that are surgically implanted into the body to treat a medical condition, monitor bodily functions, or improve the functionality of a particular organ or system [1-4]. These devices are typically made from biocompatible materials to minimize the risk of rejection by the body's immune system [5]. Implantable devices can serve a wide range of purposes and are used in various medical specialties, including cardiology, neurology, orthopaedics, and more. Here are some common types of implantable devices:

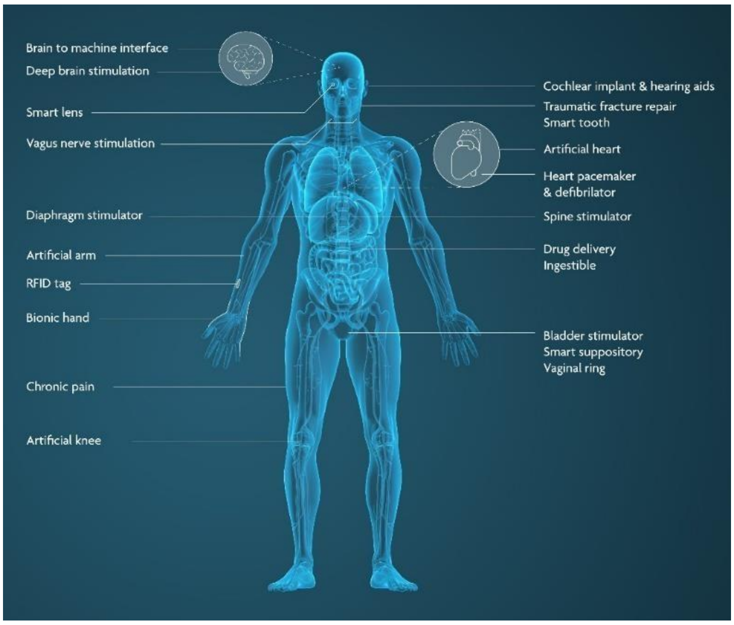


Fig .1.1. Illustration of the Medical Implants

1.1.1 Cardiac Implantable Devices

These include pacemakers, implantable cardioverter-defibrillators (ICDs), and cardiac resynchronization therapy (CRT) devices [6]. Pacemakers regulate the heart's rhythm,

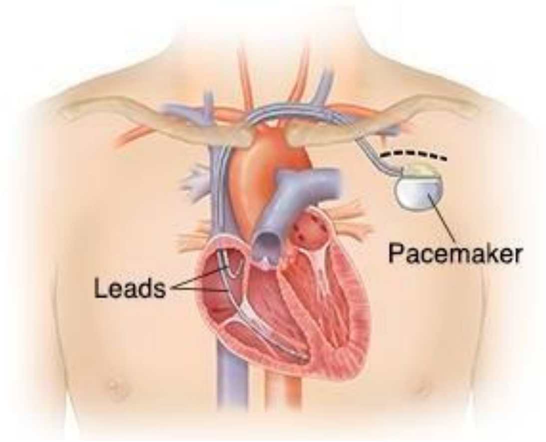


Fig.1.2. Illustration of the pacemaker

while ICDs can detect and treat life-threatening arrhythmias. CRT devices are used to improve the coordination of heart contractions in certain types of heart failure.

1.1.2 Orthopaedic Implants

These include joint replacements (such as hip or knee replacements) [7-9], spinal implants (such as rods and screws used in spinal fusion surgery), and bone grafts used to promote bone healing and fusion.

1.1.3 Implantable Drug Delivery Systems

These devices are designed to deliver medications directly into the body over an extended period [10-11]. They are used to treat conditions such as chronic pain, spasticity, and certain types of cancer.

1.1.4 Neurostimulators

These devices deliver electrical impulses to specific nerves or areas of the brain to treat chronic pain, Parkinson's disease, epilepsy [12], and other neurological conditions.

1.1.5 Implantable Cardiovascular Devices

Apart from pacemakers and ICDs [7], there are also implantable heart valves and left ventricular assist devices (L VADs) used to support heart function in patients with severe heart failure

1.2 *Implantability Factors*

Implantability factors are crucial in the design, development, and evaluation of implantable medical devices to ensure their safety, efficacy, and long-term performance [14]. Here are some key implantability factors.

Fig. 1.3. Implantability Factors

1.2.1 Bio compatibility

This property ensures that the implant material is compatible with the body's tissues and does not elicit an adverse immune response or cause toxicity [15-16]. Biocompatible materials minimize the risk of rejection and inflammation.

1.2.2 Mechanical Stability

Implants should possess mechanical stability to withstand physiological forces and maintain their structural integrity within the body. This property ensures that the implant can perform its intended function without failure or displacement

1.2.3 Surface Characteristics

Surface properties such as roughness, porosity, and chemistry influence the interaction between the implant and surrounding tissues [16]. Optimizing surface characteristics can enhance tissue integration, reduce the risk of infection, and improve overall implant performance

1.2.4 Long Term Stability

Implants should maintain their structural integrity and function over the desired lifespan within the body [17] Factors such as material degradation, wear resistance, and fatigue strength contribute to long-term stability.

1.2.5 Corrosion Resistance

Implants made from metallic materials should be corrosion-resistant to prevent degradation and release of harmful ions into the surrounding tissues. Corrosion resistance is crucial for ensuring the long-term biocompatibility and performance of the implant.

1.2.6 Design and Geometry

The design and geometry of the implant should be carefully considered to optimize tissue integration, minimize trauma during implantation, and ensure proper function within the body. Design features may include anti-migration mechanisms, anchoring structures, and compatibility with surgical techniques.

1.2.7 Infection Control

Minimizing the risk of infection is critical for implant success. Implants should incorporate features such as smooth surfaces, antimicrobial coatings, of antibiotic elution systems to reduce the risk of bacterial colonization and biofilm formation.

1.3 Types of Implantable materials

Implantable materials are substances used in the construction of medical implants that are intended to be inserted into the human body. These materials must be biocompatible [18]. Various types of implantable materials are used in medical devices, each with its owe properties and applications. Here are some common implantable materials:

1.3.1 Polypropylene

Polypropylene (PP) possesses several advantageous properties that make it suitable for implantable medical devices. Its biocompatibility ensures minimal adverse reactions or immune responses, making it well-tolerated within the body. Additionally, PP's durability. flexibility, and toughness allow for the fabrication of implants that can withstand physiological stresses while maintaining structural integrity. Its chemical inertness prevents degradation within the body, ensuring long-term stability of the implant. Overall, the combination of biocompatibility, durability, chemical inertness, and mechanical properties makes polypropylene an excellent choice for implantable medical devices, ranging from soft tissue to orthopaedic applications.

Fig.1.4. Polypropylene Material

1.3.2 Silicone

Silicone, a synthetic polymer, consists primarily of silicon, oxygen, carbon, and hydrogen atoms. Its versatility and durability make it ideal for various applications, including healthcare Biocompatible and soft, silicone is well-suited for implantable medical devices, minimizing the risk of adverse reactions. Its flexibility and natural feel make it suitable for implants like breast or facial implants. Chemically inert, silicone does not degrade over time, ensuring stability within the body. Silicone can be easily molded into complex shapes using techniques such as injection molding or casting, allowing for the fabrication of customized implants tailored to individual patient needs.

Fig.1.5. Silicone Material

1.3.3 Titanium

Titanium's exceptional properties make it highly favoured for implantable medical devices. Its outstanding biocompatibility minimizes adverse reactions, while corrosion resistance maintains stability within the body. With a high strength-to-weight ratio, titanium withstands physiological stresses, ensuring durability. Its osseointegration capability promotes bone growth, enhancing stability and longevity. Radiopacity aids in accurate placement and monitoring during medical imaging. Overall, titanium's combination of biocompatibility, corrosion resistance, mechanical strength, osseointegration, and radiopacity makes it indispensable for orthopaedics, dentistry, and cardiovascular interventions.

Fig.1.6. Titanium Material

1.3.4 Poly lactic acid (PLA)

Poly lactic acid (PLA) is a biodegradable and biocompatible polymer derived from renewable resources like corn starch or sugarcane. It is commonly used in biomedical applications due to its favourable properties. PLA breaks down naturally in the body into harmless byproducts like lactic acid, making it advantageous for implants meant to degrade over time. It is well tolerated by the body, reducing immune responses, and can be used in various medical applications, including implants and drug delivery systems. PLA can be processed using techniques such as injection molding, extrusion, or 3D printing, making it versatile for complex implant designs.

Fig.1.7. Poly lactic acid (PLA) Granules

1.3.5 Zirconium

Zirconium's biocompatibility, corrosion resistance, inertness, high strength-to-weight ratio, excellent mechanical properties, and radiopacity make it an ideal material for implantable medical devices. Its compatibility with bodily tissues minimizes the risk of adverse reactions, while its stability within the body reduces degradation over time. Zirconium's strength and durability allow implants to withstand physiological stresses, ensuring structural integrity. Its radiopacity aids in accurate placement and monitoring during medical imaging. These combined advantages render zirconium invaluable for various implantable medical devices, including dental implants, orthopaedic implants, and cardiovascular stents.

Fig.1.8. Zirconium Material

1.4 *Implantable Antenna*

Implantable antennas serve as crucial components in various medical devices, enabling wireless communication and data transfer within the human body. These antennas are meticulously designed to operate efficiently in the challenging environment of biological tissues, where signal propagation can be hindered by factors such as absorption, scattering, and attenuation.

Their miniaturized form factors allow for integration into implantable medical devices, such as pacemakers, neural stimulators, and glucose monitors, without causing significant discomfort or interference with bodily functions. Implantable antennas must exhibit robust performance characteristics, including high transmission efficiency, low power consumption, and biocompatibility to ensure safe and reliable operation within the body.

Additionally, considerations such as antenna placement, orientation, and frequency selection are vital to optimize signal reception and transmission while minimizing interference with surrounding tissues. Research and development in this field continually strive to enhance antenna performance, durability, and compatibility with emerging medical technologies, promising new frontiers in wireless healthcare monitoring and treatment.

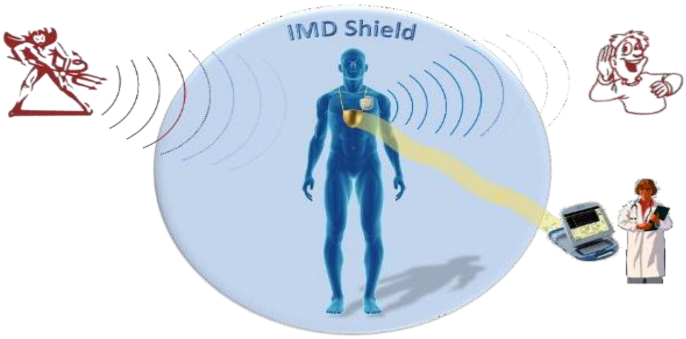


Fig.1.9. Illustration of Implantable Communication

1.5 Implantable Antenna Topology

Implantable antenna topology refers to the design configuration or structure of antennas that are intended to be implanted within the human body for medical applications. The choice of antenna topology depends on various factors such as the specific medical device requirements, operating frequency, implantation location, and desired radiation characteristics. Here are some common implantable antenna topologies:

1.5.1 Monopole Antenna

A monopole antenna for implantable applications is a simple, single-element antenna design consisting of a straight conductor with a ground plane. It offers omnidirectional radiation patterns and is suitable for lower frequency bands. Its compact size and straightforward structure make it suitable for implantation in various locations within the body. Monopole antennas provide reliable wireless communication between implanted medical devices and external equipment, contributing to advancements in remote monitoring and therapeutic interventions. Careful consideration of biocompatible materials and implantation techniques ensures safe and effective operation within the human body.

Fig.1.10. Illustration of Monopole Antenna

1.5.2 Microstrip Patch Antenna

A microstrip patch antenna is a type of antenna commonly used in various wireless communication systems due to its compact size, low profile, case of fabrication, and directional radiation characteristics [18]. It consists of a radiating patch, typically made of conductive material such as copper, printed on one side of a dielectric substrate, with a ground plane on the opposite side. The radiating patch and ground plane are usually connected by a feed line, which is used to excite the antenna and feed electromagnetic energy to the radiating element.

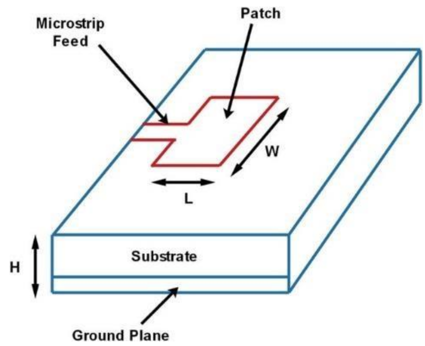


Fig.1.11. Illustration of Microstrip Patch Antenna

1.5.2.1 Advantages of microstrip patch antenna

1.5.2.1.1 Compact Size: Microstrip patch antennas are inherently small and lightweight, making them suitable for implantation in confined spaces within the body.

1.5.2.1.2 Low Profile: Their planar structure results in a low profile, which reduces the risk of discomfort or interference with surrounding tissues when implanted.

1.5.2.1.3 Ease of Fabrication: Microstrip patch antennas can be fabricated using standard printed circuit board (PCB) manufacturing techniques, allowing for cost-effective production and customization.

1.5.2.1.4 Directional Radiation: With proper design, microstrip patch antennas can achieve directional radiation patterns, enabling focused communication with external devices while minimizing interference from nearby sources.

1.5.2.1.5 Wideband Operation: Microstrip patch antennas can be designed to operate over a wide frequency range, providing flexibility for various medical device applications.

1.5.2.1.6 Biocompatibility: By choosing appropriate substrate materials and coatings, microstrip patch antennas can be made biocompatible, minimizing adverse reactions when implanted in the body

1.5.2.1.7 Efficient Radiation: Microstrip patch antennas typically exhibit high radiation efficiency, ensuring reliable wireless communication with external equipment while minimizing power consumption.

1.5.3 Dipole Antenna

A dipole antenna for implantable applications is a two-element antenna design suitable for wireless communication in medical devices. With its simple structure and compact size, it facilitates implantation in various locations within the body. Dipole antennas offer omnidirectional radiation patterns, ensuring reliable wireless connectivity for remote monitoring and data transmission in medical implants. Biocompatible materials

and careful implantation techniques are crucial for safe and effective operation within the body. Dipole antenna contributes to advancements in implantable medical technologies, enhancing patient care and treatment outcomes.

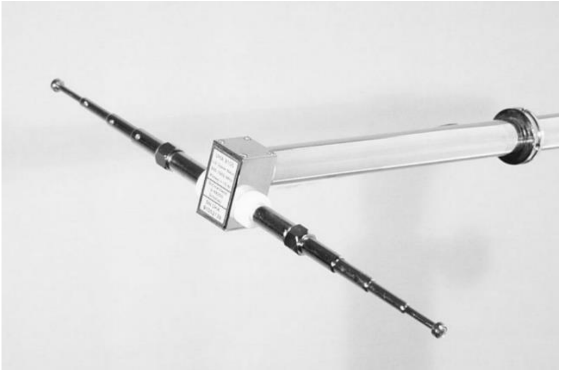


Fig.1.12. Illustration of Dipole Antenna

1.5.4 Helical Antenna

A helical antenna for implantable applications is a coiled antenna design with a compact structure suitable for medical devices. Its helical shape allows for efficient radiation and reception of electromagnetic signals within the body. Helical antennas offer directional radiation patterns, aiding focused communication with external systems. Biocompatible materials and precise implantation techniques ensure safe integration within the body. Helical antennas contribute to improved wireless connectivity in medical implants, enhancing remote monitoring and therapeutic interventions for patients.

Fig.1.13. Illustration of Helical Antenna

1.5.5 Implantable Slot Antenna

An implantable slot antenna is a compact design featuring a narrow slit or aperture in a conductive surface, suitable for medical implants. It offers directional radiation patterns, making it ideal for focused communication within the body. Implantable slot antennas are designed for areas with limited space, ensuring compatibility with various implantation locations [19]. Biocompatible materials and precise implantation techniques ensure safe integration within the body. These antennas contribute to enhanced wireless connectivity in medical implants, supporting remote monitoring and therapeutic interventions for patients.

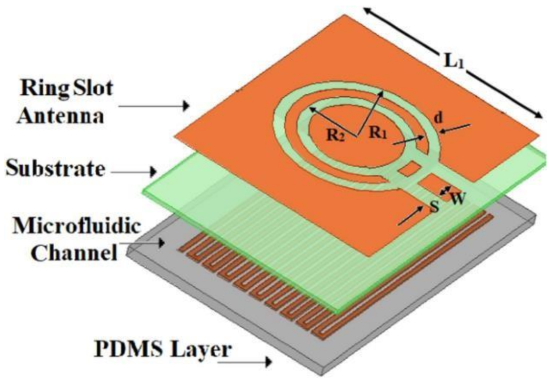


Fig.1.14. Illustration of Implantable Slot Antenna

1.6 *Implantable Antenna Parameters*

Implantable antenna parameters are key characteristics that define the performance and functionality of antennas designed for implantation within the human body. These parameters play a crucial role in determining the antenna's suitability for specific medical applications. Here are some important implantable antenna parameters:

1.6.1 Frequency band

The operating frequency range within which the antenna operates effectively. It is determined by the application requirements and the specific wireless communication protocols used in medical devices.

1.6.2 Radiation Pattern

Describes how electromagnetic energy is radiated or received by the antenna in three-dimensional space. Radiation patterns can be omnidirectional, directional, or shaped depending on the antenna's design and application needs.

1.6.3 Gain

The measure of an antenna's ability to direct or focus electromagnetic energy in a particular direction compared to an isotropic radiator. Higher gain antennas offer increased signal strength and improved communication range.

1.6.4 Efficiency

The ratio of power radiated or received by the antenna to the total input power. Efficiency is a measure of how effectively the antenna converts electrical energy into electromagnetic waves and vice versa.

1.6.5 Bandwidth

The range of frequencies over which the antenna can operate effectively while maintaining specified performance criteria. A wider bandwidth allows for communication over multiple frequency channels and supports diverse applications.

1.6.6 Polarization

It describes the orientation of the electromagnetic waves radiated or received by the antenna. Common polarization types include linear (vertical or horizontal), circular (right- hand or left-hand), and elliptical.

1.6.7 Size and Form factor

The physical dimensions and shape of the antenna, which determine its compatibility with implantation sites within the body. Compact size and low profile are desirable for implantable antennas to minimize tissue disruption and interference.

1.7 On-Body Analysis and Implantable Analysis

1.7.1 On-Body Analysis

On-body analysis refers to the examination and understanding of how on-body devices interact with the human body during usage. This type of analysis is particularly important in the context of wearable technology, where devices such as smartwatches, fitness trackers, and medical monitors are in constant contact with the user's skin.

Through on-body analysis, researchers, and engineers study factors such as heat dissipation, skin conductivity, and biomechanical effects to optimize device performance and user comfort. By understanding how these on-body devices interact with the body, manufacturers can design products that are not only functional and accurate but also safe and comfortable for prolonged wear.

On-body analysis is tested by placing on-body devices on individuals to assess their impact on the body. During this process, researchers observe how the devices affect body temperature, how well they adhere to the skin, and if they cause any discomfort. They also use computers to make virtual models to predict how the devices will interact with the body.

By doing these tests, they make sure that the devices are safe, work properly, and feel comfortable when people wear them for a long time. Overall, on-body analysis enables the creation of wearable and implantable technologies that seamlessly integrate into users' lives while prioritizing both performance and safety.

1.7.2 Implantable Analysis

Implantable analysis involves evaluating medical devices designed to be placed inside the human body, such as pacemakers, artificial joints, or drug delivery systems [20]. This analysis includes various aspects like the device's biocompatibility, functionality, and durability within the body. Testing often entails simulated conditions in laboratory setting and clinical trials to assess how the implant interacts with bodily tissues, its effectiveness in delivering treatment, and its long-term performance. Researchers scrutinize factors such as material compatibility, risk of rejection or infection, and the device's ability to withstand bodily stresses over time.

Implantable analysis undergoes rigorous testing stages, including biocompatibility assessments, functional evaluations, durability tests, in vitro studies, in vivo experiments, and regulatory compliance checks. Biocompatibility tests assess material interaction with bodily tissues, functional evaluations ensure therapy delivery or device function, and durability tests gauge long-term performance in the body. In vitro studies simulate physiological conditions for drug release kinetics, electrical properties, and mechanical behaviour analysis. In vivo experiments, from animal models to human clinical trials, evaluate safety, efficacy, and performance. Regulatory compliance checks ensure adherence to FDA or EMA standards. These processes ensure implantable devices are safe, effective, and compliant before clinical use, enhancing medical outcomes and patient safety.

CHAPTER-2

LITERATURE REVIEW

1. M. S. Singh et. al., designed the antenna by using biocompatible ceramic alumina (εr = 9.8) with the compact size of 280.035 mm^3 with the operating frequencies of 2.4-2.48 GHz Specific Absorption Rate (SAR) of the proposed antenna is evaluated that meets (SAR<1.6 W/kg) the health safety requirements. A wireless link budget analysis is performed that satisfactorily fulfils the requirements for high-speed bio-telemetry application [21].

2. T. Shaw et. al. designed the Antenna on FR-4 substrate with Dimensions of 90 × 90 × 24 mm^3 with the operating frequency of 2.45 GHz The Gains of the Antenna is -13.27dB, -17.14dB with Power Transfer Efficiency (PTE) 1.80% This Antenna has Good in Wireless Power Transfer System [22].

3. C. Xu, X. Liu and Z. Li, developed antenna Design was proposed by using Both the superstrate and substrate are made of Rogers 3210 (εr = 10.2, $\tan\delta$=0.003) the antenna is miniaturized to $\pi \times 4^2 \times 1.27$ mm^3. The operating frequency is 915 MHz, maximum realized gain -29.5 dBi. This Antenna Is Flexible and More Efficient [23].

4. D. He and Z. Chen proposed an antenna Was made by Rogers's 3010 substrate the volume of the antenna is 11 × 11 × 1.28 mm^3 and the operating frequencies are 2.3905 GHz to 2.4512GHz, the proposed antenna shows a S11 of -25.78dB and -39.95dB at WMTS and ISM band respectively. The Antenna is flexible and durable [24].

5. A. Iqbal et. al. designed the Antenna using Rogers ULTRALAM 3850HT substrate (εr=2.9 and $\tan\sigma$-0.0025). The dimensions of the antenna are 5.6 mm × 6mm × 0.2 mm with a volume of 6.72 mm^3. The satisfactory gain values of -26.8 and -18.8 dBi at 915 and 1900 MHz, respectively. The Antenna is suitable to use in the ICP monitoring applications[25].

6. A. Valanarasi et. al. designed the antenna using gallium arsenide as substrate and dimensions of patch 144 mm × 286 nms. The operating Frequency 219.2 THz with efficient return loss of -24.076 dB, Gain of 2.794 dB at band gap of 80nm. The Antenna is highly suitable for WBANs [26].

7. J. Thimot et. al. developed an Antenna design was made by Rogers ULTRALAM with a thickness 0.1 mm material is used in Antenna with the dimensions of 20 mm × 100 mm × 100 mm and Volume of 57 mm3. The Frequency ranges are 433.1-434.8 MHz, 868-868.6 MHz, 902-928 MHz, and midfield 1200 MHz. The antenna is beneficial in multitasking (i.e. telemetry, power saving, and WPT) [27].

8. S. A. A. Shah et. al. fabricated the Antenna was made by Rogers RO6010 (εr =10.2, $\tan\delta$=0.0023) substrate. The volume of the antenna is $9.8 \times 9.8 \times 1.27 mm^3$, operating frequency ranges from 2.27 to 2.66 GHz. The antenna exhibits the advantages of both miniaturization and broad bandwidth [28].

9. K. Skrivervik et. al. designed the antenna using Rogers 3010 with thickness 0.1 mm for the making of antenna with dimensions of $\pi \times 42 \times 1.27$ mm^3, the frequency ranges from 2.25-2.78 GHz and 2.32-2.63 GHz peak gain and radiation efficiency of the proposed antenna are -37.36dBi and 0.21%, respectively the antenna is suitable for the application in health monitoring microsystem [29].

10. T. N. Khajwal et. al. proposed the antenna using FR4 epoxy dielectric substrate with $\varepsilon r = 4.4$, h = 1.6 mm the dimension of proposed antenna is 14×14×1.6 mm. the proposed antenna has 200MHz impedance bandwidth which is 8.4% of its operating frequency. The Antenna is useful in Biomedical Environment [30].

11. M. Yousaf et. al. proposed an antenna made by commercial Rogers RO6010 (εr = 10.2, $\tan\delta$ = 0.0023) substrate with a thickness of h = 0.635 mm × 40mm × 40 mm frequency ranges from 2.4-2.48 GHz has been designed to exhibit its widest 3-dB AR bandwidth. The Antenna is useful for wideband frequency range [31].

12. Z.-J. Yang et. al. fabricated the Antenna was designed by ULTRALAM 3850HT (er= 2.9 and $\tan\sigma$ = 0.0025) material with a thickness of 0.025 mm which serves as a substrate and superstrate with volume of $6.5 \times 6.5 \times 0.05 = 2.11$ mm^3. The frequency ranges from 915 and 2450MHz. The Antenna is suitable for use in endoscopic applications [32].

13. S. Ahmad et al, designed the antenna using Rogers ULTRALAM (Tano = 0.0025, e = 2.9) is used as a dielectric material for superstrate and substrate the dimensions of the designed antenna are (7×7×0.2) mm, the frequency ranges from 2.55-2.13 GHz. The

Antenna is used for many applications, such as capsule endoscopy, skin implantation, and biotelemetry [33].

14. S. Ahlawat et. used Rogers 3010 (εr = 10.2, tanδ=0.0035, 0.635 mm thickness) with compact size of 103.7 (π × 5.12 × 1.27) mm^3. The gain & frequency ranges from -32 and-31.6dBi are achieved at 1.4 and 2.45 GHz respectively. The antenna is suitable for Wireless Medical Telemetry Service (WMTS) [34].

15. Z.-J. Yang et. al. manufactured an Antenna was made by Rogers RT/duriod 6010 with a dielectric constant (εr) of 10.2. loss tangent (tanδ) of 0.0035, and thickness 0.127 mm is used as the substrate and superstrate layer compact size 7mm × 6mm × 0.254mm) with frequency ranges from 902-928 MHz & 2400-2480MHz. The Antenna is useful Multiple Biomedical applications [35].

16. S. Hayat et. al proposed the Antenna was fabricated on Rogers 3010 substrate (thickness = 0.3 mm, r= 10.2, and loss tangent = 0.0035) is used for implementation. The overall dimension of the antenna is 10 × 10 × 0.3 mm^3. the frequency ranges from 2.4-2.48 GHz and peak gain in -7.8 dBi, the antenna is used for in-body biomedical

17. S. G. Muttlak et. al fabricated antenna on Rogers 3010 (εr = 10.2, tanδ = 0.0035) with a thickness of 0.635 mm, with dimensions of 10 × 10 × 127 mm^3, frequency ranges from 229 to 2.74 GHz The Antenna is made for realization of CP and Gain Enhancement [37].

18. B. Kang et. al was fabricated on Rogers 3010 (εr = 10.2, tan δ = 0.0035) substrate with dimension of 13 mm × 13 mm × 1.27 mm with frequency and received power is 673MHz, -20 dBm respectively. The antenna is Power Transmission to Deep-Body Implantable devices [38].

19. M. Zada et. al. manufactured an antenna made by Taconic RF-35 (εr = 3.5, tanδ = 0.0018) with dimensions and the volume of 39.3mm^3, frequency ranges from 2.22 to 2.55 GHz and from 2.30 to 2.67GHz. The Antenna is for Characterization of a Miniaturized Implantable Antenna in a Seven-Layer Brain Phantom [39].

20. R. K. Nehra et. al. used Rogers ULTRALAM (tan δ = 0.0025 and εr = 2, 9) for antenna design the proposed antenna with a compact size (7 × 7 × 0.2 mm^3) and a wide bandwidth (1533 MHz), frequency ranges from 2.4-2.48 GHz. The Antenna is made for Ultra-Wide Bandwidth Characteristics for Medical Implant Systems [40].

21. A. Lamkaddem et, al, designed antenna on a thin substrate layer of flexible polyimide. and coated with Polydimethylsiloxane (PDMS) size of 20mm × 4.4mm × 0.025 mm peak gains were -17.5 and -18.94 dBi for the open and closed-mouth cases, respectively operating frequency is 915MHz. The Antenna has e dynamic environment of the mouth and is therefore a good candidate for iTDS application [41].

22. K. C. Perumalla et. al. used Ethylene-vinyl acetate is a substrate used with compact size of 44 mm × 50 mm × 01 mm to design antenna, the wide bandwidth of 1100 MHz with centre frequency of 5.2 GHz. The Antenna is suitable for application in biomedical telemetry in ISM band [42].

23. M. F. Hossain et. al, fabricated antenna Rogers RT3010 ($\varepsilon r = 10.2$; $\tan \delta = 0.0023$) with compact size of 4×4×0.3 mm^3 with volume 4.8 mm^3 and having peak gain of 3.22dBi operational frequency is 915MHz. The Antenna is suitable for implantable applications [43].

24. M. K. Magill et. al. designed antenna on Rogers RT6010 with dielectric constant (εr) of 10.2, thickness of 25 mil and loss tangent ($\tan\delta$) of 0.0023 with dimensions of 22×22×0.635 mm^3, measured impedance bandwidths are 35.9% and 61.7% having frequency range from 401406MHz. The Antenna is used in Small-Size Dual-Antenna Implantable System for Biotelemetry Devices [44].

25. D. Sharma et. al fabricated-on Arlon AD 430 material for substrate and superstrate in this proposed antenna the overall area of the proposed antenna (including superstrate) is 130 mm^2 with a volume of 207.22 mm^3 realized gain of 20.6dBi in human body phantom frequency range from 2.39 GHz to 2.48 GHz. The Antenna has high flexibility [45].

26. M. Zahid et. al. proposed an antenna and printed on a flexible 70 µm thick polymide substrate with size of 11 mm × 16 mm. The simulated bandwidth of the proposed antenna is 2.34-2.58 GHz. The Antenna is couple-fed to obtain wide Bandwidth [46].

27. N. Alsaab et. al. fabricated antenna on Rogers RT6010 is used as substrate and superstrate material with dimensions of 6 × 5 × 0.5 mm^3, tri-band implantable antenna operating at 402 MHz, 915 MHz, and 2.4 GHz. This antenna is the best choice to be used in implantable medical devices [47].

28. A. K. Skrivervik et. al. designed antenna on Taconic RF-35 (εr=3.5, tanδ = 0.0018) with dimensions of 30 mm × 30 mm. In free space, the proposed antenna covers a wideband ranging from 2.392.57 GHz, thereby posing a -10 dB after implanting inside muscle layer with a peak gain value of -6.46 dB. The antenna has Compact Magnetically Symmetric Antenna Design for Implantable Biomedical Applications [48].

29. A. Vukovic et. al. used substrate material Rogers 6010 (εr=10.2, tanδ= 0.0023) consumes a compact volume with dimensions of 5×5×2.54 mm^3 (63.5 mm^3) the peak gain of -20.1 dB at 2.48 GHz, with a return loss of-25.6 dB. The antenna with the three-layer tissue resonant frequency shifted to 2.46 GHz and return loss is -24.8 dB. The Antenna is suitable for Implantable Patch antenna [49].

30. B. Mandal et.al. designed antenna is covered by 0.1 mm thick PDMS (Polydimethylsiloxane) to ensure biocompatibility with human tissue with dimensions of 110×15×32 mm^3.The measured path loss is 2.5 dB per centimetre. The measured bandwidth of the proposed antenna found to be 660MHz. The Antenna for Low Profile Implantable Antenna for Fat Intra-Body Communication [50].

31. K. F. ARBI et al. taken Rogers 3010 and used with a dielectric constant (εr) of 10.2 Its size is 10mm×10mm ×1.27mm. The gains at the resonant frequencies in the two frequency hands are -31.68dBi and -17.98dB frequency band range 1.427-1.432GHz the antenna is used for medical implant communication services (MICS) Frequency hand and Wireless Medical Telemetry Service (WMTS) [51].

32. Y. Raza et. al. used Arion AD 430 as the superstrate and substrate material having dimensions of 100mm×100mm×100mm the overall area of the proposed antenna including superstrate is 150mm^2 with a volume of 239.1mm^3 realized gain of this antenna is -16.4 dBi at the resonant frequency it ranges from 2.36 GHz and 2.56 GHz. The Antenna is Performance of a Slot Based Implantable Antenna in 2.45 GHz ISM Band [52].

33. C. Dilibal et. al. proposed the material used for antenna design as a substrate and superstrate is Ultralam with dimensions 50 × 50 × 50 mm^3) having the values of dielectric loss tangent and relative permittivity of 0.0025, and 2.9 respectively. The antenna is for a High Gain Low-profile Implantable Antenna for Medical Applications [53].

34. J. Massad et. al. used FR4 epoxy substrate at frequencies between 1.0 GHz and 3.0 GHz, and to evaluate its performance in comparison to a square-shaped microstrip patch antenna (MPA) The novel triangle-shaped Sierpinski fractal antenna's best frequency for maximum gain was 1.5 GHz, with a significance level of around 0.000423 (p 0.05). The antenna is manly used for implantable Biomedical applications [54].

35. A. N. Khan et al, is designed an antenna on a 100 μm thick flexible Preperm (εr= 2.55, $\tan\delta$ = 0.0005) substrate, antenna around the capsule (26 mm × 11.2 mm) the proposed capsule antenna has shown reflection coefficient of -11.83. dB at the desired frequency of 900MHz. The Antenna was suitable for An Ultrawideband Conformal Antenna for Implantable Drug Delivery Device [55].

36. M. Khalid et. al. proposed an antenna is designed on bio-compatible Rogers ULTRA-LAM 3850HT (εr=2.9, $\tan\delta$= 0.0025) dielectric with a thickness of 0.1 mm for substrate and superstrate with a volume of 8 mm×8 mm×0.2 mm it is preferable in terms of size and performance with a maximum gain of -28.2dBi having a bandwidth of 178.6 MHz at a single Industrial, Scientific and Medical (ISM) hand of 902-928 MII2. This antenna provides better bandwidth and gain on this frequency with these dimensions proving itself beneficial for monitoring the gastrointestinal tract of the patient [56].

37. Y. Feng et. al. was Antenna made of FR4 (εr=4.4, $\tan\theta$ = -0.02), a feedthrough, a header made of silicone rubber (εr 3.1, $\tan\theta$ = 0.04.) reflection coefficients are less than -20dB. and 6-12 dB benefit of link budget is achieved in different tissues. The Antenna in Design and System Verification of Reconfigurable Matching Circuits for Implantable Antennas in Tissues with Broad Permittivity Range [57].

38. F. Del Bono et. al. manufactured an antenna is made up of ceramic of TiO2 with r=80 is placed on PVC plastic substrate with r=2.7 of thickness 0.5 mm with dimensions of 23.5 mm× 23.5mm× 5 mm acceptable performance for the defined 'depth window" and chosen ISM band with a center frequency 2.45 GHz. The Antenna is a Study on Application of Dielectric Resonator Antenna in Implantable Medical Devices [58].

39. M. M. Omran et. al. proposed an antenna was made up of Alumina with permittivity(εr) = 9.2, conductance($\tan\delta$) = 0.008 and the thickness = 0.02 mm with dimensions 8.2×8.2×1.37 mm^3 and 8×8×1 mm^3 operate at frequencies of 2.49 Giga Hertz and 2.94 Giga Hertz with gains 1.25 decibel and 2.03 decibel respectively. The Antenna was Owing to good performance, small size, and buoyancy to many of the

effects made by the human body will prove that the antenna will have a very good potential use in the future work of glucose monitoring [59].

40. M. Särestőniemi et. al. fabricated antenna by using a Rogers 6010 substrate (εr= 10.2, $\tan\delta$ = 80.0023) with the thickness of 0.254 mm with dimension of the muscle model is $70 \times 60 \times 60$ mm^3. The simulated antenna has very wide -10 dB impedance bandwidth of 2.15-14.75 GHz, which can cover 2.4-2.48 GHz, 5.725-5.875 GHz Industrial, Scientific, and Medical (ISM) hand, 3.5-4.5 GHz impulse radio UWB (IR-UWB) and 3.1-10.6 GHz UWB. The Antenna is useful for Wireless Capsule Endoscope Systems [60].

CHAPTER-3

INTRODUCTION TO HFSS

HFSS (High-Frequency Structure Simulator) is a commercial 3D electromagnetic simulation software package developed by Ansys, Inc. It is widely used for simulating high-frequency electromagnetic fields in various types of structures, including antennas, microwave circuits, RF components, and other electromagnetic devices

It uses the finite element method (FEM) to solve Maxwell's equations in complex ID geometries. It can handle a wide range of frequency ranges, from DC to microwave and millimetre-wave frequencies. It also has advanced capabilities for simulating various types of electromagnetic phenomena, such as radiation, scattering, and resonance.

It provides a user-friendly interface for designing and analyzing electromagnetic structures. It also offers a wide range of post-processing options for analyzing the simulation results, including visualization tools, data extraction, and parameter sweeps.

HFSS is a powerful tool for electromagnetic simulation and design, and it is widely used in the fields of RF and microwave engineering, antenna design, and electromagnetic compatibility (EMC) testing

ANSYS is a commercial software suite developed by ANSYS, Inc. for engineering simulation and product development. It is widely used in the fields of mechanical, structural, fluid, electromagnetic, and multi physics simulation.

3.1 The ANSYS suite includes a range of simulation tools for various applications, such as

3.1.1 ANSYS Mechanical

This tool is used for structural and thermal analysis of mechanical components and systems. It includes capabilities for finite element analysis (FEA), nonlinear analysis, dynamic analysis, and fatigue analysis.

3.1.2 ANSYS Fluent

This tool is used for computational fluid dynamics (CFD) analysis of fluid flows, heat transfer, and chemical reactions. It includes capabilities for modelling laminar and turbulent flows, multiphase flows, and combustion processes.

3.1.3 ANSYS Electromagnetics

This tool is used for electromagnetic simulation of electric and magnetic fields, RF and microwave circuits, and antenna design. It includes capabilities for electromagnetic field simulation, circuit simulation, and electromagnetic compatibility (EMC) analysis.

3.1.4 ANSYS Multiphysics

This tool is used for simulating multiple physical phenomena, such as fluid-structure interaction, thermal-electric analysis, and acoustics-vibration analysis.

3.1.5 ANSYS Explicit Dynamics

This tool is used for simulating highly nonlinear transient events, such as impact, crash, and explosion. Overall, ANSYS is a comprehensive engineering simulation software suite that enables engineers and designers to simulate and analyze complex systems and products across various disciplines. It is widely used in industries such as aerospace, automotive, defence, energy, and biomedical engineering.

3.2 HFSS Classification

HFSS can be classified based on its application area, its solver technology, and its user interface.

3.2.1 Application Area

HFSS can be used for various applications in the field of electromagnetic simulation, such as:

3.2.1.1 Antenna Design and Analysis

HFSS can simulate various types of antennas, including microstrip, patch, horn, and dipole antennas, to analyze their radiation patterns, input impedance, and gain.

3.2.1.2 Microwave Circuit Design and Analysis

HFSS can simulate microwave circuits, such as filters, couplers, and power dividers, to analyze their frequency response, transmission characteristics, and signal Integrity

3.2.1.3 RF/Microwave Component Design and Analysis

HFSS can simulate various types of RF components, such as connectors, cables, and waveguides, to analyze their transmission characteristics, reflection coefficients, and S-parameters

3.2.1.4 Signal Integrity Analysis

HFSS can simulate signal integrity issues in high-speed digital circuits, such as crosstalk, power/ground noise, and signal distortion, to analyze their impact on signal quality and performance.

3.2.1.5 Electromagnetic Compatibility (EMC) Analysis

HFSS can simulate electromagnetic interference (EMI) and electromagnetic susceptibility (EMS) issues in electronic systems, such as radiation and coupling between components, to analyze their impact on system performance and reliability.

Overall, HFSS is a powerful tool for electromagnetic simulation and design, and it is widely used in the fields of RF and microwave engineering, antenna design, and electromagnetic compatibility (EMC) testing.

3.2.2 Solver Technology

HFSS uses the finite element method (FEM) to solve Maxwell's equations in complex 3D geometries. However, it also offers other solver technologies such as the integral equation solver (IE), and the hybrid solver (FEM-MoM).

5.2.3 User Interface

HPSN has a user-friendly interface that allows users to easily create and manipulate complex 3D models. It also has a scripting interface that enables users to automate the simulation process and customize the simulation workflow Additionally, it has an API Interface that allows users to integrate HFSS with other software tools and programs.

Overall, HFSS is a versatile electromagnetic simulation tool that can be used for a wide range of applications, and it offers various solver technologies and user interface options to meet the needs of different users.

3.3 Why HFSS is Used for Antenna Design

It is widely wed for antenna design and analysis due to its ability to accurately simulate electromagnetic behaviour in complex 3D geometries.

3.3.1 Accurate simulation of electromagnetic behaviour

HFSS uses the finite element method (FEM) to solve Maxwell's equations in complex 30 geometries. This allows for accurate simulation of electromagnetic behaviour, such as radiation patterns, input impedance, and gain, which are critical factors in antenna design

3.3.2 Flexible modelling capabilities

HFSS provides a flexible modelling environment that allows for the creation of complex 3D geometries, including various antenna shapes, sizes, and materials. This enables engineers to accurately simulate and analyze different antenna designs and configurations

3.3.3 Integration with optimization tools

HFSS can be integrated with optimization tools, such as ANSYS Optimetrics, to automate the antenna design process and optimize antenna performance based on specific designs requirements.

3.3.4 Parametric analysis

HFSS allows for parametric analysis, which enables designers to vary antenna parameters, such as frequency, shape, and material properties, and analyze the effects of these changes on antenna performance.

Overall, HFSS is a powerful tool for antenna design and analysis, providing accurate simulation, flexible modelling capabilities, and optimization tools to help engineers design antennas with optimal performance characteristics.

3.4 System Requirements For HFSS

The system requirements for HFSS (High-Frequency Structure Simulator) can vary depending on the specific version and release of the software. However, here are some general requirements for running HESS:

3.4.1 Operating System

Microsoft Windows 10 64-bit

Microsoft Windows 8.1 64-bit

Microsoft Windows 7 64-bit

3.4.2 Processor

Intel or AMD processor with 64-bit support

Minimum 2.2 GHz clock speed

Recommended 3.0 GHz or higher

3.4.3 Memory (RAM)

Minimum 8 GB

Recommended 16 GB or higher

3.4.4 Graphics Card

Minimum 1 GB of dedicated memory Recommended 4 GB or higher OpenGL 3.2 or later

3.4.5 Hard Disk Space

Minimum 10 Gll of free disk space

Recommended 50 GB or higher for large simulations

3.4.6 Other Requirements

Microsoft NET Framework 4.6.2 or later

Microsoft Visual C++ 2017 Redistributable (x64) or later

Note that these are general requirements and your specific system requirements may vary depending on the size and complexity of the simulations you plan to run. It is recommended to check the ANSYS website for the specific system requirements for the version and release of HFSS you plan to use

3.5 Modes of HFSS

It is a commercial electromagnetic simulation software that can analyze a wide range of electromagnetic structures and devices. HFSS supports several modes of analysis, including:

3.5.1 Eigenmode analysis

Eigenmode analysis calculates the resonant frequencies and corresponding modes of an electromagnetic structure, such as a cavity, waveguide, or resonator, This analysis mode can provide information about the field distribution, Q-factor, and coupling coefficients of the modes.

3.5.2 Time-domain analysis

Time-domain analysis calculates the electromagnetic fields and currents in a structure as a function of time. This mode is useful for simulating transient effects, such as pulse propagation, transient response, and electromagnetic compatibility (EMC) analysis.

3.5.3 Frequency-domain analysis

Frequency-domain analysis calculates the steady-state behaviour of an electromagnetic structure as a function of frequency. This mode is useful for simulating circuit, antennas, and electromagnetic scattering problems.

3.5.4 Wakefield analysis

Wakefield analysis calculates the electromagnetic fields generated by charged particle beams interacting with structures, such as cavities or waveguides. This mode is useful for simulating the wake fields in particle accelerators or free-electron lasers.

3.5.5 Circuit analysis

Circuit analysis calculates the electrical behaviour of circuits and interconnects, such as transmission lines, filters, and amplifiers. This mode is useful for simulating high-speed digital circuits and microwave circuits.

3.6 Advantages of HFSS

3.6.1 Accurate simulation

HESS uses the Finite Element Method (FEM) to solve Maxwell's equations, which provides accurate simulation of electromagnetic behaviour in complex 3D structures. This allows designers to accurately predict and optimize the performance of antennas, circuits, and other electromagnetic devices.

3.6.2 Wide range of applications

HFSS can simulate a wide range of electromagnetic structures and devices, including antennas, circuits, filters, waveguides, resonators, and more. This makes it a versatile tool for engineers working in various fields, such as communications, aerospace, automotive, and medical

3.6.3 User-friendly interface

HFSS provides a user-friendly interface that enables users to create and modify complex geometries, set up simulations, and analyze results with case. This allows engineers to spend more time on design and optimization rather than simulation setup and management.

3.6.4 Parametric analysis

HFSS supports parametric analysis, which enables engineers to analyze the effects of changing design parameters, such as frequency, dimensions, and materials, on the performance of the electromagnetic device. This helps engineers to optimize designs and reduce the number of physical prototypes needed.

3.6.5 Integration with other tools

HFSS can be integrated with other ANSYS tools, such as ANSYS Maxwell and ANSYS Q3D Extractor, to provide a comprehensive electromagnetic design and analysis solution. It can also be integrated with third-party tools through the HFSS Application Programming Interface (API)

HFSS is a powerful electromagnetic simulation software that provides accurate simulation, a wide range of applications, a user-friendly interface, parametric analysis, and integration with other tools. These advantages make it a popular tool for engineers and designers working in various fields.

In conclusion, High-Frequency Structure Simulator (HFSS) is a powerful electromagnetic simulation tool used in the design and optimization of transparent antennas. This software offers a range of advanced features that enable designers to model, simulate and analyze the performance of transparent antennas accurately. The introduction to HFSS on transparent antennas has highlighted the advantages of using this tool, including the ability to perform complex simulations, investigate a wide range of design parameters, and optimize the antenna's performance in different operating environments.

CHAPTER - 4

ANTENNA DESIGN

The proposed antenna design draws inspiration from the "crescent moon," symbolizing the balance between conscious awareness and subconscious thoughts. Its unique geometry was carefully optimized using ANSYS High-Frequency Structure Simulator (HFSS) version 2024 R2. The substrate material chosen for the antenna is silicone, with dimensions of 20 mm × 18 mm × 1.5 mm. The design underwent four iterations to achieve optimal performance, as described below.

4.1 Iterations of Proposed Antenna

4.1 Iteration-1

In the initial iteration, the antenna featured a semi-circular patch with a radius of 7 mm (R1) placed on a rectangular silicone substrate. To excite the patch, a symmetric microstrip feed was utilized, measuring 2 mm in length and 7 mm in height. A half-ground structure was introduced on the opposite side of the substrate. This initial design resonated at a frequency of 9.2 GHz, yielding a return loss of -10.9 dB. However, the relatively high return loss indicated the need for further optimization, leading to the next iteration. Moreover, the axial ratio in the initial iteration fell short of the required 10 dB threshold, necessitating further optimization.

4.2 Iteration-2

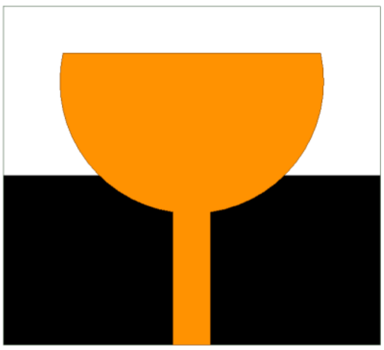
In the second iteration, modifications were made to transform the patch structure into a crescent shape. This was achieved by subtracting a circle with a radius of 7 mm (R2) from the original semi-circular patch (R1). Additionally, the half-ground plane was reduced by 5 mm, and a rectangular structure measuring 6 mm × 2 mm was added to the modified ground plane. These adjustments significantly improved the antenna's performance, resulting in a resonating frequency of 6.5 GHz with a return loss of -14 dB. While the performance improved, further iterations were necessary to enhance the design. Nevertheless, in this iteration, the axial ratio at 6 GHz measured 8.5 dB, highlighting the need for additional optimization.

4.3 Iteration-3

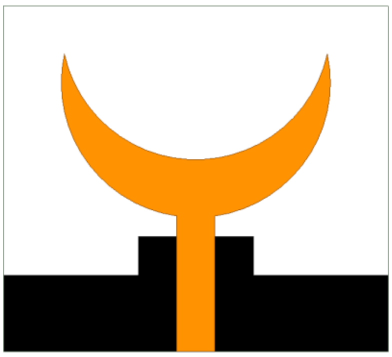
In the third iteration, the patch structure was further refined. A new circle with a radius of 3 mm (R3) was added to the crescent-shaped patch, enhancing its geometry. On the ground plane, a semi-circle with a radius of 9 mm (R5) was integrated, while another semi-circle with a radius of 8 mm (R6) was subtracted. This modification resulted in a semi-circular path. Additionally, two semi-circular extensions were added at opposite ends of the ground plane, with outer and inner radii of 3 mm (R7) and 2 mm (R8), respectively. These refinements achieved dual resonating frequencies at 5.3 GHz and 9.3 GHz, with impressive return losses of -33.6 dB and -30.9 dB, respectively. Despite the significant improvement, the design was further optimized to achieve multiple resonating bands. With the axial ratio values nearing the desired 3 dB threshold, an additional iteration was conducted to further improve circular polarization performance.

4.4 Iteration-4

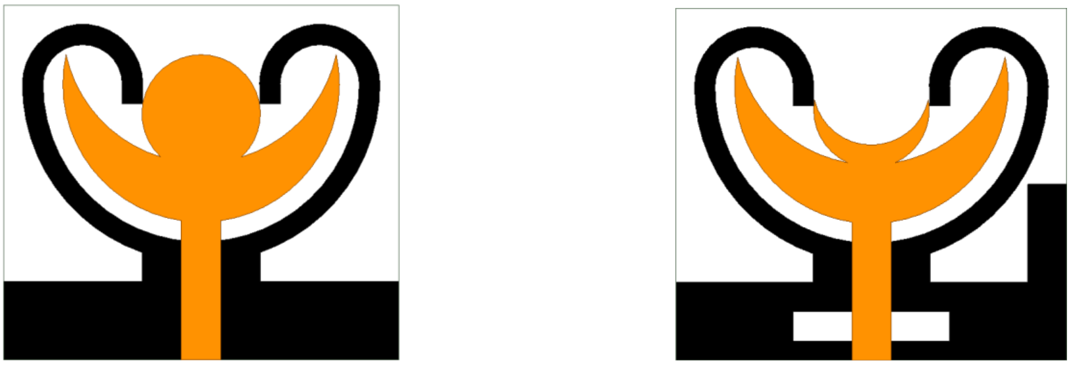
The fourth and final iteration introduced additional modifications to both the patch and ground planes. In the patch structure, a circle with a radius of 3 mm (R4) was subtracted from the existing circle (R3) to achieve a deeper crescent shape. This circle was positioned 1.2 mm away from the previous circle, refining the patch geometry. On the ground plane, a reverse T-shaped slot was introduced, along with a rectangular stub measuring 2 mm × 5 mm added to the right side of the ground plane. These final adjustments enabled the antenna to operate at four resonating frequencies: 3.6 GHz, 4.4 GHz, 5.3 GHz, and 7.5 GHz, with return losses of -25.2 dB, -16.6 dB, -21.2 dB, and -12.3 dB, respectively.



(a)



(b)



(c) (d)

Fig. 4.1. Iterations of the proposed antenna (a)Iteration-1, (b)iteration-2, (c)Iteration-3, (d)Iteration-4

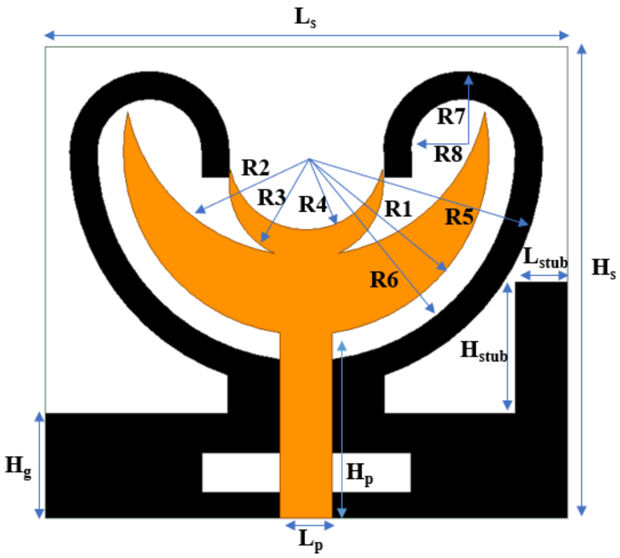


Fig. 4.2. The Dimensions of the Proposed Antenna

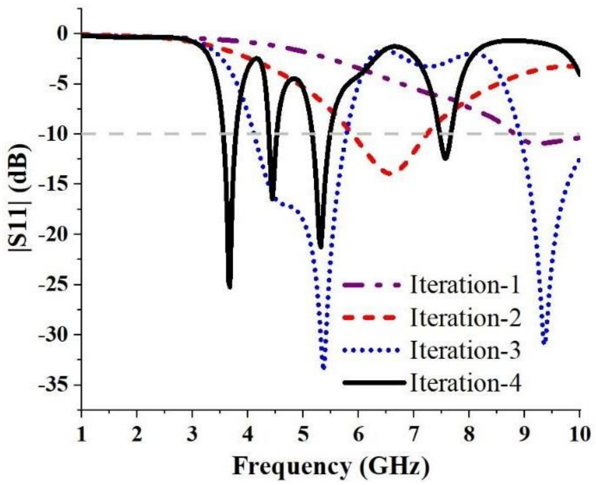


Fig. 4.3. Illustration of S11 Parameters

Table 4.1. Dimensions of the Antenna

S. No.	Antenna Parameters	Values (in mm)
1	L_s	20
2	H_s	18
3	R1	7
4	R2	7
5	R3	3
6	R4	3
7	R5	9
8	R6	8
9	R7	3
10	R8	2
11	H_g	4
12	L_p	2
13	H_p	7
14	L_{stub}	2
15	H_{stub}	5

Fig. 4.4. Prototype of the Proposed Antenna

CHAPTER-5

RESULTS AND DISCUSSIONS

5.1 Reflection Coefficient

The reflection coefficient of an antenna quantifies the portion of an incident electromagnetic wave that is reflected due to an impedance mismatch between the antenna and the surrounding medium. This parameter is critical in assessing antenna efficiency and overall performance. When an electromagnetic wave encounters an impedance discontinuity—such as at the boundary between two media with different impedances (e.g., air and a transmission line)—part of the wave is reflected, while the rest is transmitted. The reflection coefficient represents the ratio of the reflected wave amplitude to the incident wave amplitude. To ensure optimal performance, antennas are designed to operate within specific impedance ranges. When the antenna's impedance matches that of the medium or transmission line it interfaces with, the reflection coefficient is minimized, leading to efficient power transfer and minimal reflection losses. Conversely, if there is an impedance mismatch, the reflection coefficient increases, causing higher reflection levels and reduced efficiency.

After evaluating the reflection coefficient, it was concluded that the simulated performance of the designed antenna closely aligns with the practical measurements. This consistency confirms the accuracy of the simulations and validates the S11 parameter, ensuring reliable antenna performance.

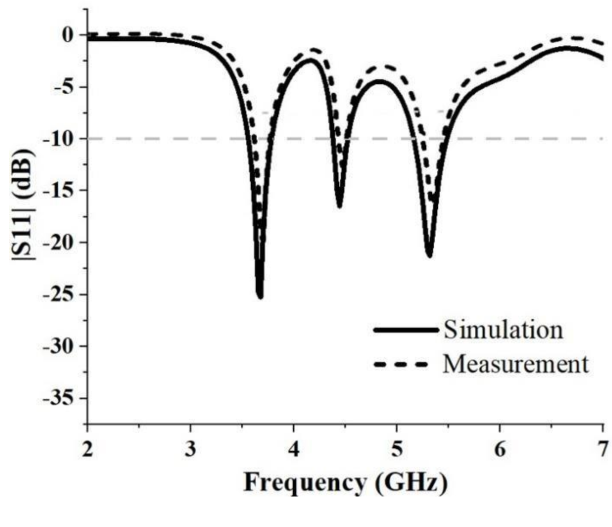


Fig. 5.1. Reflection Coefficient Plot

5.2 *Surface Current Distribution*

Surface current distribution in antennas influences radiation characteristics, impedance, and efficiency. It refers to the movement of charge on a conductor's surface, generating electromagnetic fields.

Different antennas exhibit varying current distributions. Dipole antennas have sinusoidal current patterns, while microstrip patch antennas concentrate currents along edges. Loop antennas maintain uniform current, creating strong magnetic fields, whereas horn and waveguide antennas rely on currents along their walls.

Surface current analysis helps optimize radiation patterns, impedance matching, and efficiency while ensuring electromagnetic compatibility. It is analysed using full-wave simulations (HFSS, CST, FEKO), the Method of Moments (MoM), and near-field scanning.

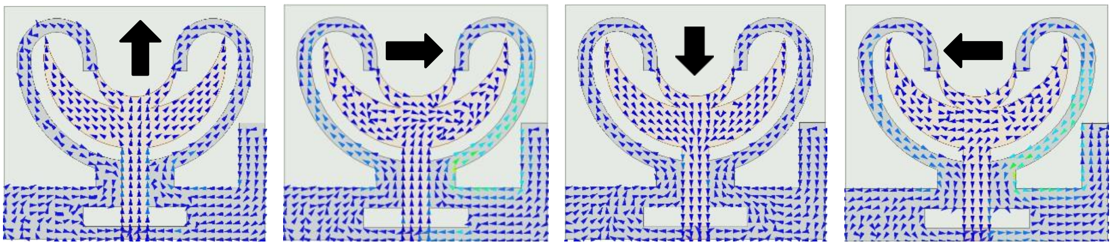


Fig. 5.2.1. Surface Current Distribution at 3.6 GHz

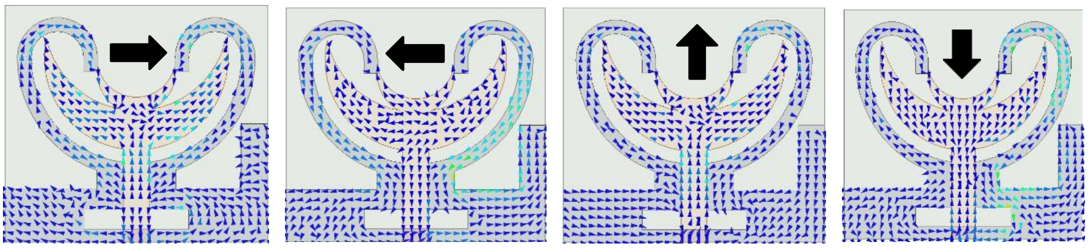


Fig. 5.2.2. Surface Current Distribution at 4.4 GHz

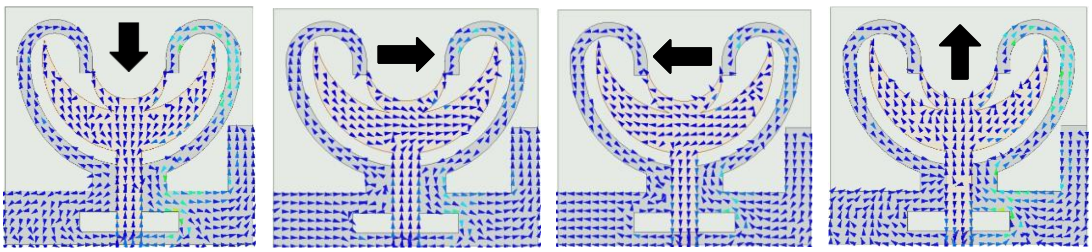


Fig. 5.2.3. Surface Current Distribution at 5.3 GHz

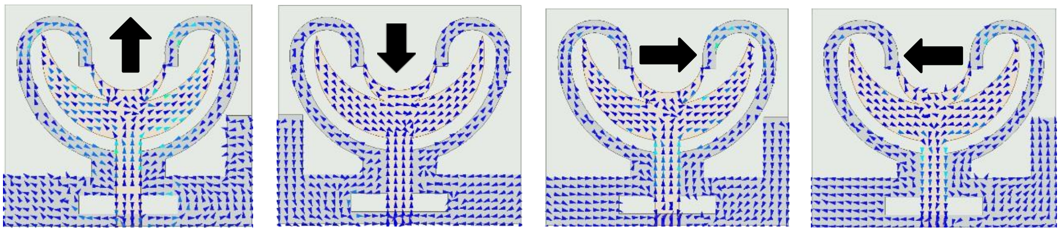


Fig. 5.2.4. Surface Current Distribution at 7.5 GHz

5.3 *Gain*

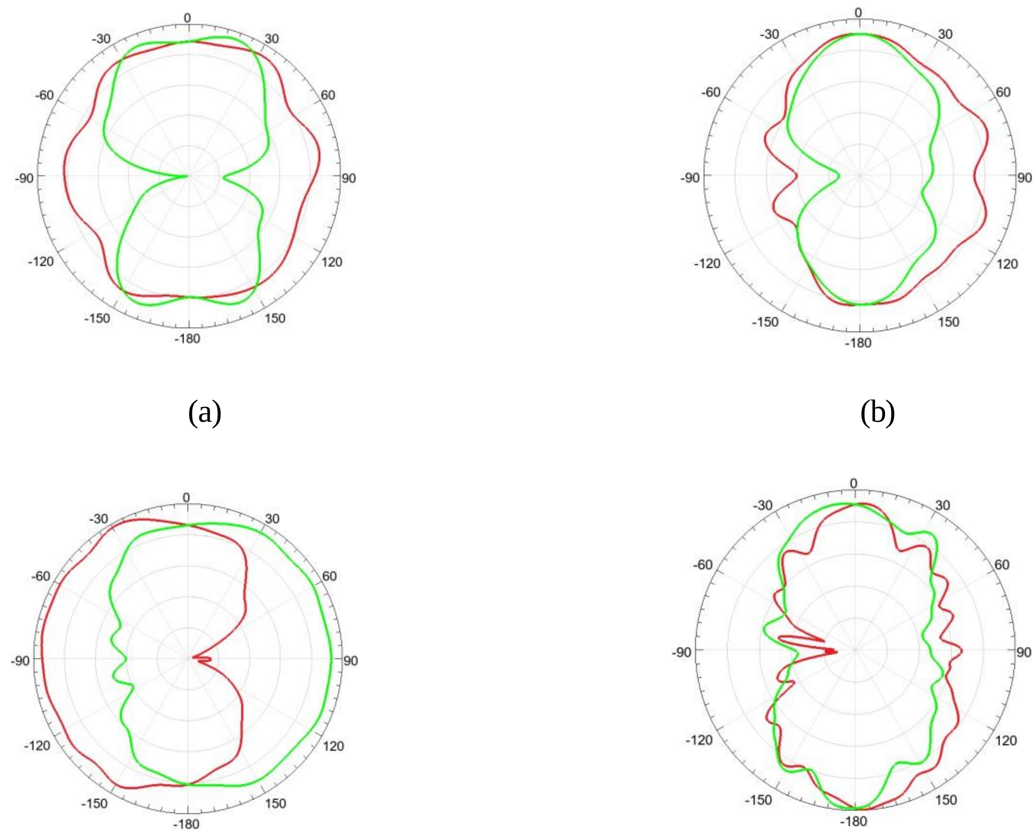
Antenna gain quantifies an antenna’s ability to direct or concentrate electromagnetic radiation in a specific direction, compared to an ideal isotropic radiator, which distributes energy uniformly in all directions. It is a critical parameter in antenna engineering, as it determines the efficiency of signal transmission and reception in a desired direction.

Mathematically, gain is defined as the ratio of the radiation intensity (power radiated per unit solid angle) in a given direction to that of an isotropic radiator operating with the same input power. A higher gain indicates greater directional focus, improving signal strength and communication range.

5.4 *Radiation Patterns*

An antenna's radiation pattern illustrates the three-dimensional spatial distribution of the electromagnetic energy it radiates. It defines how energy is emitted into space, highlighting the relative intensity and directionality of the radiated field. Understanding the radiation pattern is essential for optimizing antenna design, analysing performance, and ensuring efficient signal propagation.

Radiation patterns are commonly represented in two-dimensional plots using polar coordinates (azimuth and elevation angles) or in three-dimensional Cartesian plots. These visualizations depict the radiated power density or field intensity as a function of direction relative to the antenna, providing valuable insights into its coverage, beamwidth, and overall efficiency.



(a) (b)

(c) (d)

Fig. 5.4. Radiation Patterns at (a) 3.6 GHz, (b) 4.4 GHz, (c) 5.3 GHz, (d) 7.5 GHz

5.5 *Efficiency*

Antenna efficiency measures how effectively an antenna converts input power into radiated electromagnetic energy. It is a crucial parameter that directly impacts the antenna’s performance in transmitting and receiving signals. A highly efficient antenna ensures that most of the input power is radiated as electromagnetic waves rather than dissipated as heat or lost due to other factors. Efficiency is typically expressed as a percentage, calculated as the ratio of radiated power to the total input power supplied to the antenna. Several factors influence antenna efficiency, including conductor resistance, dielectric losses, and impedance mismatch losses.

Another key parameter is directivity, which describes how focused an antenna’s radiation pattern is. Antennas with higher directivity concentrate more energy in specific directions, enhancing signal strength and improving overall radiation performance. Additionally, an ideal antenna presents a resistive component to the transmitter, known as radiation resistance. Higher radiation resistance leads to improved efficiency, as more input power is converted into radiated energy rather than being lost within the antenna structure.

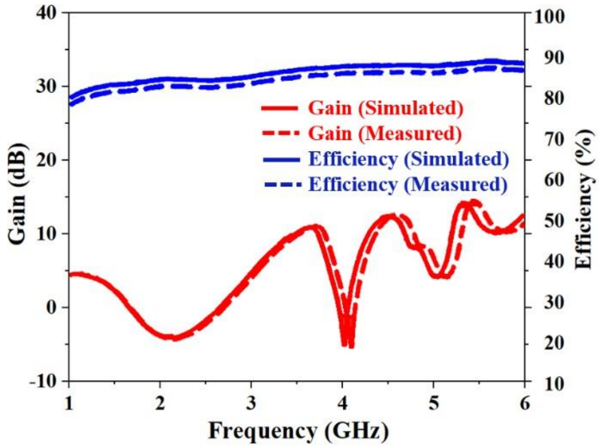


Fig. 5.6. Gain and Efficiency Plot

CHAPTER – 6

CONCLUSION

6.1 *Conclusion*

This research successfully demonstrates the design and optimization of a compact circularly polarized implantable patch antenna tailored for biomedical telemetry and advanced wireless communication. The iterative design refinements, including the crescent-shaped patch structure and the modified ground plane with a reverse T-slot and rectangular stub, significantly enhance impedance matching, bandwidth, and radiation efficiency. Operating at four resonant frequencies (3.6 GHz, 4.4 GHz, 5.3 GHz, and 7.5 GHz) with strong return loss and circular polarization characteristics, the antenna ensures robust wireless signal transmission in biological environments. The achieved axial ratio values of 1.5 dB, 1.6 dB, and 1.8 dB at key frequencies confirm stable circular polarization, making the antenna suitable for low-power, high-performance communication across C-band, 5G, ISM, military, and satellite-based applications.

Furthermore, the use of biocompatible silicone as the substrate material guarantees safe long-term implantation, making the antenna ideal for medical telemetry, neural interfaces, biosensors, and wireless body area networks (WBANs). The multi-band operation expands its usability beyond biomedical applications, offering a versatile solution for next-generation wireless healthcare systems and communication networks. With its compact size, low power consumption, and enhanced efficiency, the proposed antenna provides a reliable platform for implantable medical devices, contributing to advancements in wireless healthcare monitoring, biomedical communication, and future smart healthcare technologies.

CHAPTER – 7

FUTURE SCOPE

The proposed circularly polarized implantable patch antenna offers a strong foundation for future advancements in biomedical and wireless communication technologies. Future research can explore the integration of advanced materials such as metamaterials or flexible biocompatible polymers to further enhance miniaturization, conformability, and biostability for long-term implantation. Additionally, optimization techniques leveraging artificial intelligence (AI) and machine learning (ML) can be employed to refine antenna designs dynamically based on patient-specific tissue properties, ensuring optimal performance across varying biological conditions.

Further studies can also focus on expanding the antenna’s operational bandwidth and efficiency to support emerging wireless standards, including next-generation 6G communication and ultra-wideband (UWB) telemetry. Enhancing power efficiency and incorporating energy-harvesting techniques, such as wireless power transfer or bioenergy-based charging, could extend device longevity, reducing the need for battery replacements. The antenna’s application can be extended to real-time health monitoring systems, neural stimulation, brain-machine interfaces, and advanced biosensors for early disease detection. Additionally, collaborative research in electromagnetic biocompatibility and safety regulations can help standardize implantable antennas, facilitating broader clinical adoption and commercial deployment.

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(57) Abstract :
This research presents the design and development of a compact circularly polarized implantable patch antenna optimized for wireless biomedical telemetry and advanced communication applications. The proposed antenna addresses key challenges associated with implantable antennas, including signal attenuation, impedance mismatching, and polarization sensitivity in biological environments. The substrate material chosen for the antenna is silicone, with dimensions of 20 mm × 18 mm × 1.5 mm. The design underwent four iterative modifications to achieve optimal performance, refining the patch and ground plane structure to enhance radiation efficiency and circular polarization. In the final iteration, a crescent-shaped patch structure was implemented by subtracting a 3 mm circular section (R4) from an existing circular cut (R3), positioned 1.2 mm apart. Additionally, the ground plane was modified with a reverse T-shaped slot and a 2 mm × 5 mm rectangular stub, significantly improving impedance matching, bandwidth, and radiation efficiency. The optimized antenna operates at four distinct resonant frequencies—3.6 GHz, 4.4 GHz, 5.3 GHz, and 7.5 GHz—with return losses of -25.2 dB, -16.6 dB, -21.2 dB, and -12.3 dB, respectively. It achieves circular polarization at these bands, with axial ratio values of 1.5 dB at 3.6 GHz, 1.6 dB at 4.4 GHz, and 1.8 dB at 5.3 GHz, ensuring robust and stable wireless communication. The antenna's multi-band functionality enables its application in C-band communications, 5G networks, ISM-band wireless systems, military communications, and satellite-based radar systems. Designed using biocompatible silicone, the antenna ensures safe and long-term implantation, making it ideal for medical telemetry, neural interfaces, biosensors, and wireless body area networks (WBANs). The proposed design provides a low-power, energy-efficient, and high-performance solution for next-generation implantable medical devices, contributing to advancements in wireless healthcare monitoring and biomedical communication technologies

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