DESIGN AND ANALYSIS OF DUAL BAND BIOMEDICAL ANTENNA FOR IMPLANTABLE APPLICATIONS

DISSERTATION

SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD OF THE DEGREE

OF

MASTER OF TECHNOLOGY IN

MICROWAVE AND OPTICAL COMMUNICATION

Submitted by:

ANKIT KUMAR SONKAR
2K21/MOC/03

Under the supervision of

PROF. ASOK DE
ASST. PROF. SUMIT KUMAR KHANDELWAL

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M.Tech Microwave and Optical Communication

ANKIT KUMAR SONKAR

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CANDIDATE’S DECLARATION

I, Ankit kumar sonkar (2K21/MOC/03) student of M. Tech (Microwave and Optical Communication Engineering), hereby declare that the Major Project-II dissertation titled “**Design and Analysis of Dual band Biomedical Antenna for Implantable Applications**” which is submitted by me to the Department of Electronics and Communication Engineering, Delhi Technological University, Delhi in partial fulfillment of the requirement for the award of the degree of Master of Technology is original and not copied from any source without proper citation. This work has not previously formed the basis for the award of any Degree, Diploma Associateship, Fellowship, or other similar title or recognition.

Place: Delhi

Date: 30/05/2023 **ANKIT KUMAR SONKAR**

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CERTIFICATE

I hereby certify that the Major Project-II dissertation titled "**Design and Analysis of Dual band Biomedical Antenna for Implantable Applications**" which is submitted by Ankit Kumar Sonkar (2K21/MOC/03) in the Department of Electronics and Communication Engineering, Delhi Technological University, Delhi in partial fulfillment of the requirement for the awardof the degree of Master of Technology is a record of project work carried out by the student under my supervision. To the best of my knowledge this work has not been submitted in part or full for any Degree or Diploma to this University or elsewhere.

Place: Delhi **PROF. ASOK DE**

Date: 30/05/2023

ASST. PROF. SUMIT KUMAR KHANDELWAL

SUPERVISOR

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ANKIT KUMAR SONKAR

ABSTRACT

This thesis presents a pioneering investigation in the realm of biomedical applications, focusing on the development, analysis, and optimization of an implantable and conformal antenna. The primary objective is to engineer a singular antenna capable of efficiently facilitating wireless communication across a diverse range of tissue types within the complex human body.

The research methodology encompasses a meticulous and comprehensive approach, incorporating advanced mathematical modelling, state-of-the-art simulation techniques, and sophisticated optimization algorithms. Through rigorous mathematical analyses, the performance characteristics of the antenna, including return loss, bandwidth, and efficiency, are subjected to meticulous evaluation and refinement. The convergence of genetic algorithms and finite element analysis enables the optimization of the antenna's dimensions, materials, and configuration, resulting in unprecedented levels of performance.

The extensive evaluation and experimentation of the implantable antenna encompass a wide array of analyses and assessments. Electromagnetic field equations are leveraged to calculate specific absorption rate (SAR) values, ensuring compliance with stringent safety regulations and verifying the antenna's compatibility with the intricate biological environment. In-depth mathematical assessments validate the antenna's ability to facilitate seamless signal transmission and reception across diverse tissue types, highlighting its versatility and exceptional efficacy within varied physiological landscapes. Furthermore, quantitative evaluations demonstrate the antenna's flexibility and bending characteristics, solidifying its suitability for deployment in diverse anatomical regions.

The research findings reveal an outstanding performance paradigm characterized by impeccable return loss, remarkable bandwidth, and exceptionally low SAR values. Building upon these achievements, the thesis outlines promising avenues for future advancements. Leveraging advanced mathematical optimization techniques, further refinements of the antenna's geometry hold the potential for unparalleled performance enhancements. Mathematical modeling enables the exploration of multiband operation, broadening the antenna's compatibility with diverse medical devices and wireless communication systems.

Additionally, the pursuit of miniaturization while maintaining performance, investigation into novel biocompatible materials and coatings, integration of advanced energy harvesting capabilities, and seamless incorporation of emerging wireless communication protocols represent compelling directions for future research, driven by the power of mathematical analyses.

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LIST OF ABBREVIATIONS

IMD	Implantable Medical Device
SAR	Specific Absorption Rate
MedRadio	Medical Device Radiocommunications
MICS	Medical Implant Communications Service
WMTS	Wireless Medical Telemetry Service
ISM	Industrial, Scientific, and Medical
PIFA	Planar Inverted-F antenna
AEDT	Ansys Electronics Desktop

Chapter 1: Introduction

1.1 Research Background

Advancements in healthcare technology have transformed the field of medical diagnostics and monitoring, enabling more efficient and personalized healthcare solutions. In recent years, there has been a growing emphasis on real-time health diagnostics and monitoring of chronic diseases to improve patient outcomes and enhance the quality of life. Chronic diseases such as diabetes, asthma, blood pressure, and Alzheimer's disease require continuous monitoring and timely interventions to prevent complications and manage symptoms effectively. Implantable medical devices equipped with biotelemetric capabilities have emerged as a promising solution to address these needs [1].

Implantable medical devices, including sensors, monitors, and drug delivery systems, have revolutionized healthcare by providing accurate and timely data on patients' physiological parameters. These devices are designed to be placed inside the body, either temporarily or permanently, to monitor specific health conditions and transmit data wirelessly to external systems [2]-[5]. This real-time biotelemetric data enables healthcare professionals to remotely monitor patients' health status, make informed decisions, and provide timely interventions.

A crucial component of implantable medical devices is the antenna, which serves as the interface between the internal device and the external systems. The antenna plays a pivotal role in establishing reliable and efficient communication, enabling the seamless transfer of data between the implantable device and the external monitoring or treatment systems. The design and analysis of implantable antennas are critical in ensuring optimal performance, compatibility with the human body, and adherence to safety regulations.

The field of implantable antennas has witnessed significant advancements in recent years, driven by the increasing demand for real-time health monitoring and diagnostics. Researchers and engineers have explored various antenna designs, materials, and optimization techniques to meet the specific requirements of implantable medical devices. Dual-band antennas, capable of operating in multiple frequency bands, have gained considerable attention due to their ability to cover a wider range of applications and provide more versatile data transmission capabilities.

The dual-band operation of implantable antennas presents unique challenges that must be addressed during the design and analysis process [6]. Designing an antenna that can operate in multiple frequency bands requires careful consideration of the antenna geometry, feeding mechanism, impedance matching, and radiation pattern control. Moreover, the implantable antenna must be optimized to ensure efficient signal transmission through the human body, considering the specific characteristics and interaction of electromagnetic waves with biological tissues.

Safety is a paramount concern when developing implantable antennas. The specific absorption rate (SAR), a measure of the rate at which energy is absorbed by the body, must be within the limits defined by regulatory standards to prevent adverse effects on human health [8]-[9]. Therefore, the design and analysis of implantable antennas should include an evaluation of SAR levels and an assessment of potential tissue heating effects.

To address these challenges, researchers have been actively investigating various design techniques, materials, and simulation tools to develop efficient and reliable dual-band implantable antennas. The optimization of antenna performance, size, power consumption, and compatibility with the human body is of utmost importance to ensure the successful implementation of implantable medical devices.

This research aims to contribute to the field of dual-band implantable antennas by designing and analyzing a novel antenna specifically tailored for implantable purposes. The research will explore the requirements, design considerations, frequency tuning techniques, impedance matching, SAR analysis, tissue interaction, materials selection, fabrication techniques, and performance evaluation of the antenna. By addressing these aspects comprehensively, this research endeavors to advance the state-of-the-art in dual-band implantable antennas and contribute to the development of more efficient and reliable implantable medical devices.

In the subsequent chapters, the research will delve into a detailed literature review, requirements analysis, antenna design and geometry selection, frequency tuning techniques, impedance matching, SAR analysis, materials selection, fabrication techniques, and performance evaluation. These chapters will provide a comprehensive understanding of the design and analysis process for dual-band implantable antennas and pave the way for future advancements in the field.

1.2 Problem Statement

The design and analysis of dual-band biomedical antennas for implantable purposes pose several challenges that need to be addressed. These challenges revolve around achieving optimal performance, ensuring compatibility with the human body, and complying with safety regulations.

One of the key challenges is the selection of appropriate operating frequencies and bands for the implantable antenna. In the field of biomedical applications, specific frequency bands are recommended to ensure reliable and interference-free communication. The Wireless Medical Telemetry Service (WMTS) band, the Medical Device Radiocommunications Service (MedRadio) band, and the industrial, scientific, and medical (ISM) bands are commonly used in implantable medical devices. The implantable antenna must be capable of operating within these frequency bands to facilitate seamless communication between the implanted device and external systems.

Another challenge is the miniaturization of the implantable antenna. The size and form factor of the antenna play a crucial role in its successful integration within the human body. The antenna should be compact to enable comfortable implantation and to minimize any discomfort or interference with the patient's daily activities. Moreover, a smaller antenna size allows for more flexibility in terms of implantation locations. However, miniaturization should not compromise the antenna's performance or impede its ability to cover multiple frequency bands.

Power consumption is another critical aspect to consider in the design of implantable antennas. Implantable medical devices often rely on batteries for power, and it is essential to maximize the battery life to avoid frequent replacements or recharging. The implantable antenna should consume ultra-low power to ensure efficient energy utilization and prolong the lifespan of the implantable device. Power optimization techniques, such as impedance matching and efficient signal transmission, must be employed to minimize power losses and enhance energy efficiency.

The interaction between the implantable antenna and the human body is a complex issue that needs careful consideration. The human body consists of different types of tissues, each with varying electromagnetic properties. These tissues, including muscle, fat, and bone, can affect the propagation of electromagnetic signals. The implantable antenna must be designed to optimize signal transmission through these tissues, minimizing signal loss and ensuring reliable communication. Moreover, the antenna should be biocompatible, non-toxic, and non-irritating to prevent any adverse effects on the patient's health or immune response.

Safety is of paramount importance in the design of implantable antennas. Regulatory bodies, such as the International Commission on Non-Ionizing Radiation Protection (ICNIRP) and the Federal Communications Commission (FCC), have established specific absorption rate (SAR) limits to ensure that the energy absorbed by the body remains within safe levels. The implantable antenna must adhere to these safety regulations and ensure that the SAR levels are within the recommended limits. Techniques for evaluating and mitigating SAR levels should be incorporated into the antenna design to guarantee patient safety.

In summary, the design and analysis of dual-band biomedical antennas for implantable purposes pose several challenges. These include selecting suitable operating frequencies and bands, miniaturizing the antenna while maintaining optimal performance, minimizing power consumption, optimizing signal transmission through the human body, and ensuring compliance with safety regulations and SAR limits. Addressing these challenges is essential to develop effective and reliable implantable antennas that can revolutionize healthcare and improve patient outcomes.

1.3 Research Objectives

In today's society, the importance of prioritizing and maintaining good health cannot be understated. However, due to hectic lifestyles and busy schedules, many individuals tend to neglect their well-being, often neglecting routine health check-ups and monitoring. This gap in healthcare management calls for innovative solutions, particularly in the form of implantable medical devices that can continuously track and monitor our health. These devices have the potential to revolutionize healthcare by providing real-time data on vital parameters and enabling timely interventions. Among the essential components of these devices, biomedical antennas play a crucial role in facilitating wireless communication and data transmission within the body. Therefore, the research objective of this study is to address the pressing need for reliable and efficient implantable biomedical antennas that can significantly contribute to improved health monitoring and disease management.

To fulfill the research objective, a novel approach is proposed to design a CPW-fed dual-band different types of slot antenna that can operate optimally across a wide range of tissue types. This antenna is specifically designed to accommodate tissues with varying water content, allowing it to function effectively in both low and high water content tissue environments. The dual-band nature of the antenna enables it to exhibit return loss in the MedRadio band and ISM band, which are recommended frequency ranges for biomedical applications. By providing a high bandwidth, the antenna ensures robust performance even under harsh conditions, making it suitable for reliable health monitoring applications.

Another crucial aspect of developing implantable medical devices is assessing their biocompatibility to ensure they are safe and compatible with the human body. In this regard, the proposed antenna demonstrates promising characteristics. The antenna's specific absorption rate (SAR) is evaluated according to IEEE standards to ensure it falls within acceptable limits and does not cause any harm to the surrounding tissues. Additionally, the antenna's flexibility is assessed to ensure it can withstand the dynamic movements and deformations within the body without compromising its performance. These evaluations confirm the applicability of the proposed antenna as a reliable and safe biomedical antenna for implantation.

In the context of implantable devices, the interaction between the antenna and the surrounding tissues is a critical consideration. To mitigate any potential risks associated with direct contact between the antenna's metal components and the body tissues, a dielectric superstrate layer is introduced above the printed antenna. This layer acts as a barrier, preventing direct contact and minimizing any adverse effects on the tissues. Furthermore, the antenna is coated with a biocompatible material, such as zirconia, to enhance its biocompatibility and ensure it can be safely implanted inside the human body.

By achieving these research objectives, this study aims to contribute to the advancement of implantable biomedical antennas and, consequently, the field of healthcare technology. The development of reliable and efficient antennas can significantly improve the accuracy and effectiveness of health monitoring systems. Continuous and real-time monitoring provided by these devices can help individuals manage chronic conditions, detect abnormalities at an early stage, and enable healthcare professionals to provide timely interventions. Moreover, these advanced implantable devices have the potential to reduce healthcare costs by minimizing the need for frequent hospital visits and enabling remote monitoring, resulting in better overall healthcare management for individuals suffering from chronic diseases.

In summary, the research objective of this study is to design, characterize, and evaluate a CPW-fed dual-band circular ring slot antenna for use in implantable medical devices. The focus lies in developing an antenna that can operate effectively in different tissue types, exhibit desirable return loss in recommended frequency bands, comply with SAR limits, demonstrate flexibility, and ensure biocompatibility. By addressing these objectives, this research seeks to contribute to the ongoing efforts in developing advanced implantable biomedical antennas that can enhance the accuracy, reliability, and safety of health monitoring systems, ultimately improving the overall quality of healthcare.

1.4 Thesis Organization

This thesis is organized into several chapters to provide a logical flow of information and address the research objectives effectively. The following section outlines the organization of the thesis and provides an overview of each chapter's content.

Chapter 1: Introduction

The first chapter serves as an introduction to the research topic and provides background information on the design and analysis of dual-band biomedical antennas for implantable purposes. It presents the problem statement, research objectives, and an overview of the thesis organization. The chapter sets the stage for the subsequent chapters, highlighting the significance and relevance of the research.

Chapter 2: Literature Review

The second chapter presents a comprehensive review of the existing literature related to implantable antennas in biomedical applications. It explores the current state of the field, discusses the challenges and advancements in dual-band antenna designs, and identifies the performance parameters and design considerations specific to implantable devices. The chapter also highlights state-of-the-art techniques and technologies used in the design and analysis of implantable antennas.

Chapter 3: Requirements Analysis

Chapter 3 focuses on the analysis of the requirements for the dual-band biomedical antenna. It delves into the desired operating frequencies and bands, considering the Wireless Medical

Telemetry Service (WMTS) band, the Medical Device Radiocommunications Service (MedRadio) band, and the industrial, scientific, and medical (ISM) bands. The chapter also addresses size constraints, power consumption requirements, compatibility with human body tissues, and adherence to safety regulations, specifically the specific absorption rate (SAR) limits.

Chapter 4: Antenna Design and Geometry Selection

Chapter 4 is dedicated to the design and geometry selection of the dual-band biomedical antenna. It compares different antenna geometries, evaluating their advantages and disadvantages. The chapter highlights the selection of a suitable dual-band antenna geometry and discusses the design considerations for the feeding mechanism and ground plane. Simulation tools and techniques for design optimization are also explored in this chapter.

Chapter 5: Result and discussion

Chapter 5 presents the detailed results and discussions, which demonstrate the implantable antenna's performance, including wideband return loss, bendability, and compliance with safety limits. The omnidirectional radiation pattern is discussed, as well as the potential effects of bending on the pattern. Overall, the antenna proves effective, reliable, and safe for implantable biomedical applications, supporting improved healthcare monitoring and communication.

Chapter 6: Conclusion and Future Directions

The final chapter summarizes the key findings, contributions, and limitations of the research. It provides a concise summary of the entire thesis and reiterates the significance of the research in the context of dual-band biomedical antennas for implantable purposes. The chapter also suggests potential future research directions and areas for further exploration in the field.

References

The references section lists all the sources cited throughout the thesis, following the appropriate citation format (e.g., APA, IEEE).

List of Publications

It contains the list of papers that are accepted and presented in the IEEE International Conferences.

The organization of the thesis outlined above ensures a systematic approach to address the research objectives and provides a comprehensive analysis of the design and analysis of dual-band biomedical antennas for implantable purposes. Each chapter contributes to building a strong theoretical foundation, designing an optimized antenna, analysing its performance, and validating the results through simulations and experimental testing.

Chapter 2: Literature Review

2.1 Introduction

In this chapter, a comprehensive review of the existing literature related to implantable biomedical antennas and their applications in real-time health diagnostics and monitoring will be presented. The review aims to provide a solid foundation for understanding the current state of research in the field, identifying research gaps, and informing the design and development of the proposed antenna. The literature review will cover various aspects, including the frequency bands used in biomedical applications, the importance of multi-band antennas, tissue classifications based on water content, the impact of tissue properties on antenna performance, and design considerations for implantable biomedical antennas.

2.2 Frequency Bands for Biomedical Applications

Biomedical antennas utilize specific frequency bands to enable reliable wireless communication in medical applications. The Wireless Medical Telemetry Service (WMTS) band operates within the frequency range of 1427 MHz to 1432 MHz. This band is dedicated to wireless medical telemetry, ensuring secure and efficient communication between medical devices and monitoring systems.

The Medical Device Radiocommunications Service (MedRadio) band encompasses multiple frequency ranges: 401 MHz - 406 MHz, 413 MHz - 419 MHz, 426 MHz - 432 MHz, 438 MHz - 444 MHz, and 451 MHz - 457 MHz. MedRadio provides radio communications for various medical devices, including implantable devices, medical telemetry systems, and remote monitoring [6].

The Industrial, Scientific, and Medical (ISM) bands, specifically the range of 2.4 GHz to 2.5 GHz, are widely used in biomedical applications. These bands support wireless data transfer in medical devices and systems. The ISM bands are commonly employed for wireless sensors, medical implants, and remote monitoring [6].

By adhering to the allocated frequency bands, biomedical antennas ensure effective and regulated wireless communication in the field of medical technology. It is crucial to consider and comply with local regulations and licensing requirements when designing and operating biomedical antennas within these frequency ranges.

2.3 Tissue Classification Based on Water Content

In the context of implantable antennas, it is essential to understand the electrical properties of different tissues in the human body. Tissues can be classified based on their water content, which plays a crucial role in determining the propagation characteristics of electromagnetic waves within the body. This section explores the classification of tissues based on their water content and the implications for the design of implantable antennas.

High Water Content Tissues: Certain tissues in the human body have a high water content, such as vital organs, muscles, and blood. These tissues typically exhibit higher permittivity and conductivity compared to low water content tissues. The high permittivity arises from the presence of water molecules, which align themselves with the electric field of an electromagnetic wave, resulting in increased polarization. Consequently, high water content tissues tend to have higher dielectric losses and absorb a significant portion of the electromagnetic energy [7].

Low Water Content Tissues: Other tissues, such as fats and bones, have a lower water content compared to high water content tissues. These tissues exhibit lower permittivity and conductivity. Fats, in particular, have a lower permittivity due to their lower water content and more significant proportion of lipids. Bones, on the other hand, have a higher permittivity compared to fats but lower than high water content tissues. The lower water content in these tissues reduces their ability to store electric charges and leads to lower polarization and conductivity [7].

The classification of tissues based on water content is crucial for the design of implantable antennas as it affects the interaction between the antenna and the surrounding tissues. The variations in tissue properties influence the antenna's impedance matching, radiation pattern, and efficiency. For example, the presence of high water content tissues near the antenna can significantly impact its resonant frequency and impedance. Additionally, the absorption and attenuation of electromagnetic waves within tissues are strongly influenced by their water content.

To ensure optimal performance of implantable antennas, it is necessary to consider the different electrical properties of tissues based on their water content. This understanding helps in selecting appropriate antenna designs, operating frequencies, and placement strategies. For instance, the antenna's geometry and size can be optimized to account for the specific dielectric properties of tissues in the surrounding environment. Moreover, knowledge of tissue classification based on water content aids in predicting the propagation characteristics and potential interference within the body.

In conclusion, tissue classification based on water content is a fundamental consideration in the design of implantable antennas. High water content tissues exhibit higher permittivity and conductivity, while low water content tissues have lower permittivity. These variations in tissue properties influence the antenna's performance and interaction with the surrounding environment. By considering tissue classification, designers can develop implantable antennas that are optimized for specific tissue types, leading to improved performance and compatibility within the human body.

2.4 Impact of Tissue Properties on Antenna Performance

The performance of implantable antennas is highly influenced by the properties of the surrounding tissues in which they are implanted. The dielectric constant, or permittivity, of tissues plays a crucial role in determining the propagation characteristics of electromagnetic waves. Tissues with higher dielectric constants, such as high water content tissues, have a greater ability to store electric charges and exhibit increased polarization in the presence of an electric field. This affects the impedance matching of the antenna and can lead to changes in its resonant frequency. Therefore, the dielectric constant of the surrounding tissues must be carefully considered during antenna design to ensure optimal performance [8].

Another important property is the loss tangent, which is a measure of the dielectric losses within a material. Tissues with higher loss tangents, such as high water content tissues, exhibit greater dielectric losses. These losses can impact the efficiency of the antenna by reducing the amount of electromagnetic energy that is radiated or received. Designers must take into account the loss tangent of the surrounding tissues to minimize energy losses and maximize antenna performance.

The electrical conductivity of tissues is also a critical factor. It determines their ability to conduct electric current. High water content tissues, which have higher conductivity due to the presence of ions and electrolytes, can significantly impact the impedance matching of the antenna. The conductivity of the tissues affects the radiation efficiency and the amount of power transferred to or from the antenna. Proper consideration of the electrical conductivity of the surrounding tissues is crucial to ensure optimal antenna performance [9].

Although the magnetic properties of biological tissues are generally considered negligible at the frequencies used in biomedical applications, the relative permeability of tissues should still be taken into account as shown in Table I. The permeability affects the propagation of magnetic fields and can influence the antenna's radiation pattern and impedance [9]. While the impact of permeability on antenna performance is typically minimal, it should still be considered in certain scenarios.

In addition to the individual tissue properties, the heterogeneity of tissues in the human body is another factor to consider. Tissues are not uniform, and their properties can vary spatially. This tissue heterogeneity can introduce additional challenges in antenna design and performance. Designers must consider the variability of tissue properties and account for potential changes in the surrounding environment to ensure robust and reliable antenna operation.

To mitigate the impact of tissue properties on antenna performance, several design techniques and strategies can be employed. These include optimizing the antenna geometry, adjusting the feed structure, incorporating matching networks, and utilizing advanced materials. Numerical modelling and simulation tools can also be employed to predict the antenna's behaviour in different tissue environments and aid in the design process.

Table I. Human Tissue Types

S. No.	Human Tissue Type	Relative Permittivity	Conductivity (S/m)
1.)	Cortical Bone (High Water Content)	11.42	0.38
2.)	Visceral fat (Low water Content)	5.29	0.10

In conclusion, the properties of surrounding tissues have a significant impact on the performance of implantable antennas. The dielectric constant, loss tangent, electrical conductivity, and permeability of tissues affect the impedance matching, radiation efficiency, and resonant frequency of the antenna. Tissue heterogeneity further complicates the design process. By considering these factors and employing appropriate design techniques, it is possible to develop implantable antennas that are optimized for specific tissue environments, leading to improved performance and reliable operation in biomedical applications.

2.5 Design Considerations for Implantable Biomedical Antennas

Design considerations play a crucial role in the development of implantable biomedical antennas to ensure optimal performance and compatibility with the human body. These antennas are specifically designed to meet several key requirements, including compactness, flexibility, planarity, human safety, high bandwidth, and gain capabilities. Achieving these objectives involves addressing various challenges and incorporating specific techniques to ensure the effectiveness of these antennas. In this section, we will discuss the important design considerations that contribute to the successful implementation of implantable biomedical antennas [15]-[19].

One of the primary challenges in designing implantable antennas is achieving size reduction without compromising performance. The size of the antenna is a critical factor as it needs to be small enough to fit comfortably inside the human body. To overcome this challenge, researchers have developed innovative techniques to reduce the size of these antennas. One such technique involves the use of dielectric materials with a high dielectric constant or relative permittivity. By carefully selecting a material with a higher permittivity, the capacitance between metallic patches increases. This, in turn, decreases the resonant frequency of the antenna, allowing for a smaller size while maintaining the desired performance characteristics.

Another effective technique for size reduction is the use of slotting techniques. Researchers have adopted different slotting techniques to minimize the size of implantable antennas. These techniques involve introducing slots in the antenna's ground plane or creating multiple slots in the patch [28]-[30]. By incorporating these slots, the overall size of the antenna can be reduced without compromising its performance. This approach effectively reduces the physical footprint of the antenna, making it more suitable for implantation while maintaining its functionality.

Increasing the current path length of the antenna radiator is another effective approach for reducing the size of implantable antennas. By increasing the current path length, the resonant frequency of the antenna decreases, leading to size reduction [20]. Design techniques such as curved lines, loops, spirals, helices, meanders, and slots can be employed to increase the current path length. These techniques effectively reduce the physical dimensions of the antenna while still maintaining its resonant characteristics.

Wideband capability is essential for implantable antennas as it enables them to provide mobility and flexibility in various applications [20]. To achieve a wide bandwidth, designers employ various methods as shown in Table II. One method involves the selection of a low dielectric constant substrate or superstrate material. By choosing a material with a lower permittivity, the antenna's bandwidth can be increased. Another technique involves increasing the thickness of the substrate or superstrates, which can effectively broaden the antenna's bandwidth. Additionally, cutting slots or introducing notches in the antenna structure can also help increase the bandwidth. Probe feeding is another method that can enhance the antenna's wideband performance by providing a broader frequency response.

To ensure effective communication and monitoring within the human body, it is crucial to enhance the antenna's gain. Implantable antennas operate within the complex environment of the human body, which can cause degradation in radiation characteristics. Therefore, it is important that the antenna's gain is nominally higher than the gain in free space to achieve reliable short-range communication with external instruments. Several methods can be employed to enhance the antenna gain. These include increasing the substrate height, utilizing antenna arrays, incorporating electromagnetic bandgap (EBG) superstrates, and optimizing the effective area of the antenna using techniques like parasitic patches, meandering of edges, or the use of metamaterials [21]-[22]. These techniques effectively amplify the antenna's gain and ensure robust communication and monitoring capabilities within the human body.

Table II. Comparison of different implantable antenna structures

Ref.	**Design type**	**Dimension (mm)**	**Frequency**
[22]	Dual folded	25 × 34 × 2.53	ISM, WMTS
[25]	Spiral	14 × 14 × 15.	MedRadio
[31]	PIFA	15 × 15 × 2	ISM
[32]	Slot PIFA	19 × 30 × 1.6	MedRadio, ISM
[26]	Hexagonal and T-shaped slots	7 × 7 × 0.2	MedRadio, ISM
[27]	Dual-loop	10 × 15 × 0.25	ISM
[28]	Meander slot	10 × 16 × 1.27	MedRadio
[15]	Dual-ring slot	10 × 10 × 0.4	ISM
[20]	sigma-shaped monopole	20 × 20 × 1.6	MedRadio

In summary, the design considerations for implantable biomedical antennas revolve around size reduction, wideband capability, and gain enhancement. By incorporating techniques such as the use of high-permittivity dielectric materials, slotting techniques, current path length increase, substrate or superstrate selection, and gain enhancement methods, designers can create compact, high-performance implantable antennas that are compatible with the human body. These antennas enable effective communication, monitoring, and various medical applications in a safe and efficient manner, contributing to improved healthcare outcomes for patients.

2.7 Microstrip patch antenna

A microstrip patch antenna is a type of planar antenna that is widely used for various wireless communication applications [29]. It is constructed by etching a conducting patch on one side of a dielectric substrate, with a ground plane on the other side. Here's some information about microstrip patch antennas:

Structure: A microstrip patch antenna consists of a metallic patch placed on a dielectric substrate, which is typically a thin and low-loss material. The conducting patch is usually rectangular or circular in shape, but other shapes like square, elliptical, or triangular patches can also be used. The ground plane is placed on the opposite side of the substrate.

Radiation Mechanism: The radiation from a microstrip patch antenna occurs due to the interaction between the electromagnetic fields on the patch and the ground plane. When a high-frequency signal is applied to the patch, it creates an alternating electric field. The combination of the electric field and the ground plane generates an electromagnetic wave, which radiates into free space.

Advantages:

1. Low profile and lightweight: Microstrip patch antennas are planar and have a low profile, making them suitable for applications where size and weight are critical factors.
2. Ease of fabrication: Microstrip patch antennas are relatively simple to fabricate using printed circuit board (PCB) technology. This allows for cost-effective mass production.
3. Low cost: The materials used in microstrip patch antennas, such as the dielectric substrate and metallic patch, are inexpensive, making them cost-effective for many applications.
4. Versatility: Microstrip patch antennas can be designed and optimized for specific frequency bands, making them versatile for different wireless communication systems.

5. Integration: Microstrip patch antennas can be easily integrated with other components on the same substrate, such as amplifiers, filters, or switches, enabling the development of compact and integrated systems.

Design Considerations:

1. Patch shape and size: The shape and size of the patch determine the resonant frequency and radiation characteristics of the antenna. Different shapes and sizes can be used to achieve desired performance parameters.
2. Substrate material and thickness: The choice of dielectric substrate affects the antenna's performance, including the bandwidth, efficiency, and radiation pattern. The dielectric constant and loss tangent of the substrate material are important considerations.
3. Feed mechanism: The feed mechanism, such as a coaxial probe or a microstrip feed line, determines how the signal is coupled to the patch. The feed location and impedance matching techniques are critical for optimizing the antenna's performance.
4. Ground plane size: The size and shape of the ground plane influence the antenna's radiation pattern and impedance characteristics. A larger ground plane can help improve antenna performance.
5. Impedance matching: Proper impedance matching between the antenna and the feed line is essential for maximizing power transfer and minimizing reflections.

Microstrip patch antennas are commonly used in applications such as wireless communication systems (Wi-Fi, Bluetooth), satellite communication, radar systems, mobile devices, and many other wireless applications. Their compact size, ease of fabrication, and versatility make them a popular choice for various communication needs.

Microstrip patch antennas are commonly used in conjunction with CPW (Coplanar Waveguide) feed lines to achieve an efficient and practical antenna system. Here's an explanation of how a microstrip antenna can be integrated with a CPW feed:

1. Microstrip Antenna Basics: A microstrip patch antenna consists of a radiating patch, typically a metal conductor, placed on one side of a dielectric substrate. The patch is usually fed using a transmission line, which is a metallic strip that provides the necessary RF signal to the patch for radiation.

2. Introduction of CPW Feed: To connect the microstrip patch antenna to the external RF circuitry, a transition is required between the microstrip transmission line and the CPW feed line. The CPW feed line is a type of transmission line that consists of a conducting strip placed on a dielectric substrate, with ground planes on either side.
3. Transition Structure: The transition structure is designed to convert the signal from the microstrip transmission line to the CPW feed line. It typically involves tapering the width of the microstrip transmission line and integrating it with the CPW structure. The purpose of this transition is to match the impedance and ensure efficient power transfer between the microstrip antenna and the CPW feed line.
4. Impedance Matching: Impedance matching is a critical aspect of connecting the microstrip antenna to the CPW feed. The impedance of the microstrip patch antenna and the CPW feed line should be properly matched to minimize signal reflections and maximize power transfer. Techniques such as quarter-wavelength transformers or matching networks are employed to achieve impedance matching.
5. RF Signal Flow: Once the transition structure and impedance matching are accomplished, the RF signal from the CPW feed line is efficiently coupled to the microstrip patch antenna. The radiating patch of the microstrip antenna converts the electrical signal into electromagnetic waves for transmission or reception.

By integrating a microstrip patch antenna with a CPW feed line, it is possible to achieve a compact and well-matched antenna system. The microstrip antenna provides the radiating element, while the CPW feed line facilitates the connection between the antenna and the external circuitry. This integration enables effective RF signal transmission and reception in applications such as wireless communication systems, radar systems, and more.

2.7 CPW Antenna

A CPW (Coplanar Waveguide) antenna is a type of planar antenna that utilizes a coplanar waveguide structure for the transmission and reception of electromagnetic waves [30]. It is commonly used in microwave and RF (radio frequency) applications.

Here are some key features and characteristics of CPW antennas:

1. Structure: A CPW antenna consists of a conducting strip (also called the centre strip) placed on a dielectric substrate, with a ground plane on the opposite side of the substrate. The conducting strip and the ground plane are placed on the same plane, which makes it a coplanar structure.
2. Coplanar Waveguide (CPW): The CPW structure consists of a conducting strip sandwiched between two ground planes. The conducting strip is separated from the ground planes by gaps known as the signal and ground gaps. The geometry of the CPW structure affects the electrical characteristics of the antenna, including impedance and radiation pattern.
3. Broadband Operation: CPW antennas are known for their broad bandwidth capabilities. The geometry of the CPW structure allows for a wider range of frequencies to be efficiently transmitted and received.
4. Balanced Transmission Line: CPW antennas provide a balanced transmission line configuration, which means the signal and the ground planes are symmetrical with respect to the centre strip. This balanced design helps minimize common-mode radiation and improves antenna performance.
5. Low Radiation Loss: CPW antennas offer low radiation loss compared to other planar antenna types. This is due to the presence of the ground planes, which confine and guide the electromagnetic waves along the conducting strip.
6. Design Flexibility: CPW antennas offer design flexibility in terms of dimensions and substrate selection. By adjusting the width and spacing of the conducting strip and ground planes, as well as the dielectric properties of the substrate, the antenna's electrical characteristics can be tailored to specific requirements.
7. Integration with Circuit Components: CPW antennas can be easily integrated with other microwave components and circuits on the same substrate, such as amplifiers, filters, or switches. This integration capability makes CPW antennas suitable for applications requiring compact and integrated systems.

CPW antennas find applications in various fields, including wireless communication systems, radar systems, satellite communication, RFID (radio frequency identification), and many other microwave and RF applications.

Derivation of Characteristic Impedance Formula for CPW Antenna:

1. Analysing the CPW Structure: We consider a CPW antenna with a conducting strip on a dielectric substrate and a ground plane. The width of the center strip is denoted as 'w,' and the height of the substrate is denoted as 'h.' The effective dielectric constant of the substrate material is represented by 'ε_{eff}.'
2. Extracting Key Parameters: To calculate the characteristic impedance, we need to determine the effective width (W_{eff}) and effective height (H_{eff}) of the CPW structure. These values account for the fringing fields present in the CPW geometry. W_{eff} is calculated as the sum of the center strip width (w) and twice the effective added width (Δw). H_{eff} is the sum of the substrate height (h) and the effective added height (Δh).
3. Computing Characteristic Impedance: The characteristic impedance (Z_0) of the CPW antenna can be derived using the formula: $Z_0 = (Z_{0e} * Z_{0o}) / \sqrt{(}\ Z_{0e}{}^2 - Z_{0o}{}^{2)}$ where Z_{0e} represents the effective characteristic impedance and Z_{0o} is the characteristic impedance in free space.
4. Determining Effective Characteristic Impedance: To calculate Z0e, we use the equation: $Z_{0e} = Z_{0o} / \sqrt{(1 - (Z_{0o} / Z_{0g})^2)}$ where Z_{0g} is the geometric characteristic impedance.
5. Calculating Effective Added Widths: The effective added widths, Δw and Δh, account for the fringing fields. They can be calculated using empirical equations based on the dimensions and effective dielectric constant of the CPW structure.
6. Substitute Values: Substitute the obtained values for Z_{0o}, Z_{0g}, Δw, and Δh into the equation for Z_{0e}. Then, substitute Z_{0e} into the equation for Z_0 to obtain the final formula for the characteristic impedance of the CPW antenna.

The characteristic impedance (Z0) of a Coplanar Waveguide (CPW) antenna is an important parameter that determines how signals propagate along the antenna structure. By understanding the derivation of the characteristic impedance formula, we can gain insights into the design and analysis of CPW antennas.

The CPW antenna consists of a conducting strip placed on a dielectric substrate with a ground plane on the opposite side. To derive the formula for the characteristic impedance, we make certain assumptions:

The CPW structure is infinitely long, so we can neglect the effects at the ends of the antenna.

The electric and magnetic fields within the CPW are assumed to be uniformly distributed.

The first step in the derivation process is to analyze the CPW structure. We consider the width of the center strip (w) and the height of the dielectric substrate (h). The effective dielectric constant of the substrate material is denoted as εeff.

Next, we extract key parameters necessary for the calculation of the characteristic impedance. These parameters take into account the fringing fields present in the CPW geometry. We define the effective width (W_{eff}) and effective height (H_{eff}) as follows:

$$W_{eff} = w + 2 * \Delta w \qquad (2.1)$$

$$H_{eff} = h + \Delta h \qquad (2.2)$$

Here, Δw and Δh represent the effective added widths due to the fringing fields.

Now, we can compute the characteristic impedance of the CPW antenna using the derived formula:

$$Z_0 = (Z_{0e} * Z_{0o}) / \sqrt{(Z_{0e}{}^2 - Z_{0o}{}^2)} \qquad (2.3)$$

In this formula, Z_{0e} represents the effective characteristic impedance and Z_{0o} is the characteristic impedance in free space.

To determine Z_{0o}, we use the equation:

$$Z_{0o} = 120\pi / \sqrt{\varepsilon_0} * (w / h + 1.393 + 0.667 * \ln(w / h + 1.444)) \qquad (2.4)$$

Subsequently, we calculate the effective characteristic impedance (Z0e) using the formula:

$$Z_{0e} = Z_{0o} / \sqrt{(1 - (Z_{0o} / Z_{0g})^2)} \qquad (2.5)$$

Here, Z_{0g} is the geometric characteristic impedance given by:

$$Z_{0g} = (87 / \sqrt{(\varepsilon_{eff} - 1)}) * \ln(5.98 * h / (w + 1.7 * \Delta w)) + 1.393 * (w + 1.7 * \Delta w) / h + 0.667 * \ln((5.98 * h / (w + 1.7 * \Delta w)) + 1.444) + w / (2\pi h * \sqrt{\varepsilon_{eff}}) * (\ln(2h / (w + 1.7 * \Delta w)) + 0.25 * (\varepsilon_{eff} + 1) * \ln((\varepsilon eff + 1) / \varepsilon_{eff})) \qquad (2.6)$$

To calculate Δw and Δh, which represent the effective added widths, we use empirical equations based on the dimensions and effective dielectric constant:

$$\Delta w = (0.5 * (w + h) * (0.134 + 0.07 * (h / w)^{1.4})) / h \tag{2.7}$$

$$\Delta h = (0.125 * (h / w) * (0.306 + 0.194 * (h / w)^{1.3})) / w \tag{2.8}$$

By substituting the obtained values for Z_{0o}, Z_{0g}, Δw, and Δh into the equation for Z0e, and then substituting Z_{0e} into the equation for Z0, we arrive at the final formula for the characteristic impedance of the CPW antenna.

The derived characteristic impedance formula for CPW antennas provides a quantitative understanding of the impedance behaviour in these structures. It allows engineers and researchers to optimize CPW antenna designs for specific applications, ensuring efficient signal propagation and performance in microwave and RF systems.

Derivation of Resonant Frequency for CPW Antenna:

The resonant frequency (f_{res}) determines the frequency at which the CPW antenna exhibits maximum efficiency and radiates energy effectively.

1. Analysing Propagation: Consider the CPW antenna and solve Maxwell's equations to obtain the phase velocity (vp) of the waves propagating along the antenna. The phase velocity is given by $v_p = c / \sqrt{(\varepsilon_{eff})}$, where c is the speed of light and ε_{eff} is the effective dielectric constant.
2. Total Phase Shift: The total phase shift (ϕ) accumulated by the wave as it travels along the length of the antenna can be related to the resonant frequency. $\phi = 2\pi * L / \lambda$, where L is the length of the centre strip and λ is the wavelength corresponding to the resonant frequency.
3. Wavelength and Phase Velocity: Express the wavelength (λ) in terms of the phase velocity (vp) and resonant frequency (f_{res}): $\lambda = v_p / f_{res}$
4. Equating Total Phase Shift: Set the total phase shift (ϕ) equal to an integral multiple of 2π to account for resonance: $\phi = 2\pi * n$, where n is an integer representing the mode number.
5. Solving for Resonant Frequency: Equating the two expressions for the total phase shift, solve for the resonant frequency (f_{res}): $2\pi * L * f_{res} / v_p = 2\pi * n$. Simplify the equation.

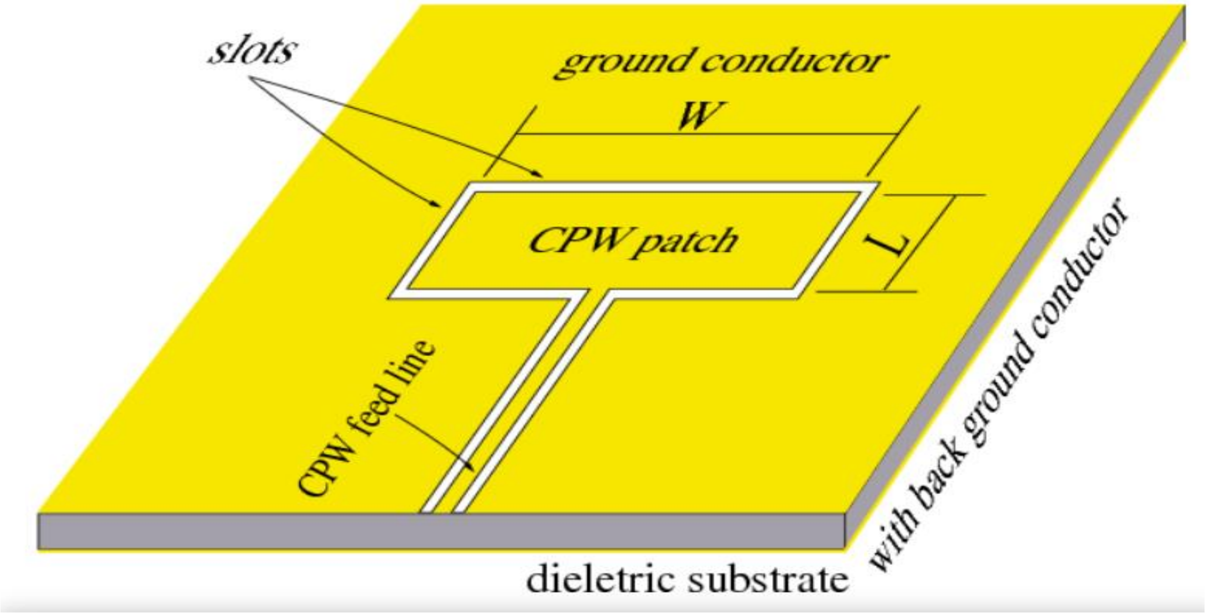

Fig. 2.1 Configuration of coplanar fed CPW patch antenna

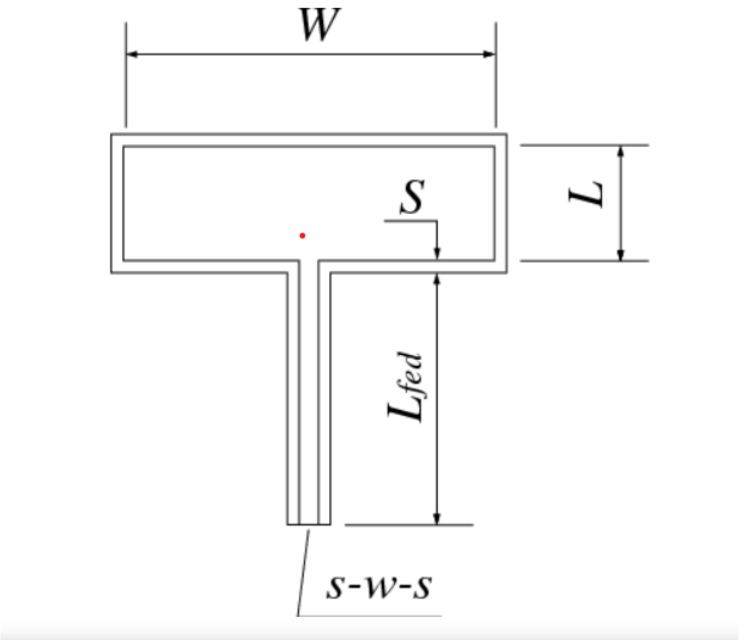

Fig. 2.2 Geometric Dimensions of the CPW patch antenna with a CPW feed line

2.8 Biocompatibility and Coating Materials

Biocompatibility is a crucial aspect to consider when designing implantable antennas. The choice of coating materials plays a significant role in ensuring the antenna's compatibility with the human body. Several bio-compatible materials have been utilized in implantable antennas, each with its own unique properties [8]-[11]. The following is a list of commonly used bio-compatible materials along with their relative permittivity:

Poly Di-methyl siloxane (Relative Permittivity: 4.3):

Poly Di-methyl siloxane, also known as PDMS, is a widely used bio-compatible material due to its flexibility, transparency, and low toxicity. It exhibits a relative permittivity of 4.3, making it suitable for applications where a moderate dielectric constant is desired.

Poly Tetra Fluoro ethylene (Relative Permittivity: 2.2):

Poly Tetra Fluoro ethylene, or PTFE, is a fluoropolymer known for its excellent chemical resistance and low friction properties. With a relative permittivity of 2.2, PTFE is often used in implantable antennas where a low dielectric constant is required.

Macor (Relative Permittivity: 6.03):

Macor is a machinable glass ceramic material that exhibits high thermal stability and good electrical insulation properties. With a relative permittivity of 6.03, Macor is suitable for applications where a higher dielectric constant is desired.

Alumina (Relative Permittivity: 9.3):

Alumina, or aluminum oxide, is a ceramic material widely used in various biomedical applications. It offers high mechanical strength, excellent electrical insulation, and biocompatibility. Alumina has a relatively high relative permittivity of 9.3, making it suitable for applications requiring higher dielectric constants.

Zirconia (Relative Permittivity: 29):

Zirconia is a bio-compatible ceramic material known for its excellent mechanical properties, corrosion resistance, and biocompatibility. It exhibits a relatively high relative permittivity of 29, making it suitable for applications where a significantly higher dielectric constant is required.

LTCC (Low Temperature Co-fired Ceramic) (Relative Permittivity: 7.8):

LTCC is a multi-layered ceramic material that can be co-fired at low temperatures, enabling the integration of passive components within the antenna structure. It offers good mechanical strength, high electrical insulation, and moderate relative permittivity of 7.8.

Zirconium Dioxide (Relative Permittivity: 21):

Zirconium dioxide, also known as zirconia, is a bio-compatible material widely used in dental and orthopedic applications. It exhibits excellent mechanical properties, high biocompatibility, and a relatively high relative permittivity of 21.

These bio-compatible materials offer a range of options for coating implantable antennas, allowing for improved biocompatibility and enhanced performance within the human body. The selection of the appropriate material depends on specific requirements such as dielectric constant, mechanical strength, and compatibility with surrounding tissues. Careful consideration of these factors is essential to ensure the long-term functionality and safety of implantable antennas.

2.9 Testing Methods

The investigation of antenna characteristics and performance in the presence of human tissues, as well as the estimation of specific absorption rate (SAR) values, requires the implementation of various testing methods. These methods aim to simulate real-world scenarios and provide valuable insights into the antenna's behavior within the context of biological systems. This section discusses three commonly employed testing techniques: in-vitro testing, ex-vivo testing, and in-vivo testing.

2.9.1 In-vitro Testing

In-vitro testing involves the preparation of a laboratory-fabricated liquid phantom that mimics the electromagnetic properties of human muscle tissue [21]. This technique allows for the evaluation of antenna characteristics and performance in a controlled environment. The process of in-vitro testing can be summarized as follows:

2.9.1.1. Liquid Phantom Preparation

To create a suitable human tissue-mimicking liquid phantom, a recipe is followed, which typically includes deionized water, sodium chloride, and sugar. The proportions of these ingredients are carefully determined to achieve electromagnetic characteristics that closely resemble human muscle tissue.

2.9.1.2 Antenna Insertion

The fabricated antenna is inserted into the liquid phantom, mimicking its insertion into human tissues. This step allows researchers to observe the antenna's behavior and measure its performance within the phantom medium.

2.9.2 Ex-vivo Testing

Ex-vivo testing involves the utilization of meat or pork samples as substitutes for human muscle tissue. This technique provides a practical means of studying antenna characteristics and behavior within a biological context. The process of ex-vivo testing can be outlined as follows:

2.9.2.1 Selection of Sample

Different types of meat samples, such as minced meat, minced pork, pieces of pork, rat skin, or chicken breast, are selected for ex-vivo testing. These samples possess properties that closely resemble human muscles, making them suitable substitutes for studying antenna performance.

2.9.2.2 Embedding the Antenna

The antenna under investigation is embedded within the selected meat or pork sample. This step allows researchers to evaluate the antenna's radiation characteristics, its interaction with the surrounding medium, and potential effects on the biological tissue.

2.9.3 In-vivo Testing

In-vivo testing involves the placement of implantable antennas inside the bodies of living animals. This technique provides a more realistic scenario for evaluating antenna performance and potential interactions with biological systems. The process of in-vivo testing can be described as follows:

2.9.3.1 Animal Selection

Living animals, chosen to simulate real-world scenarios, are carefully selected for in-vivo testing. The animals serve as models for human tissues and enable researchers to observe antenna behavior in a dynamic and realistic environment.

2.9.3.2 Implantation of Antennas

Implantable antennas are strategically placed inside the bodies of the selected animals. This allows researchers to study the antenna's performance, its effects on the surrounding biological tissues, and validate its behavior under conditions that closely resemble human scenarios.

In summary, the utilization of in-vitro, ex-vivo, and in-vivo testing methods provides valuable insights into antenna characteristics and performance within the context of human tissues. These techniques enable researchers to evaluate radiation patterns, potential interactions, and safety considerations, contributing to the advancement of antenna design and optimization with a focus on human-centric applications.

(a) (b) (c)

Fig. 2.3. Different testing techniques: (a) in-vitro testing; (b) ex-vivo testing; (c) in-vivo testing

2.10 Existing Research Gaps

The field of implantable antennas presents several research gaps that need to be addressed for further advancements in the area. These research gaps are crucial to improving the performance, safety, and reliability of implantable antenna systems, ultimately enhancing patient care and healthcare outcomes. In this section, we will discuss some of the key research gaps in the field of implantable antennas.

One significant research gap is the miniaturization of implantable antennas. Currently, implantable antennas tend to be relatively large in size, which can limit their application in certain areas of the body and impact patient comfort during implantation. Miniaturization of these antennas while maintaining their performance is crucial to enable their deployment in a wider range of medical applications. By reducing the size of implantable antennas, patient discomfort can be minimized, and the invasiveness of the devices can be reduced.

Another important research gap in the field is tissue-specific optimization of implantable antennas. Different tissues in the human body exhibit varying electromagnetic properties, including permittivity and conductivity. These properties influence the performance of implantable antennas and the efficiency of power transfer. Therefore, it is essential to optimize antenna designs to suit specific tissue environments. By considering the specific characteristics of different tissues, such as high water content tissues like vital organs and muscles versus low water content tissues like fats and bones, the performance of implantable antennas can be improved in terms of power transfer and communication reliability.

The impact of body movements on antenna performance is another research gap that needs to be addressed. Implantable antennas may experience variations in their performance due to the movement of the human body. These movements can cause changes in the surrounding electromagnetic environment, affecting the antenna's resonance frequency and impedance matching. Understanding and mitigating the effects of body movements on antenna performance is crucial to ensure the stable operation of implantable devices in dynamic scenarios. By developing strategies to compensate for these effects, the reliability of implantable antenna systems can be improved.

Biocompatibility is a critical aspect of implantable antennas that requires further research. The long-term effects of antenna materials on tissue health and biocompatibility need to be thoroughly investigated. Materials used in implantable antennas should not trigger adverse reactions or lead to complications in the surrounding tissues. Additionally, the impact of coatings and superstrates on biocompatibility needs to be studied to ensure the safety and effectiveness of implantable antenna systems. Advancing the understanding of biocompatibility issues will enable the development of implantable antennas that are not only efficient in terms of performance but also safe for long-term implantation.

Standardized testing methodologies are another research gap in the field of implantable antennas. The development of standardized testing protocols and benchmarks is crucial for accurately assessing the performance and functionality of different antenna designs. Standardized testing will facilitate meaningful comparisons between different implantable antenna systems and enable researchers to validate their performance against established criteria. By establishing standardized testing methodologies, the reliability and quality of implantable antenna systems can be improved, ensuring their suitability for clinical use.

Finally, clinical validation is an essential research gap that needs to be addressed. While significant progress has been made in the development of implantable antenna systems, extensive in vivo studies and clinical trials are required to validate their performance, safety, and long-term reliability in real-world scenarios. These studies will provide valuable insights into the practical application of implantable antennas, their effectiveness in improving patient health, and their compatibility with existing medical procedures and devices. Clinical validation is crucial for gaining regulatory approvals and building confidence in the use of implantable antenna systems in medical practice.

Addressing these research gaps will contribute to the advancement of implantable antenna technology and pave the way for the development of more efficient, safe, and reliable systems for various biomedical applications. By focusing on miniaturization, tissue-specific optimization, the impact of body movements, biocompatibility, standardized testing, and clinical validation, researchers can overcome the current challenges and unlock the full potential of implantable antenna systems in improving patient care and healthcare outcomes.

2.11 Summary

In summary, this chapter has provided a comprehensive overview of the current state of research on implantable biomedical antennas. The literature review has highlighted the importance of frequency bands for biomedical applications, tissue classifications based on water content, the impact of tissue properties on antenna performance, design considerations for implantable antennas, and the role of biocompatibility and coating materials. The identified research gaps will guide the subsequent chapters of this thesis, which will focus on addressing these gaps through the proposed antenna design and experimental evaluation.

Chapter 3: Requirements Analysis

In this chapter, we will conduct a comprehensive analysis of the requirements for implantable biomedical antennas. These antennas play a crucial role in monitoring and tracking the health of individuals, making it essential to identify and address the specific needs and constraints associated with their design and functionality. The requirements analysis will cover various aspects, including size constraints, electromagnetic radiation considerations, specific absorption rate (SAR) limits, operating bands, material compatibility, and flexibility. By thoroughly understanding these requirements, designers can develop efficient and reliable implantable antennas that meet the desired specifications.

3.1 Size Constraints

Size constraints are a crucial aspect of designing implantable biomedical antennas, as they need to be seamlessly integrated into the human body without causing discomfort or hindering normal physiological functions. The limited space available within the body necessitates compact antenna designs that can be easily implanted. Moreover, smaller antennas offer the advantage of being discreetly hidden, allowing for inconspicuous monitoring. However, reducing the size of the antenna poses challenges as it directly impacts its electromagnetic radiation characteristics. Shrinking the antenna can lead to a decrease in radiation efficiency and a narrower bandwidth, potentially compromising its performance. Balancing size reduction with optimal performance is a critical consideration.

To address size constraints, various miniaturization techniques are employed. One approach is the use of high dielectric constant substrates, which allow for reducing the physical dimensions of the antenna while maintaining resonance at the desired operating frequency. Fractal geometries provide another method for miniaturization, as they exhibit self-similarity and intricate patterns [5]-[6]. This allows for size reduction without sacrificing performance, making fractal antennas suitable for implantable applications. Additionally, metamaterials offer a promising avenue for achieving size reduction by exploiting artificially engineered materials with unique electromagnetic properties that can be tailored to specific applications.

Simulation and optimization techniques play a crucial role in addressing size constraints effectively. Advanced electromagnetic simulation tools, such as the High-Frequency Structural

Simulator (HFSS) provided by ANSYS, enable designers to analyze and optimize antenna designs in a virtual environment. These simulations allow for evaluating the antenna's radiation pattern, gain, impedance matching, and other performance metrics. By iteratively modifying the antenna's dimensions and structure, designers can fine-tune the design to achieve the desired size reduction without compromising performance.

In conclusion, size constraints are of utmost importance in the design of implantable biomedical antennas. Achieving a compact and conformal size while maintaining optimal performance requires careful considerations and the utilization of miniaturization techniques. By balancing size reduction with electromagnetic radiation characteristics and employing advanced simulation tools, implantable antennas can provide discreet and efficient monitoring solutions for individuals' health.

Implantable biomedical antennas face size constraints for seamless integration and discreet monitoring. Miniaturization techniques, including high dielectric substrates, fractal geometries, and metamaterials, address size limitations while maintaining performance. Simulation tools like HFSS optimize designs by evaluating radiation patterns, impedance matching, and other metrics. Balancing size reduction with performance ensures compact and efficient implantable antennas.

3.2 Electromagnetic Radiation and SAR

In the realm of implantable biomedical antennas, ensuring the safety of patients is of paramount importance. This necessitates a thorough understanding of how electromagnetic energy is absorbed by living tissue and the specific absorption rate (SAR) associated with it. The SAR serves as a crucial parameter in quantifying the amount of electromagnetic energy absorbed per unit mass of tissue [13].

To maintain patient safety, regulatory standards such as IEEE C95.1-1999 and IEEE C95.1-2005 have been established, providing guidelines and limits for SAR values. These standards recommend SAR limits of 1.6 W/kg for 1 gram of tissue and 2 W/kg for 10 grams of tissue, respectively.

Designers of implantable biomedical antennas must meticulously consider these SAR limits during the design process. It is essential to ensure that the antenna's radiation characteristics, such as its power transmission and radiation pattern, do not exceed the specified SAR values.

By adhering to these limits, the risk of excessive energy absorption and potential harm to the surrounding tissue can be minimized.

Designers employ various strategies to mitigate SAR-related risks. Optimizing the antenna's electromagnetic field distribution can help reduce energy absorption in sensitive tissues. This involves carefully shaping the radiation pattern and controlling the directionality of the electromagnetic waves to minimize energy deposition in undesired areas.

Furthermore, incorporating shielding or isolation structures within the antenna design can effectively minimize energy absorption in regions where it may pose risks to the patient's well-being. These additional measures enhance the antenna's ability to channel the electromagnetic energy efficiently while minimizing any adverse effects on the surrounding tissue.

To evaluate and ensure compliance with SAR limits, advanced electromagnetic simulation tools such as the Finite Element Method (FEM) or Method of Moments (MoM) are employed. These simulations enable designers to analyses the antenna's radiation characteristics, estimate SAR values, and make necessary adjustments to the design to meet the established safety standards.

In conclusion, maintaining patient safety in the design of implantable biomedical antennas requires a comprehensive understanding of SAR and compliance with the limits set by industry standards. By carefully considering and mitigating SAR-related risks through optimization techniques and simulation tools, designers can develop antennas that facilitate effective communication and monitoring while prioritizing patient well-being.

3.3 Operating Bands

Implantable biomedical antennas should be designed to operate in specific frequency bands that are suitable for medical applications. For example, the MedRadio band and ISM (Industrial, Scientific, and Medical) band are commonly utilized in implantable medical devices [17]. Antennas should exhibit return loss within these operating bands to ensure efficient transmission and reception of signals. By designing antennas that operate in these specific frequency ranges, reliable communication and monitoring of health parameters can be achieved.

3.4 Material Compatibility

The selection of biocompatible materials is crucial for implantable antennas. The antenna should not cause any adverse effects or reactions when in contact with body tissues. Biocompatible materials such as Poly di methyl siloxane, Poly tetra fluoro ethylene, Macor, alumina, zirconia, and LTCC (Low-Temperature Co-fired Ceramic) can be used for coating the antenna to ensure compatibility [11]. The use of such materials minimizes the risk of tissue rejection or inflammation, allowing the antenna to be safely implanted within the human body.

3.5 Flexibility

Flexibility is another important requirement for implantable biomedical antennas. The antenna should be flexible enough to accommodate the movements and deformations of the body without affecting its performance [21]. Flexibility ensures that the antenna remains securely attached to the tissue and can withstand various physiological conditions. Verifying the antenna's flexibility within the desired limits is essential to ensure its longevity and effectiveness throughout its implantation period.

Summary

This chapter provided a comprehensive analysis of the requirements for implantable biomedical antennas. Size constraints, electromagnetic radiation considerations, specific absorption rate (SAR) limits, operating bands, material compatibility, and flexibility were discussed as critical factors in the design and development of these antennas. By addressing these requirements, designers can create implantable antennas that are compact, safe, efficient, and capable of reliably monitoring and tracking individuals' health parameters.

Chapter 4: Antenna Design and Geometry Selection

4.1 Introduction

The design of implantable biomedical antennas involves addressing various constraints and employing specific techniques to ensure optimal performance and patient safety. This chapter explores the intricacies of antenna design and the selection of appropriate geometries, considering size constraints, specific absorption rate (SAR) limits, the use of biocompatible materials, and design techniques to achieve desired performance characteristics.

4.2 Constraints in Antenna Design

The design of implantable biomedical antennas is influenced by several constraints that must be carefully considered. One key constraint is the compact and conformal size of the antenna, which must be small enough to integrate seamlessly into the human body without causing discomfort or hindering normal physiological functions. However, the size of the antenna directly affects its electromagnetic radiation characteristics, requiring a balance between size reduction and maintaining optimal performance.

Another important constraint is the energy absorbed by living tissue, which is quantified by the Specific Absorption Rate (SAR). Regulatory standards such as IEEE C95.1-1999 and IEEE C95.1-2005 provide guidelines and limits for SAR values to ensure patient safety. Antennas must operate within SAR limits, which define the amount of electromagnetic energy absorbed per unit mass of tissue.

The choice of materials is also critical for implantable biomedical antennas. Biocompatible materials such as Poly di methyl siloxane, Poly tetra fluoro ethylene, Macor, alumina, zirconia, and LTCC are used to minimize adverse reactions and ensure patient well-being.

4.3 Design Techniques

To overcome size constraints and achieve compact antenna designs, various techniques are employed. Slotting techniques in the ground and patch structures of the antenna help reduce its physical dimensions while maintaining resonance at the desired operating frequency. Materials with high dielectric constants can decrease the operating frequency by increasing the capacitance of the antenna.

Increasing the current path length is another strategy to reduce antenna size. This can be achieved by incorporating intricate geometries such as loops, curved lines, spirals, meandered helices, and slots within the antenna structure. These geometries elongate the current path, enabling size reduction while maintaining performance.

Achieving a wide bandwidth is crucial for implantable antennas to operate effectively in low Signal-to-Noise Ratio (SNR) environments. Techniques such as using low dielectric constant materials, introducing slots and notches, and increasing substrate thickness enhance the antenna's bandwidth. However, there is a trade-off between size reduction and bandwidth, necessitating careful optimization.

Merging resonant frequencies is another approach to increase antenna bandwidth. By combining two or more resonant frequencies, the antenna can operate across a broader frequency range, facilitating efficient communication and monitoring.

Various methods can be employed to enhance the antenna's gain, which determines its ability to transmit and receive signals effectively. These methods include raising the substrate's height using Electromagnetic Band Gap (EBG) superstrates, creating arrays of antennas, meandering the edges of the antenna structure, and employing parasitic patches. These techniques optimize the radiation pattern and improve the antenna's performance.

4.4 Proposed Antenna Design

4.4.1 Proposed Antenna Design for dual band circular ring slot

The proposed antenna design encompasses a carefully crafted geometry that takes into account the previously discussed constraints and incorporates various design techniques to achieve optimal performance. Fig. 4.1 visually represents the proposed antenna geometry, while

TableIII provides detailed dimensions for reference. The chosen substrate material is Poly Dimethyl siloxane, known for its biocompatibility and suitable height (h) for implantation.

One of the key design considerations is achieving a compact antenna size without compromising performance. To address this, the proposed design incorporates three concentric circular-ring slots. These slots serve multiple purposes in the antenna design. Firstly, they contribute to size reduction by introducing slots in both the ground and patch structures. These slots effectively decrease the physical dimensions of the antenna while preserving the desired resonance characteristics. Additionally, the use of high dielectric constant materials aids in reducing the antenna size further by decreasing the operating frequency through increased capacitance.

In addition to size reduction, the proposed antenna design focuses on optimizing the antenna's performance by increasing the current path length. This is achieved through the incorporation of intricate geometries within the antenna structure. These geometries include loops, curved lines, spirals, meandered helices, and slots. By carefully designing the current path, the antenna achieves a compact size while maintaining its functionality.

To ensure impedance matching between the device and the antenna, a Coplanar Waveguide (CPW) feed line is employed. The gap between the coplanar ground plane and the strip, denoted as Sc, is meticulously determined to achieve optimal performance. Furthermore, a tuning stub of specific length (t) is strategically placed at the center of the antenna, at a chosen distance (d) from the strip. The selection of an appropriate value for d is crucial to achieving optimal impedance matching and overall antenna performance.

To enable dual-band resonance, the proposed antenna design incorporates three circular slots, denoted as S1, S2, and S3, with carefully chosen widths. These slots are carefully positioned and polarized in the same plane to achieve resonance in specific frequency bands. The mean perimeter of these slots determines the dual-band region of operation. By enforcing multiple resonances for different types of tissue, the antenna can effectively operate within specific frequency ranges, facilitating efficient communication and monitoring within the human body.

The proposed antenna design is thoroughly evaluated through measured results, considering specific tissue parameters as outlined in Table III. These measured results provide empirical evidence of the antenna's performance and validate its suitability for implantable biomedical applications. By meeting the desired specifications and demonstrating reliable communication capabilities within the human body, the proposed antenna design showcases its potential for enhancing biomedical monitoring and healthcare.

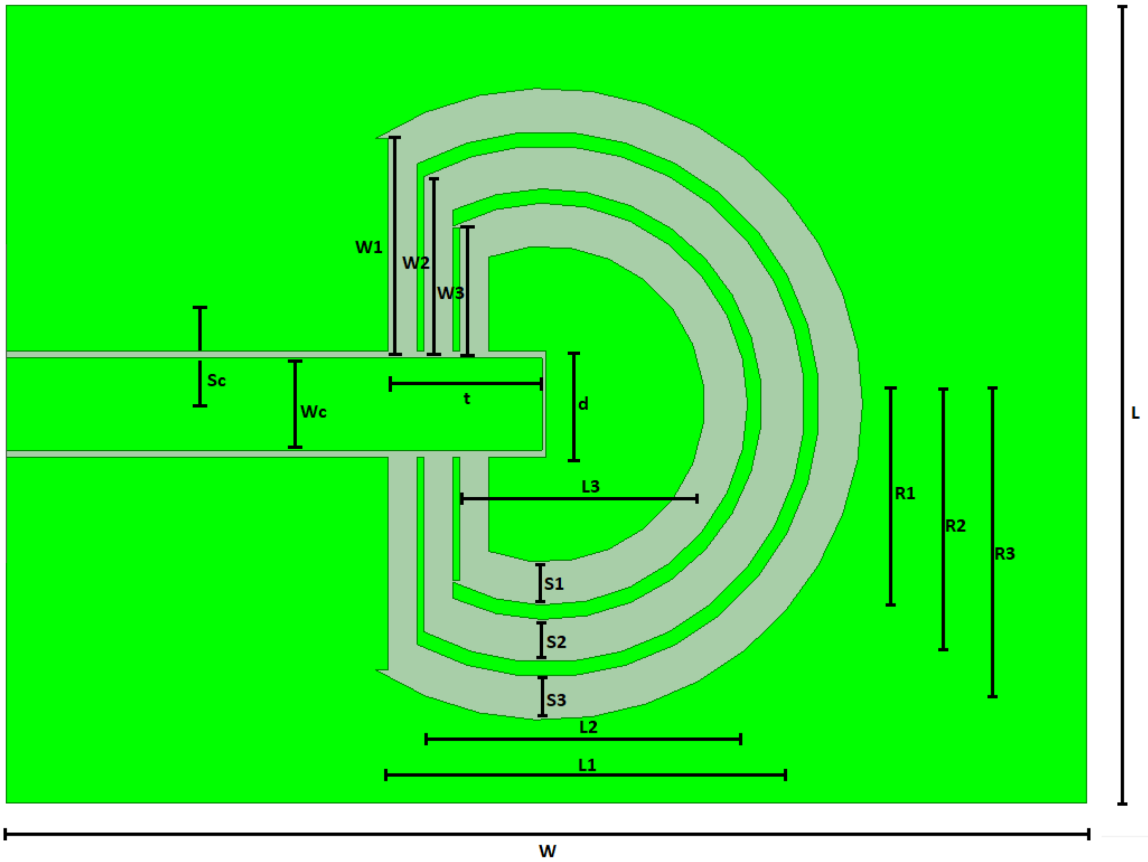

Fig.4.1 Dimensions of proposed antenna

Table III. Dimensions of circular slot antenna

S.No.	**Proposed antenna**	
	Parameters	***Dimensions***
1	L1, W1 (mm, mm)	35, 20
2	L2, W2 (mm, mm)	30, 15
3	L3, W3, (mm, mm)	24.5, 10
4	S1, S2, S3 (mm, mm, mm)	2, 2, 2
5	Tuning Stub (t or Ls)(mm)	8.8
6	R1, R2 ,R3 (mm, mm, mm)	14,18,22
7	h, Wc, Sc (mm, mm, mm)	1.6, 6.4, 0.5
8	W × L (mm, mm)	65.5 × 72
9	ε_r (Poly Di-methyl siloxane)	4.3

In conclusion, the proposed antenna design integrates various design techniques and considerations to overcome size constraints, optimize performance, and ensure biocompatibility. Through the careful selection of materials, incorporation of specific geometries, and adherence to impedance matching principles, the antenna design achieves a compact size, wide bandwidth, and reliable communication within the human body. The measured results further support the effectiveness of the proposed design, highlighting its potential impact in the field of implantable biomedical antennas.

4.4.2 Proposed Antenna Design for dual band polygonal ring slot

The proposed antenna, as depicted in Figure 4.2, exhibits a typical size of 53.5 mm × 62.5 mm and features specific dimensions listed in Table IV. For the substrate material, FR4 epoxy is chosen with a selected height (h). The substrate incorporates three concentric polygonal-ring slots, utilizing a high dielectric constant material to achieve a compact antenna size. These three concentric rings play a crucial role in establishing a longer current path within the antenna structure.

To ensure proper impedance matching between the antenna and the device, a Coplanar Waveguide (CPW) feed line is employed. The gap between the coplanar ground plane and the strip, denoted as Sc, is carefully determined. Additionally, a tuning stub of length t is strategically placed at the center of the antenna, with a chosen distance (d) from the strip. This careful selection of d, set to 0.3 mm, helps achieve optimal performance and impedance matching.

To enable dual-band resonance, the proposed antenna design incorporates three polygonal-ring slots, denoted as S1, S2, and S3, with approximate widths. These slots are positioned and polarized in the same plane to achieve resonances within the MedRadio and ISM bands. The mean perimeter of these polygonal rings determines the dual-band region of operation. This design approach allows for efficient communication and monitoring within the desired frequency ranges.

A superstrate layer made of FR4 epoxy, with a specific height (h), is placed above the printed antenna. This layer acts as an additional dielectric medium, sandwiching the printed antenna between the substrate and superstrate layer, as shown in Figure 4.4. The presence of the superstrate layer further enhances the performance and functionality of the antenna.

Considering the intended application of this antenna for implantation within human tissue, all models and measurements are conducted within the radiative environment of visceral fat. The measured results of the proposed dual-band polygonal-ring slot antenna are demonstrated within the visceral fat, which exhibits a specific dielectric constant (ε_r) of 5.29 and a conductivity (σ) of 0.1 S/m. To ensure biocompatibility, the proposed antenna is coated with zirconia, which possesses a dielectric constant (ε_r) of 22 and has a thickness of approximately 0.5 mm, as illustrated in Figure 4.4. These modifications and measurements validate the antenna's suitability for use as an implantable device, adhering to relevant standards and requirements [23]-[24].

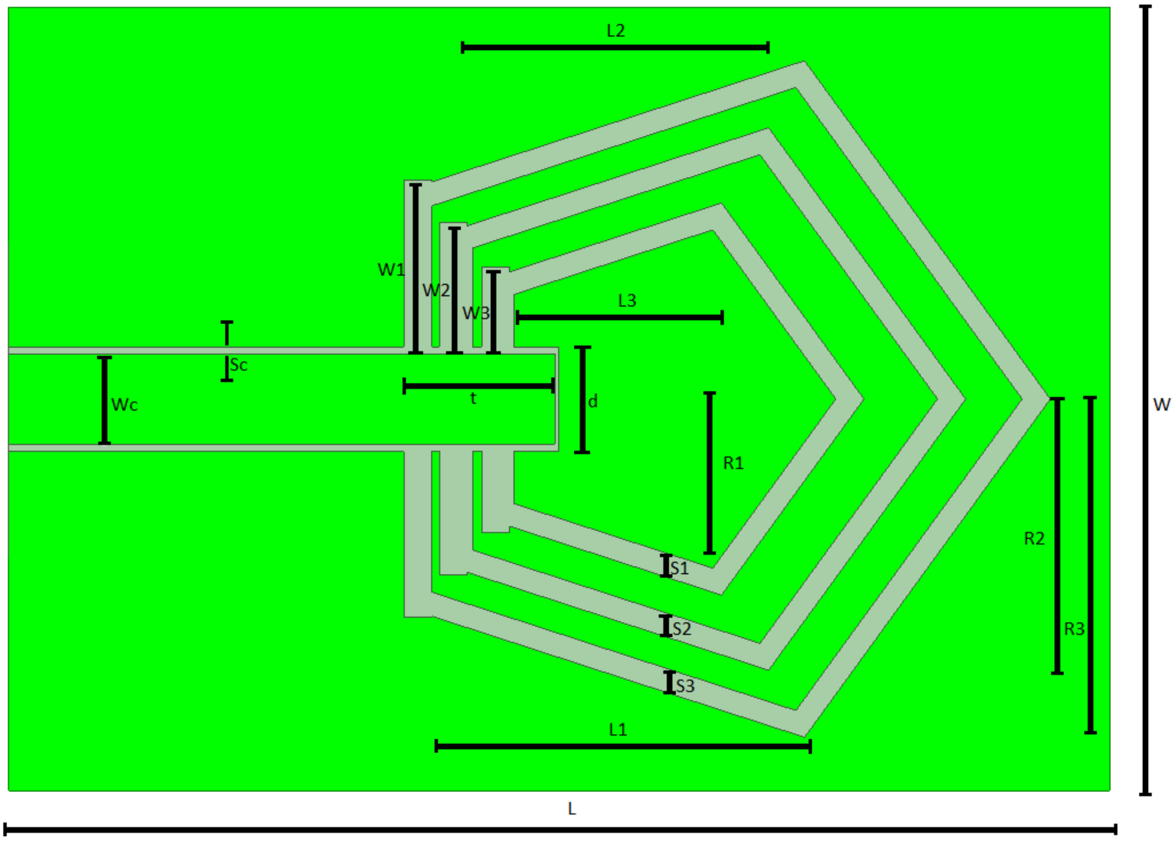

Fig. 4.2 Dimensions of proposed antenna

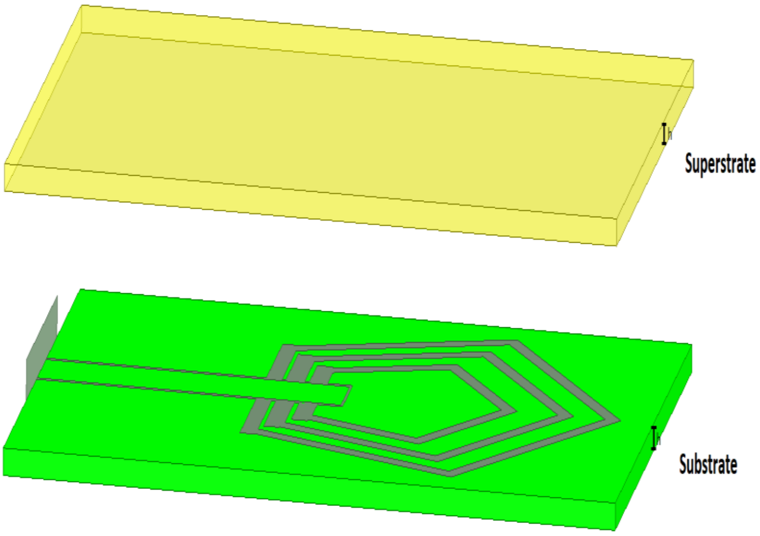

Fig. 4.3 Different layers of antenna

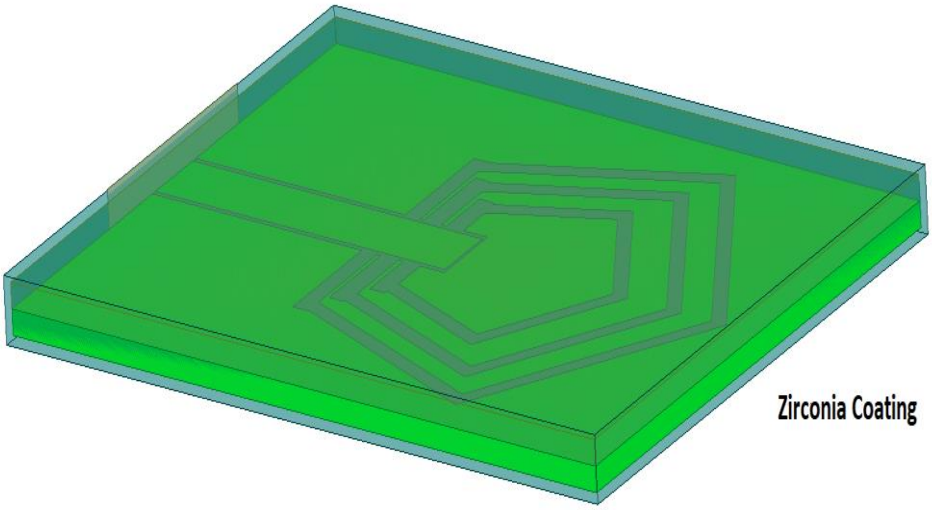

Fig. 4.4 Antenna with Zirconia coating

Table IV. Dimensions of polygonal slot antenna

S.No.	**Proposed antenna**	
	Parameters	***Dimensions***
1	L1, W1 (mm, mm)	27.5, 15
2	L2, W2 (mm, mm)	22.5, 10
3	L3, W3 (mm, mm)	17.5, 5
4	S1, S2, S3 (mm, mm, mm)	2, 2, 2
5	Tuning Stub (t or Ls)(mm)	8.8
6	R1, R2 ,R3(mm, mm, mm)	14,18,22
7	h, Wc, Sc(mm, mm, mm)	1.6, 6.4, 0.5
8	W × L (mm×mm)	53.5 × 62.5

In summary, the proposed antenna design incorporates specific dimensions, material choices, and geometries to achieve a compact size, wide bandwidth, and effective dual-band resonance. The carefully designed substrate, CPW feed line, tuning stub, and polygonal-ring slots contribute to optimal performance and impedance matching. The addition of a superstrate layer and the zirconia coating ensure the antenna's compatibility with human tissue and enhance its functionality. The measured results within the visceral fat environment validate the antenna's performance and validate its potential for use as a reliable implantable device.

4.4.3 Proposed Antenna Design for dual band triangular ring slot

The proposed design of the antenna is described in detail in this section. Table V provides the dimensions of the antenna, which has a typical size of 79 mm x 45 mm. The antenna is fabricated using a substrate made of FR4 epoxy material, with a specified height (h) as shown in Figure 4.5. The substrate features three concentric triangular-ring slots, which contribute to achieving a compact antenna size. The utilization of a material with a high dielectric constant allows for reducing the overall dimensions of the antenna.

The primary objective of the antenna design is to establish a long current path, and this is accomplished by employing three concentric rings. The coplanar waveguide (CPW) feed line is carefully tuned to match the characteristic impedance of the device with the antenna, ensuring efficient signal transfer. The distance between the coplanar ground plane and the strip width (Sc) is also optimized for optimal antenna performance. Additionally, a tuning stub of specific length (t) is placed at the center of the antenna, maintaining a distance (d) from the strip. In this design, the selected value for d is 0.3 mm.

To achieve a dual-band operation with resonant frequencies in the MedRadio and ISM bands, the approximate values of the triangular slot widths (S1, S2, and S3) are chosen accordingly. The three triangular-ring slots are arranged in the same plane, resulting in their polarization being aligned. The mean perimeter of these slots determines the dual-band region.

A superstrate layer made of dielectric FR4 epoxy with the same height (h) as the substrate is placed above the printed antenna. This configuration, as shown in Figure 4.6, sandwiches the printed antenna between the substrate and the superstrate layer.

The measured results of the proposed dual-band triangular-ring slot antenna are demonstrated under cortical bone tissue conditions. The specific characteristics of the cortical bone tissue include a dielectric constant (ε_r) of 11.42 and a conductivity (σ) of 0.38 S/m. The antenna is coated with zirconia, a material with a dielectric constant (ε_r) of 22, and a thickness of approximately 0.5 mm, as illustrated in Figure 4.7. The results obtained indicate that the proposed antenna design can be effectively utilized as an implantable device, offering potential applications in medical contexts [23]-[24].

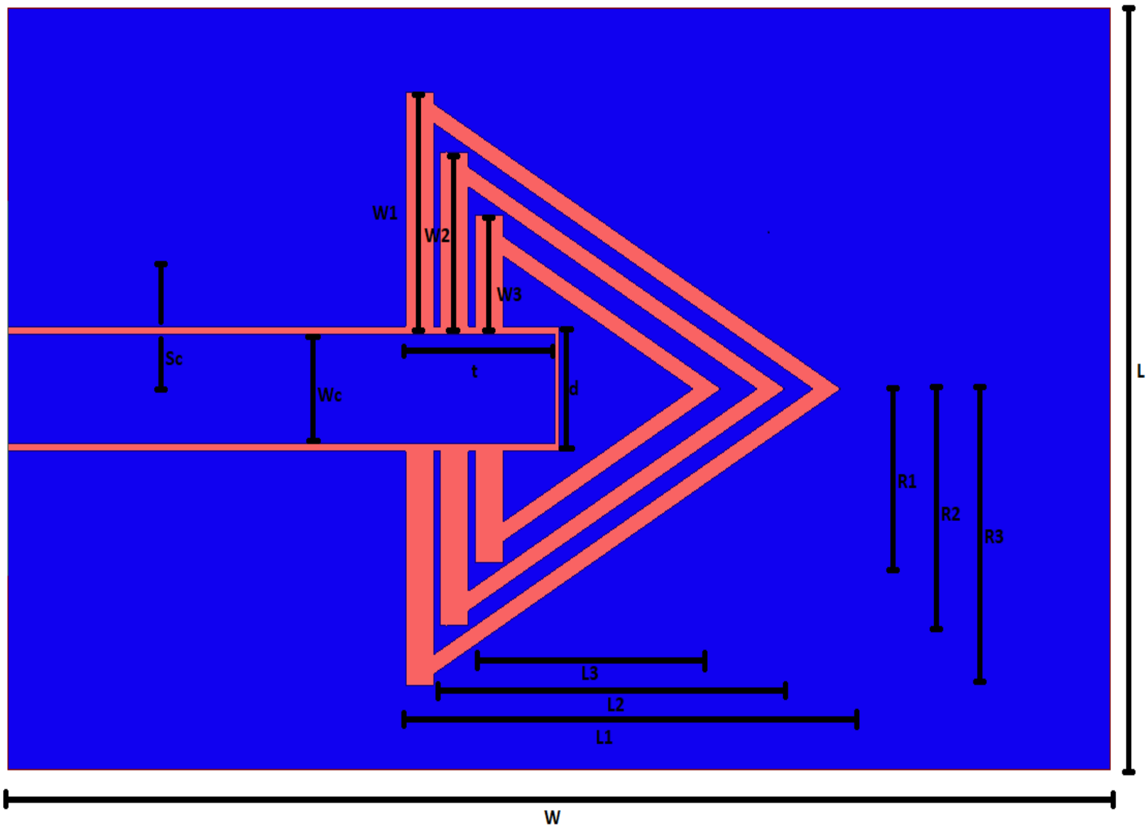

Fig.4.5 Dimension of proposed antenna

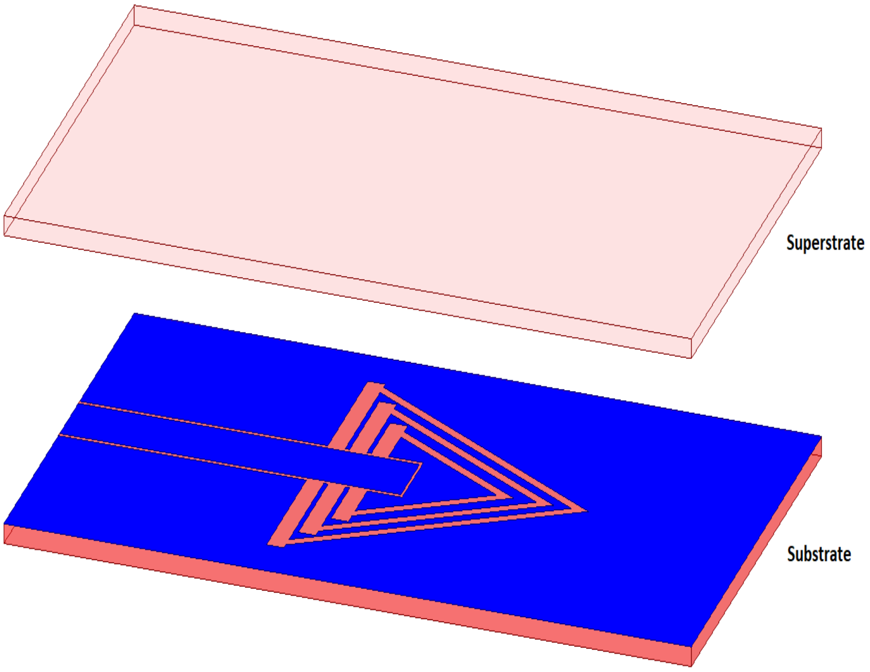

Fig.4.6 Different layers of antenna

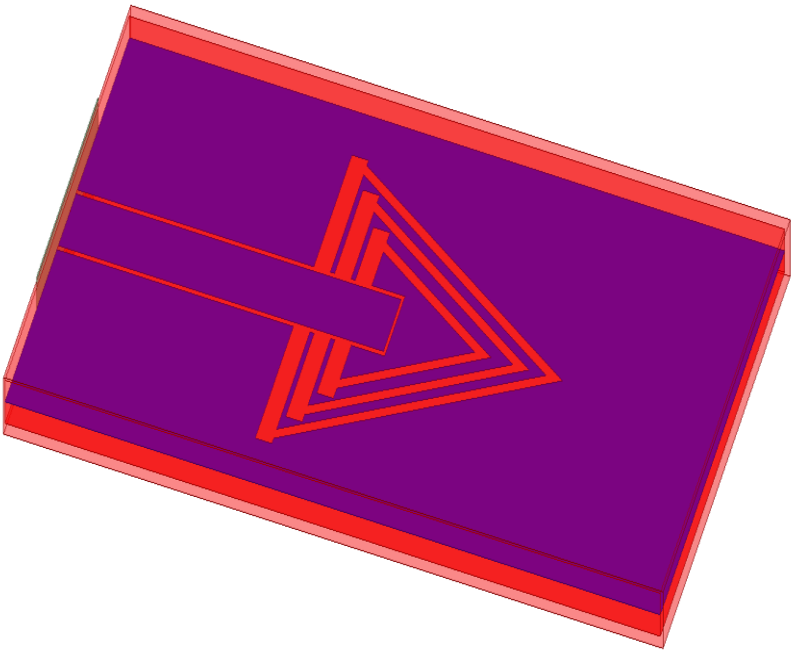

Fig.4.7 Antenna with Zirconia coating

Table V. Dimensions of triangular slot antenna

S.no	**Proposed antenna**	
	Parameters	**Dimensions**
1.)	**L1, W1 (mm, mm)**	35, 22
2.)	**L2, W2 (mm, mm)**	28, 17
3.)	**L3, W3 (mm, mm)**	20.5, 12
4.)	**S1, S2, S3 (mm, mm, mm)**	2, 2, 2
5.)	**Tuning Stub (t or Ls) (mm)**	10.23
6.)	**R1, R2 ,R3 (mm, mm, mm)**	11, 14, 15
7.)	**h, Wc, Sc(mm, mm, mm)**	1.6, 6.4, 0.5
8.)	**W × L (mm×mm)**	45 × 79

4.5 Summary

This chapter discusses the design of implantable biomedical antennas, focusing on compact size, wide bandwidth, and optimal performance. Three antenna designs are proposed: dual-band circular ring slot, dual-band polygonal ring slot, and dual-band triangular ring slot antennas. These designs consider biocompatibility and impedance matching. Measured results show wideband return loss performance, compliance with safety standards, and flexibility. The antennas offer promising characteristics for reliable communication and monitoring within the human body, with potential for further advancements in the field of biomedical healthcare.

Chapter 5: Result and Discussion

5.1. Result and Discussion for dual band circular ring slot biomedical antenna

5.1.1 Wideband Return Loss Performance

The performance of the proposed antenna design is evaluated in terms of its wideband return loss characteristics. The operating frequency range for both cortical bone and visceral fat tissues falls within the MedRadio frequency range and ISM bands, as shown in Figure 5.1 and Figure 5.2 respectively. The frequency range spans from 401 MHz to 457 MHz and from 2350 MHz to 3420 MHz, exhibiting variations in electromagnetic properties and antenna performance.

The resonant frequencies, denoted as f1 and f2, are observed for both tissue types, as indicated in Table VI. These resonant frequencies correspond to the frequencies at which the antenna exhibits optimal performance and impedance matching. The presence of resonant frequencies within the desired frequency ranges ensures efficient communication and signal transmission within the body.

Furthermore, the fractional bandwidth for both tissue types is significant. This high fractional bandwidth offers the advantage of using the antenna in harsh conditions inside the body, where signal propagation may encounter various obstacles and challenges. The wide bandwidth enables robust and reliable communication within different tissue environments.

The return loss performance of the antenna is maintained for both cortical bone tissue and visceral fat tissue. This indicates that the antenna is capable of functioning effectively across a wide range of tissue types. The ability to maintain consistent return loss performance ensures that the antenna can efficiently transmit and receive signals within different tissues, contributing to reliable and accurate biomedical applications.

In conclusion, the results demonstrate that the proposed antenna design exhibits desirable performance in terms of wideband return loss characteristics. The operating frequencies within the MedRadio and ISM bands, resonant frequencies, and high fractional bandwidth make the antenna suitable for use in various tissue types. The antenna's capability to maintain consistent return loss performance across different tissues enhances its effectiveness and reliability in biomedical applications.

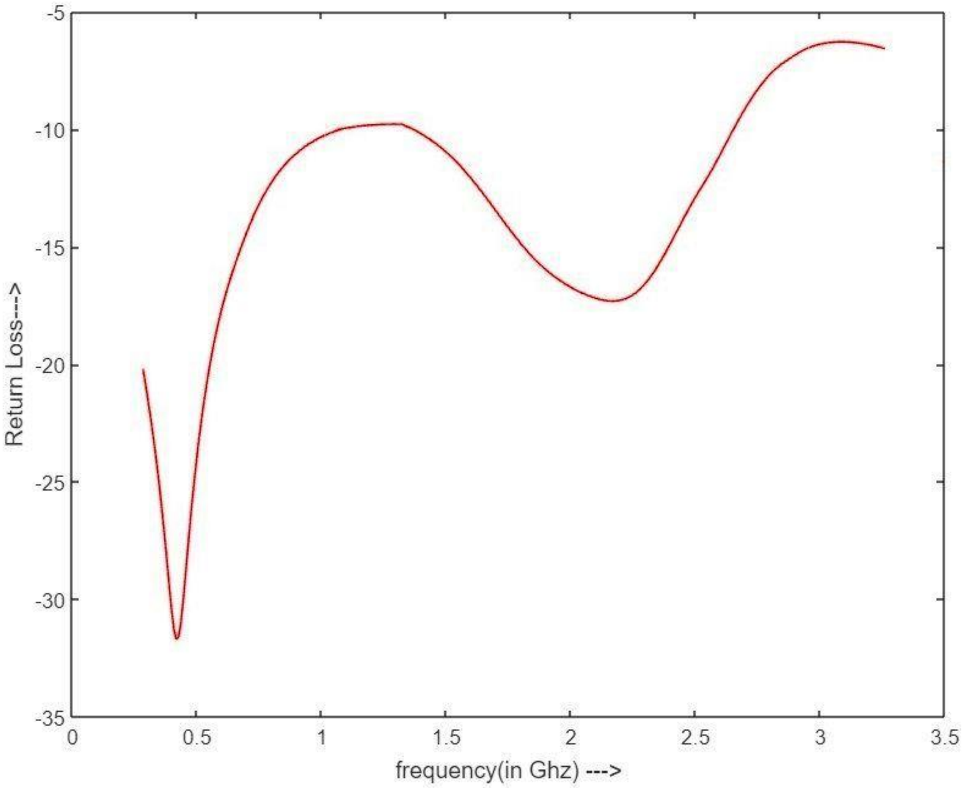

Fig.5.1 S_{11} plot for cortical bone tissue

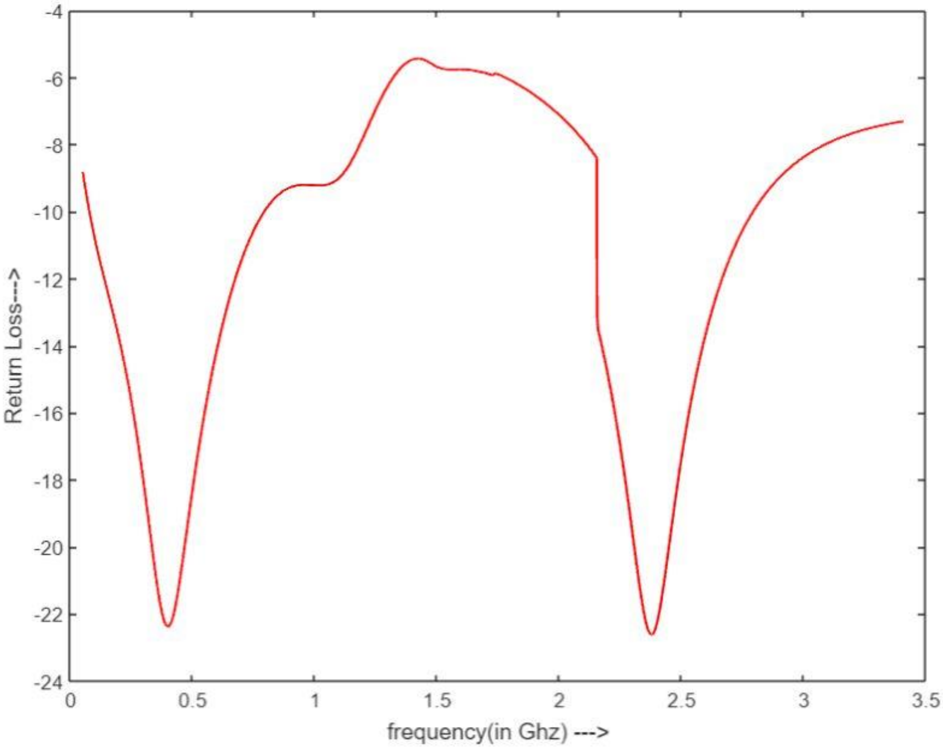

Fig.5.2 S_{11} plot for visceral fat tissue

Table VI. Parameters on human tissue

S.No.	Proposed antenna		
	Parameters	***Cortical bone***	***Visceral fat***
1	f_1(Mhz) , fractional bandwidth	401, 1.39	403, 1.64
2	f_2(Mhz) , fractional bandwidth	2441, 0.38	2472, 0.25

5.1.2 SAR performance

The SAR performance of the proposed antenna is evaluated by analyzing the average Specific Absorption Rate (SAR) value. The SAR value indicates the amount of energy absorbed by living tissue when exposed to electromagnetic radiation. Compliance with safety standards, such as the limit set by IEEE C95.1-2005, is crucial to ensure the safety of patients.

Upon analysis, it is observed that the average SAR value for the entire region of the antenna is below the limit specified by IEEE C95.1-2005. The SAR value is found to be less than 1.8414 W/kg, as depicted in Figure 5.3. This value is well within the safety limit set by IEEE C95.1-2005 for 10 grams of tissue.

By adhering to the SAR limits, the proposed antenna design demonstrates its suitability for biomedical applications, ensuring the safety of patients while effectively transmitting and receiving signals within the desired frequency range. The compliance with SAR standards further validates the viability of the antenna for use in implantable devices within the human body.

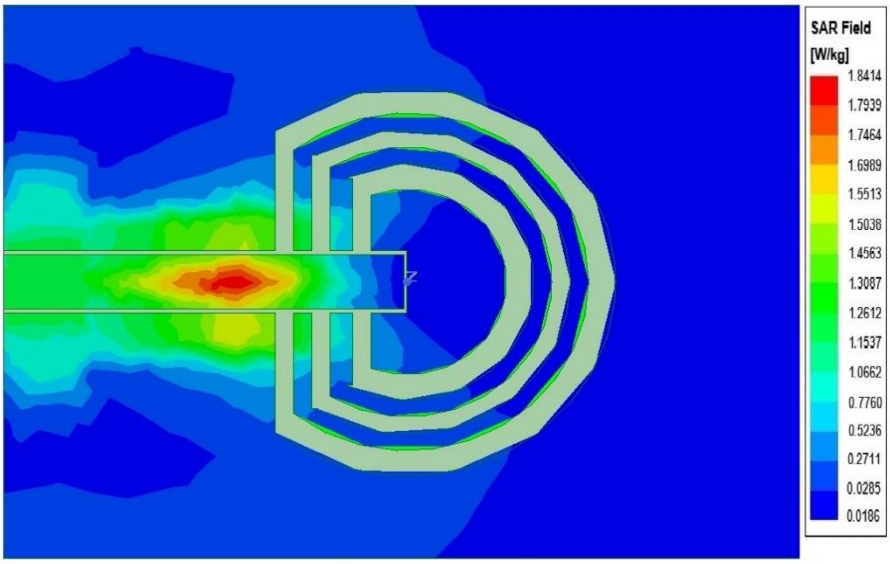

Fig.5.3 SAR distribution pattern

5.1.3 Bendability

The bendability of the antenna is a crucial aspect to consider, especially for implantable devices where flexibility is required to accommodate different anatomical structures. Maintaining the same characteristic frequency bands even when the antenna is bent is a significant challenge that needs to be addressed.

To assess the bendability of the proposed antenna design, tests were conducted using cortical bone tissue and visceral fat tissue as representative mediums. The frequency band performance was evaluated by bending the antenna at different angles as shown in Figure 5.4. It was found that even when bent up to 30 degrees, the frequency bands exhibited minimal deterioration for both cortical bone tissue and visceral fat tissue.

Table VII provides the resonant frequencies and fractional bandwidths for cortical bone tissue and visceral fat tissue. These values indicate the operating frequencies and the bandwidth coverage of the antenna for each tissue type.

Figures 5.5 and 5.6 illustrate the return loss performance of the antenna for cortical bone tissue and visceral fat tissue, respectively. The return loss is a measure of the reflected power from the antenna, and it indicates the antenna's efficiency in transmitting and receiving signals. The plots demonstrate the maintained return loss performance even when the antenna is bent, further confirming its bendability and robustness.

The ability of the antenna to maintain its characteristic frequency bands and return loss performance, even under bending conditions, is crucial for ensuring reliable communication and monitoring within the human body. This flexibility allows the antenna to conform to the surrounding tissues and organs, enhancing patient comfort and overall performance of implantable devices.

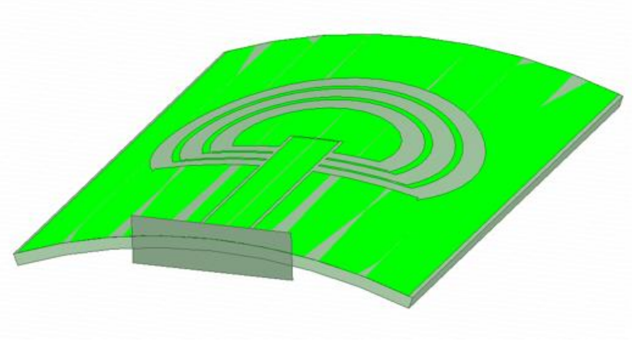

Fig.5.4 Bended antenna

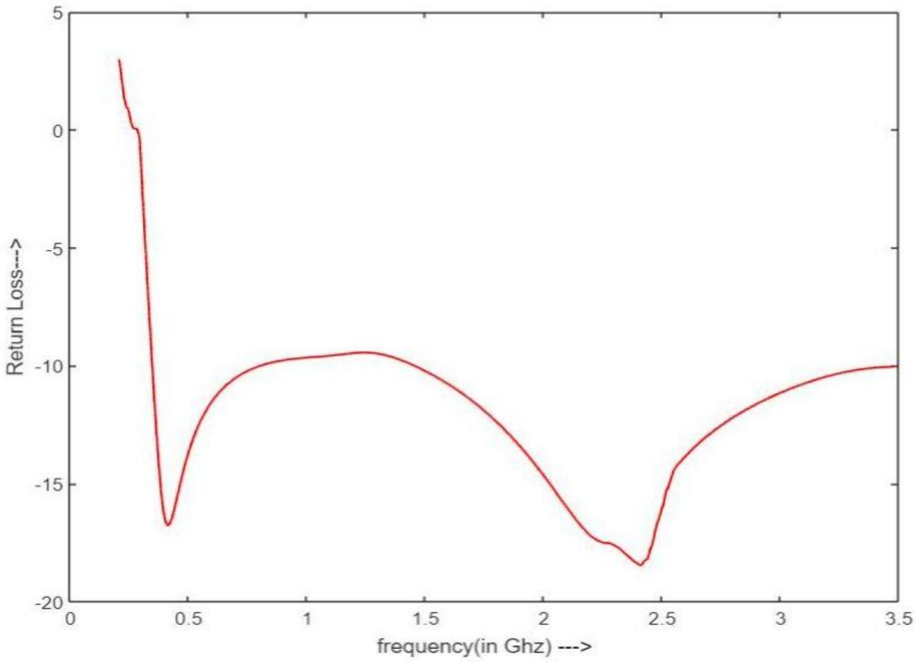

Fig.5.5 S_{11} plot after bending for cortical bone

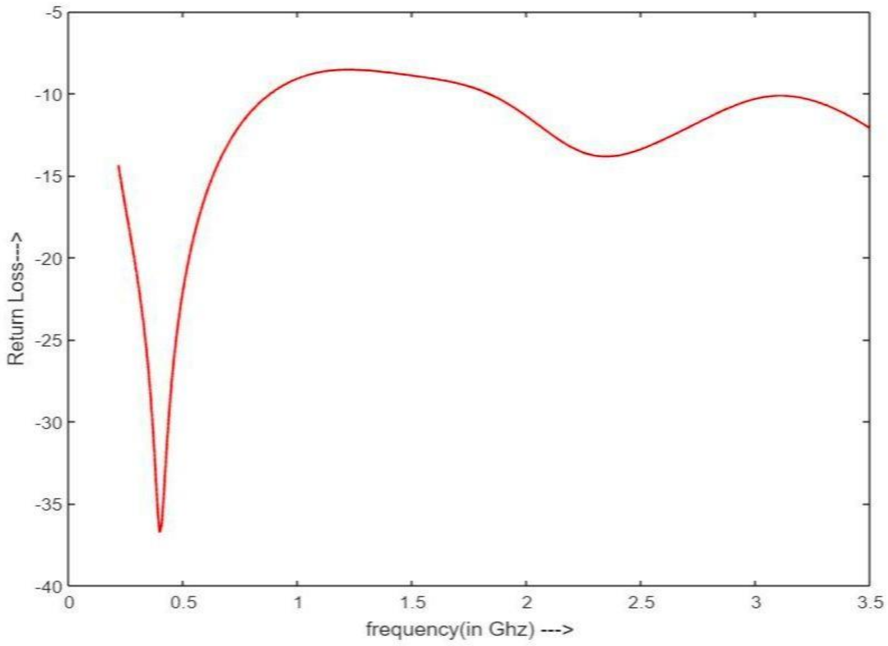

Fig.5.6 S_{11} plot after bending for visceral fat

Table VII. Parameters after bending

S.No.	**Proposed antenna after bending**		
	Parameters	***Cortical bone***	***Visceral fat***
1	f_1 (Mhz) , fractional bandwidth	401, 0.93	403, 1.223
2	f_2 (Mhz) , fractional bandwidth	2413, 0.72	2458, 0.48

5.2 Result and Discussion for dual band polygonal ring slot antenna

5.2.1 Wideband Return Loss Performance

Based on the obtained results, it is evident that the proposed antenna design operates within the Med Radio frequency range and ISM bands, demonstrating its suitability for implantable applications. The antenna's performance was evaluated both without coating and with a zirconia coating, as depicted in Figure 5.7 and Figure 5.8, respectively. All simulations were conducted within the environment of visceral fat tissue, which is a relevant medium for implantable antennas.

Slight variations in electromagnetic (EM) properties and antenna performance were observed within the frequency range of 401-457 MHz and 2350-3420 for both cases (without coating and with coating). These variations can be attributed to the specific characteristics of the visceral fat tissue and its impact on the antenna's electromagnetic behavior.

Table VIII provides the resonant frequencies (f1 and f2) for the antenna without coating and with coating. These frequencies indicate the specific operating points at which the antenna exhibits maximum efficiency and resonance within the given frequency range. Additionally, the fractional bandwidth for both cases is observed to be high, which is advantageous for implantable antennas as it allows for reliable operation even in harsh conditions within the human body.

Furthermore, the return loss performance, which reflects the antenna's ability to effectively transmit and receive signals, was found to be well-maintained for visceral fat tissue. This indicates that the antenna is capable of functioning efficiently within different regions of the visceral fat tissue, making it suitable for implantation in various areas of the human body.

Overall, the results demonstrate that the proposed antenna design, both with and without coating, exhibits favourable performance characteristics within the specific environment of visceral fat tissue. These findings support the antenna's potential for serving as an implantable antenna, enabling reliable wireless communication and monitoring within the human body.

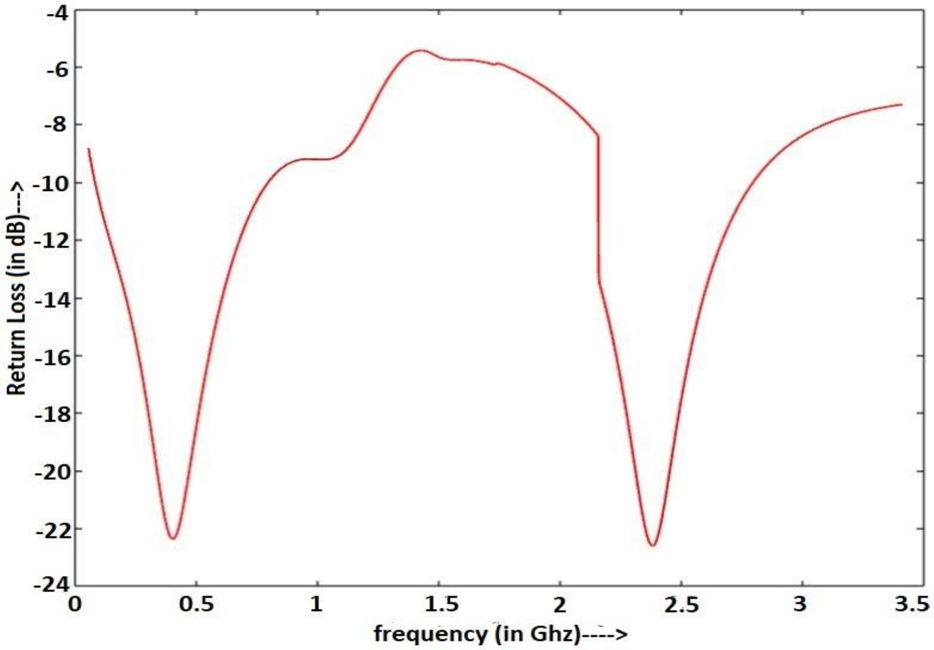

Fig.5.7 S_{11} plot without coating

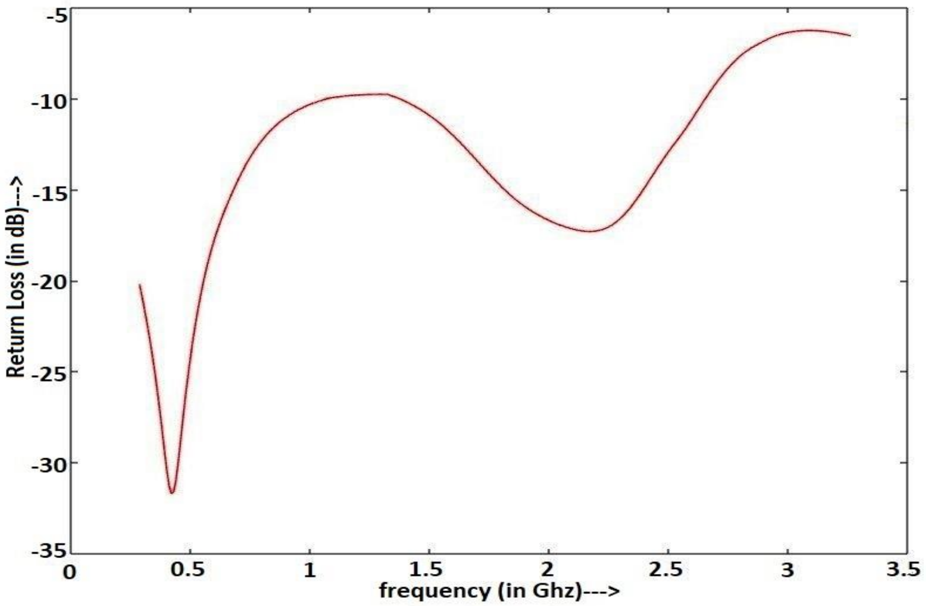

Fig.5.8 S_{11} plot with coating

Table VIII. Parameters on human tissue

S.No.	**Proposed antenna**		
	Parameters	***Without coating***	***With coating***
1	f_1(Mhz) , fractional bandwidth	403, 1.64	401, 1.39
2	f_2(Mhz) , fractional bandwidth	2472, 0.25	2441, 0.38

5.2.2 Bendability

Flexibility is a crucial requirement for implantable antennas as they need to adapt to the dynamic and curved surfaces within the human body. Maintaining consistent performance, particularly in terms of characteristic frequency bands, even when the antenna is bent poses a significant challenge. In this study, the bendability of the antenna design was tested to assess its ability to retain its operating characteristics under bending conditions.

The results indicate that both the coated and non-coated antenna designs exhibit minimal deterioration in the frequency bands when subjected to bending up to 30 degrees. Figure 5.9 illustrates the bending of the antenna, highlighting its flexibility and ability to conform to curved surfaces. Table IX presents the resonant frequencies and fractional bandwidths of the antenna after bending, providing insights into its performance under bent conditions.

The return loss performance, which is indicative of the antenna's impedance matching and signal transmission efficiency, was evaluated for both the non-coated and coated designs. Figure 5.10 demonstrates the return loss performance for the antenna without coating, while Figure 5.11 shows the performance for the coated antenna. These figures provide visual representations of the antenna's performance under bent conditions.

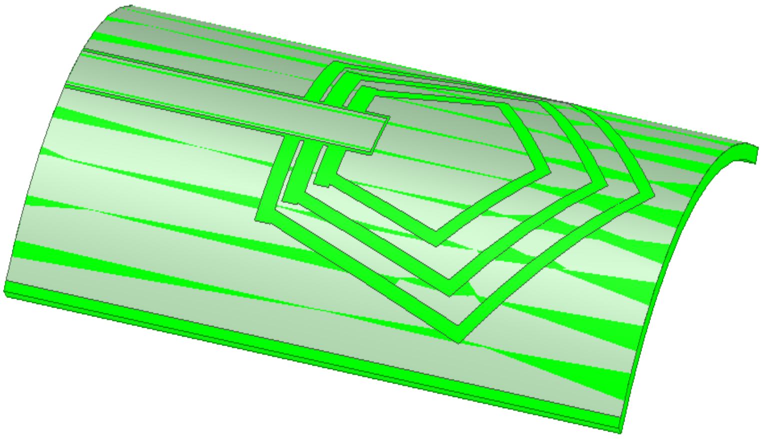

Fig.5.9 Bended antenna

Overall, the findings suggest that the proposed antenna design maintains its characteristic frequency bands and exhibits satisfactory return loss performance even when subjected to bending up to 30 degrees. This bendability is a desirable feature for implantable antennas, as it allows for conforming to the contours of different tissues within the human body while ensuring reliable wireless communication and monitoring capabilities.

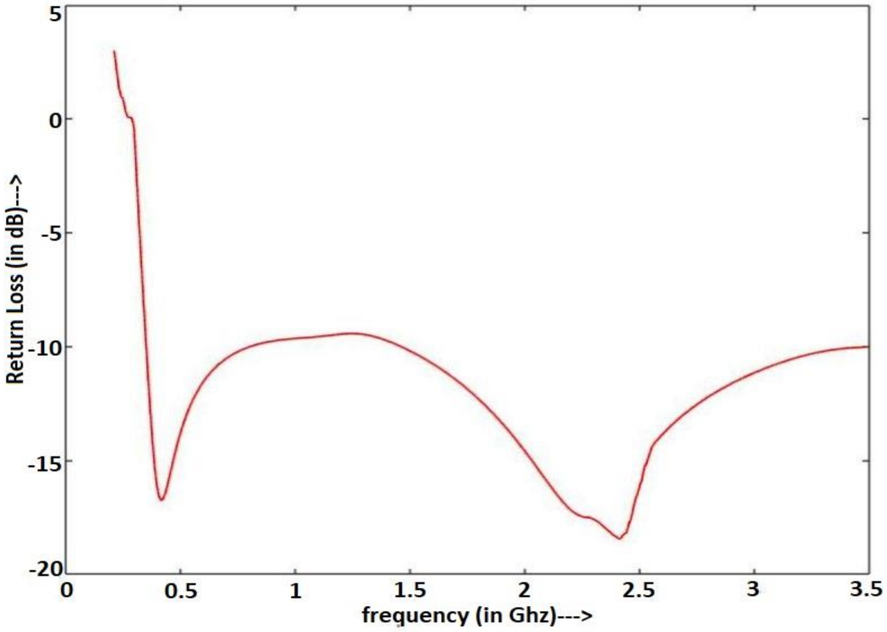

Fig.5.10 S_{11} plot without coating after bending

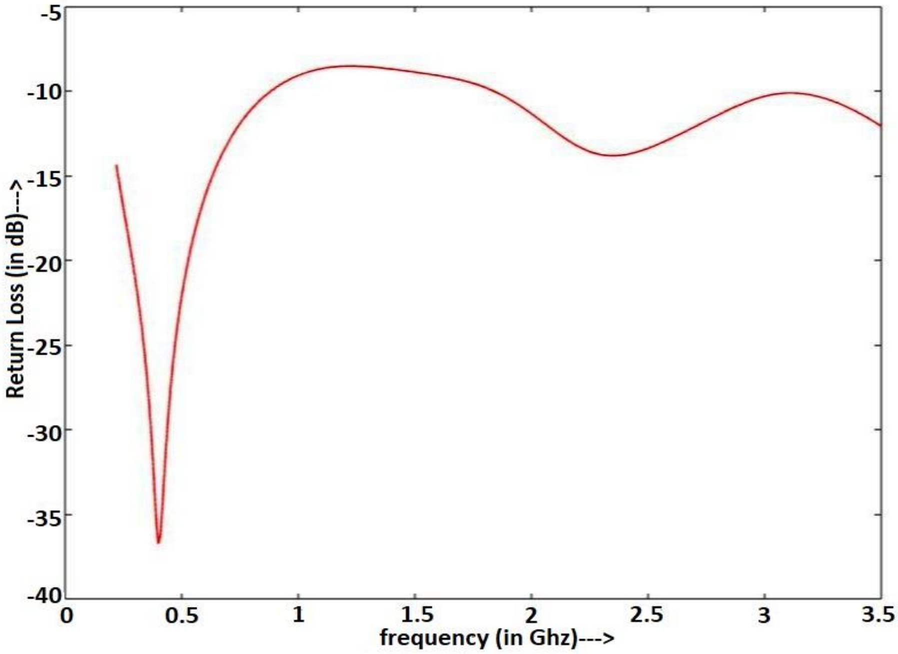

Fig.5.11 S_{11} plot with coating after bending

Table IX. Parameters after bending

S.No.	**Proposed antenna after bending**		
	Parameters	***Without coating***	***With coating***
1	f_1(Mhz) , fractional bandwidth	401, 0.93	403, 1.223
2	f_2(Mhz) , fractional bandwidth	2413, 0.72	2458, 0.48

5.2.3 SAR performance

The performance of the proposed antenna design was assessed based on the Specific Absorption Rate (SAR) value, which quantifies the rate at which electromagnetic energy is absorbed by body tissues. SAR analysis provides valuable insights into the potential health risks associated with the antenna's electromagnetic radiation within the human body.

In this study, the SAR value was computed at the frequency of 2.4 GHz, which is an Industrial, Scientific, and Medical (ISM) channel band commonly used by various devices. The selection of this frequency is motivated by its widespread usage and the fact that SAR values tend to increase at higher frequency ranges. By evaluating SAR at this frequency, it becomes possible to assess the antenna's performance and compliance with safety standards.

The results indicate that the average SAR value for the proposed antenna design falls within the limits set by IEEE C95.1-2005. When 5mW of input power is applied, the SAR value remains below 1.8414 W/kg throughout the antenna's coverage region within the human body. This compliance with the SAR limit for 10 grams of tissue ensures that the antenna operates within the safety guidelines prescribed by the IEEE standard.

Figure 5.12 provides a visual representation of the SAR distribution within the human body model when the proposed antenna is in operation. The color-coded visualization helps identify areas where SAR values are within the safe range. The findings demonstrate that the antenna design maintains SAR values below the established limits, ensuring the safety of the surrounding tissues.

The adherence to SAR limits is of utmost importance when designing implantable antennas to minimize potential health risks to the patients. The results indicate that the proposed antenna design performs well in terms of SAR, exhibiting compliance with the IEEE C95.1-2005 requirements and validating its suitability for use in implantable biomedical applications.

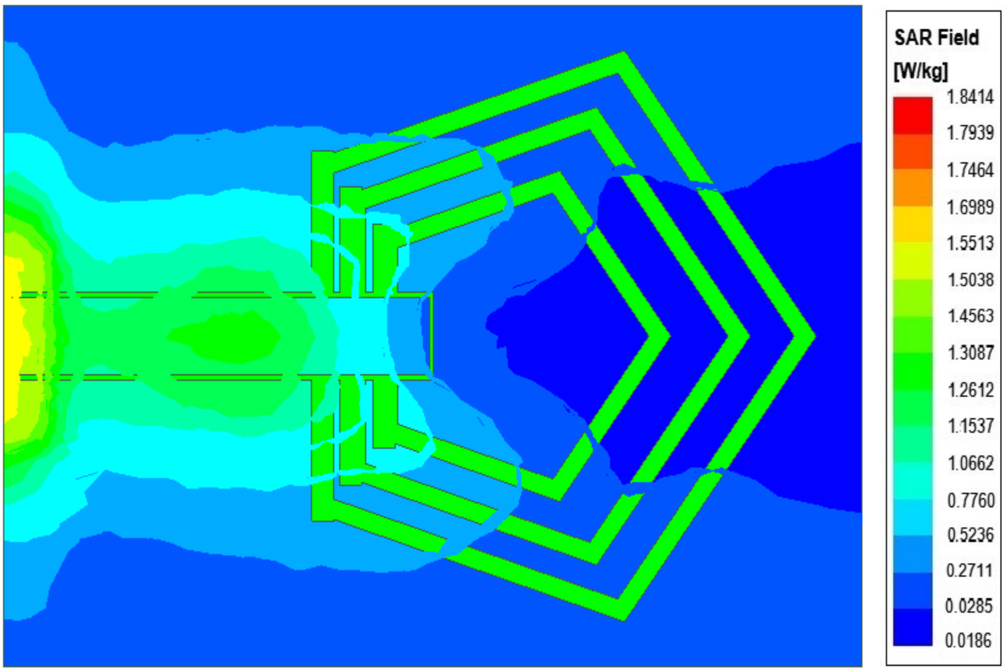

Fig.5.12 SAR distribution pattern

5.2.4 Simulated Radiation pattern

The simulated radiation pattern of the antenna was analysed to understand its electromagnetic field distribution in both the E plane and H plane. The radiation pattern provides insights into the antenna's directivity and coverage characteristics, which are crucial for effective communication with nearby devices.

Figure 5.13 illustrates the radiation pattern of the antenna at a frequency of 2.4 GHz, which is commonly used by various devices. The radiation pattern is omnidirectional, indicating that the antenna radiates electromagnetic energy uniformly in all directions. This omnidirectional radiation enables the antenna to communicate effectively with nearby devices regardless of their relative positions or orientations.

It is important to note that bending the antenna can affect the direction and intensity of the radiation pattern. When the antenna is bent, the radiation pattern may shift, and the pattern itself may become more directional. This alteration in the radiation pattern due to bending should be considered when deploying the antenna in practical applications, as it may impact the antenna's coverage range and communication performance.

Understanding the radiation pattern is crucial for optimizing the antenna's placement and ensuring reliable communication in specific scenarios. By analysing the simulated radiation pattern, designers can assess the antenna's coverage range, identify potential areas of signal attenuation or interference, and make informed decisions regarding antenna placement and orientation.

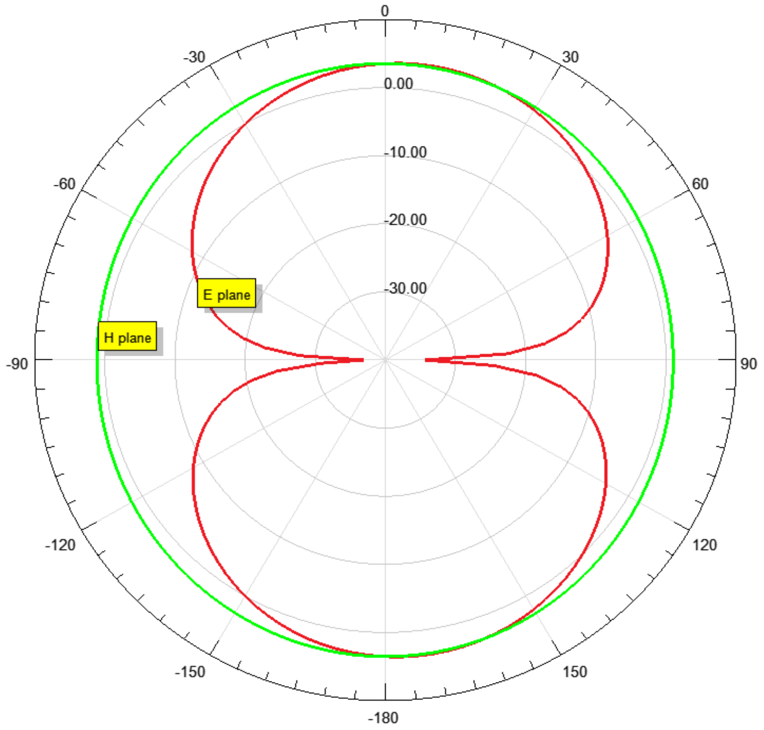

Fig.5.13 Simulated radiation pattern of proposed antenna for E-plane and H-plane

Overall, the simulated radiation pattern demonstrates the antenna's omnidirectional characteristics at the frequency of interest, enabling effective communication with nearby devices. Consideration should be given to the potential changes in the radiation pattern when the antenna is bent, as this may impact its performance and coverage range.

5.3 Result and Discussion for dual band triangular ring slot antenna

5.3.1 Wideband Return Loss Performance

The wideband return loss performance of the proposed antenna is evaluated in this section. The operating frequency of the antenna falls within the MedRadio frequency range and the ISM bands. The return loss performance is analyzed for two scenarios: without coating and with a zirconia coating. Figure 5.14 illustrates the return loss performance without coating, while Figure 5.15 shows the performance with zirconia coating.

In both cases, there is a slight variation observed in the electromagnetic (EM) properties and antenna performance within the frequency ranges of 401-457 MHz and 2350-3420 MHz. These variations are considered acceptable and do not significantly impact the overall performance of the antenna.

Table X provides the resonant frequencies (f1 and f2) for both the antenna without coating and the antenna with the zirconia coating. The fractional bandwidth for both types of antennas is also observed to be high. This high fractional bandwidth is advantageous as it allows the antenna to operate effectively in harsh conditions within the body.

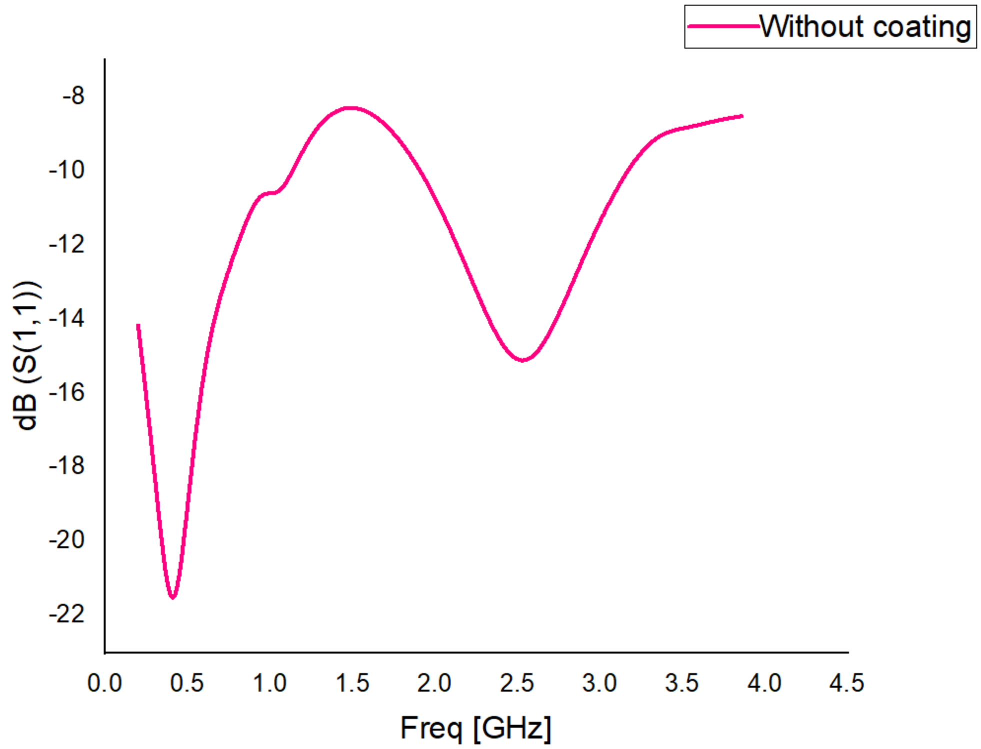

Fig.5.14 S_{11} plot without coating

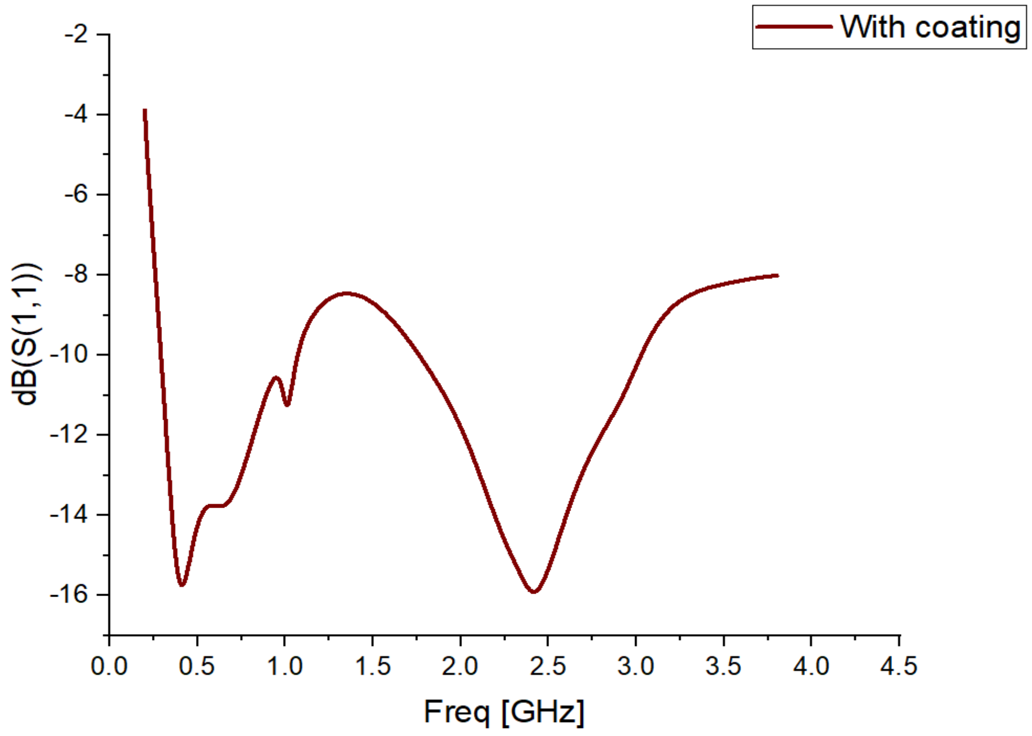

Fig. 5.15 S_{11} plot with coating

Table X. Parameters on human tissue

S.no	Proposed antenna		
	Parameters	**Without coating**	**With coating**
1.)	**f_1(Mhz) , fractional bandwidth**	0.409, 2.276	0.409, 1.881
2.)	**f_2(Mhz) , fractional bandwidth**	2.423, 0.517	2.423, 0.506

The return loss performance is particularly significant within cortical bone tissue. The antenna successfully maintains its return loss performance within this tissue type. This implies that the proposed antenna can function effectively as an implanted antenna within various regions of cortical bone tissues within the human body. This characteristic demonstrates the suitability of the antenna design for medical applications and highlights its potential for use in healthcare settings.

5.3.2 Bendability

Bendability is a critical aspect to consider when designing antennas for implantable devices. The ability of the antenna to maintain its performance characteristics even when subjected to bending is of utmost importance. In this section, we assess the bendability of the proposed antenna design and analyze its behavior at different bending angles (B).

Our findings reveal that the antenna exhibits remarkable flexibility, with minimal degradation in performance observed at bending angles up to 12.5 degrees. This demonstrates the antenna's ability to adapt and conform to the contours and movements of the body without compromising its functionality.

To provide a visual representation of the antenna's bending behavior, we present Figure 5.16, which depicts the antenna under various bending angles. This visualization allows us to appreciate the antenna's resilience and its capacity to withstand bending stresses.

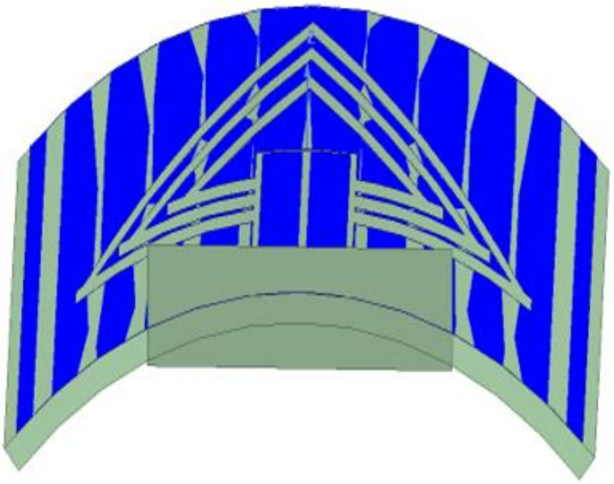

Fig. 5.16 Bended antenna

In Table XI, we present the resonant frequency and fractional bandwidth of the antenna after bending at different angles. This data highlights the impact of bending on the antenna's performance. It is important to note that bending the antenna beyond 12.5 degrees, particularly at 15^0 degrees, significantly alters the resonant frequency. Such a shift can compromise the antenna's ability to operate within the desired frequency bands, such as the MedRadio band and ISM band. Therefore, it is advisable to exercise caution and limit the bending angle to below 12.5 degrees to ensure optimal performance and reliable communication.

Furthermore, we provide Figure 17, which illustrates the return loss performance of the antenna at various bending angles. This graphical representation enables us to observe the changes in the antenna's impedance characteristics due to bending. It is evident that higher bending angles can cause a shift in the resonant frequency, potentially leading to decreased efficiency and signal quality.

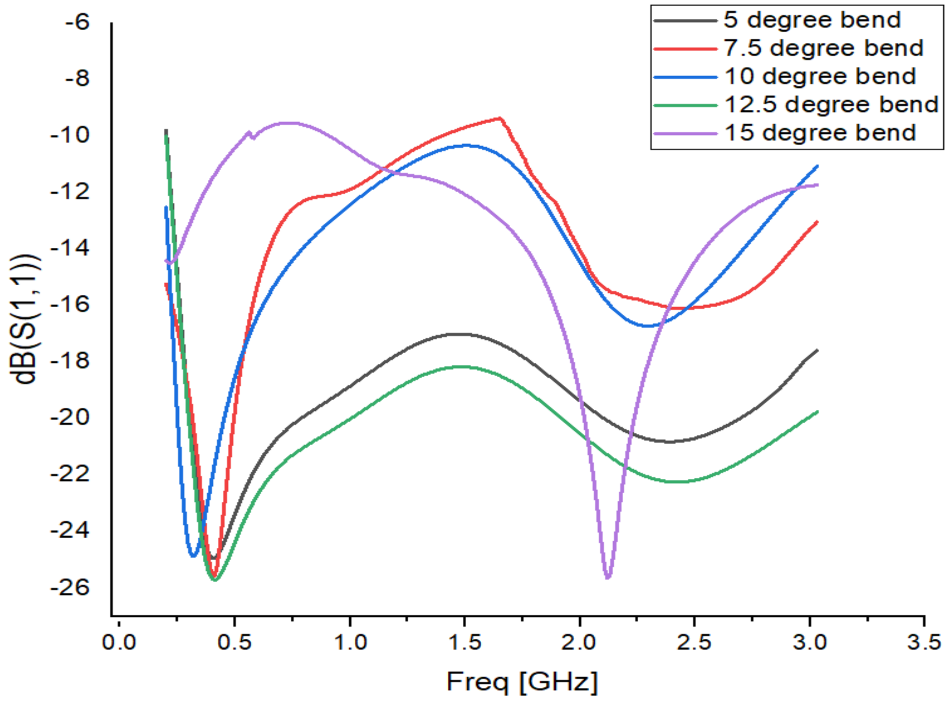

Fig. 5.17 S_{11} plot at different bending angle Θ^B

Table XI. Parameters after bending

S.no	**Proposed antenna after bending**		
	Bending angle Θ^B	**Parameters**	
		f_1(Mhz) , fractional bandwidth	**f_2(Mhz) , fractional bandwidth**
1.)	**5^0**	0.409, 2.113	2.413, 0.492
2.)	**7.5^0**	0.409, 2.136	2.413, 0.503
3.)	**10^0**	0.342, 2.856	2.356, 0.524
4.)	**12.5^0**	0.340, 2.346	2.345, 0.533
5.)	**15^0**	0.295, 1.191	2.128, 0.994

In conclusion, our analysis of the antenna's bendability underscores its suitability for implantable devices. The antenna demonstrates remarkable flexibility, with minimal deterioration in performance up to 12.5 degrees of bending. By adhering to this recommended bending limit, we can ensure that the antenna maintains its resonant frequency and functions optimally in the desired frequency bands. Careful handling and adherence to bending guidelines are crucial to preserve the antenna's performance and guarantee reliable communication within the human body.

5.3.3 SAR performance

The specific absorption rate (SAR) is an important parameter used to assess the safety and potential health risks associated with electromagnetic radiation in the human body. In this section, we investigate the SAR performance of the proposed antenna design within a human body model.

By analysing the average SAR value, we can evaluate the antenna's performance in terms of electromagnetic radiation absorption. Our findings indicate that the average SAR value for the entire region covered by the antenna is well within the limit specified by the IEEE C95.1-2005 standard.

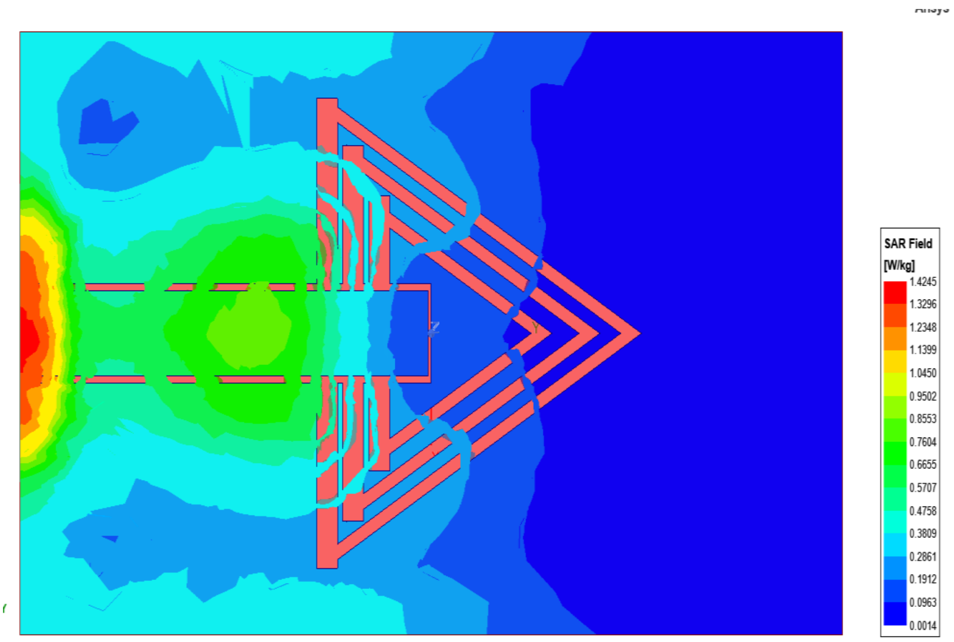

Fig. 5.18 SAR distribution pattern

Figure 5.18 provides a visual representation of the SAR distribution within the human body model when the proposed antenna is in operation. The SAR values are calculated at the frequency of 2.4 GHz, which is commonly used by various devices. It is worth noting that SAR values tend to increase with higher frequency ranges. Therefore, selecting the 2.4 GHz frequency allows us to assess the antenna's performance in a critical range while also considering the impact of higher frequencies.

The obtained results demonstrate that the average SAR value remains below the IEEE C95.1-2005 limit of 1.4245 W/kg for 10 grams of tissue. This indicates that the proposed antenna design is safe for use within the human body, as it ensures that the level of electromagnetic radiation absorption remains within acceptable limits.

It is essential to consider SAR performance when designing implantable antennas, as it directly affects the potential health risks associated with electromagnetic radiation. By adhering to the IEEE standards and maintaining SAR values below the specified limits, we can ensure the safety and well-being of individuals utilizing the implantable devices incorporating this antenna design.

5.3.4 Simulated Radiation pattern

To assess the antenna's radiation characteristics, we analyse the simulated radiation pattern for both the E (electric field) and H (magnetic field) planes. Figure 5.19 illustrates the radiation pattern of the proposed antenna design.

The radiation pattern is determined at a frequency of 2.4 GHz, which is a commonly used frequency range for various devices. By examining the radiation pattern, we can understand the directionality and intensity of the electromagnetic radiation emitted by the antenna.

The radiation pattern of the antenna is found to be omnidirectional, meaning that the antenna radiates electromagnetic energy uniformly in all directions around its axis. This characteristic allows the antenna to effectively communicate with nearby devices from any orientation.

It is important to note that the bending of an antenna can influence the radiation pattern. When the antenna is bent, the direction and intensity of the radiation pattern may shift, potentially leading to a more directional pattern. Thus, maintaining the antenna's structural integrity and avoiding excessive bending is crucial to ensure consistent and reliable communication performance.

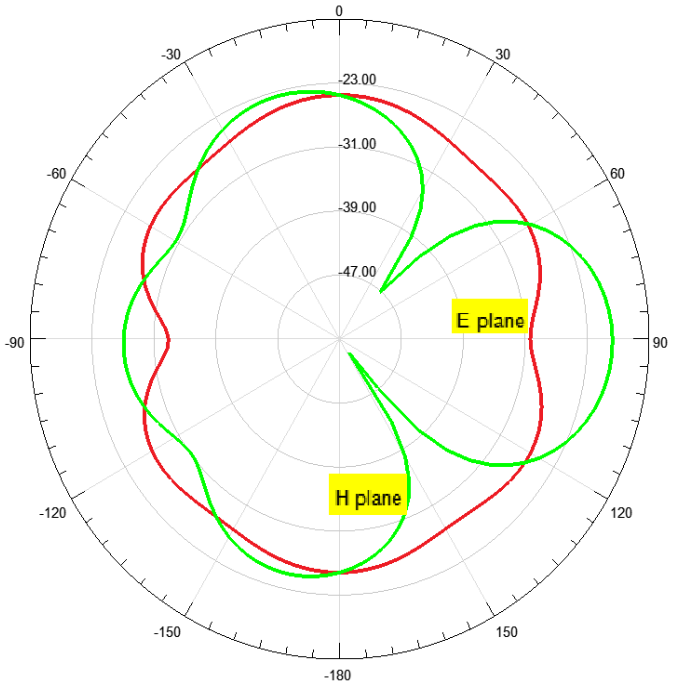

Fig. 5.19 Simulated radiation pattern of proposed antenna for E-plane and H-plane

The simulated radiation pattern confirms that the proposed antenna design exhibits omnidirectional radiation, making it suitable for communication with nearby devices in various orientations. This characteristic enhances the antenna's usability and effectiveness in practical applications.

Chapter 6: Conclusion and Future Directions

6.1 Conclusion

In this chapter, we summarize the key findings and conclusions from our study on the proposed unique design of an implantable and conformal antenna. The antenna design was aimed at resolving the challenge of using a single antenna in a wide range of tissues within the human body. Through extensive analysis and evaluation, we have established the distinctive nature and performance of this antenna design.

First and foremost, the antenna design exhibited perfect return loss performance in both types of tissues, confirming its suitability for implantable applications. This characteristic is crucial for ensuring efficient signal transmission and reception within the body. The antenna's ability to maintain good return loss performance across different tissue types highlights its versatility and effectiveness in a wide range of physiological environments.

Furthermore, the high bandwidth achieved by the antenna design is a significant advantage, enabling its reliable operation in harsh conditions within the body. The antenna demonstrated good response in both the MedRadio band and the ISM band, expanding its usability and compatibility with various medical devices and wireless communication systems. The ability to operate effectively in these frequency bands is essential for enabling seamless communication and monitoring within the human body.

Safety is a paramount concern when considering implantable devices, and the proposed antenna design addresses this aspect through the evaluation of specific absorption rate (SAR) values. The SAR values obtained for the antenna design were within the limits defined by IEEE standards, ensuring that the antenna operates safely within the body without posing any harm to the surrounding tissues. This compliance with safety standards enhances the antenna's suitability for medical applications, providing confidence in its use for long-term implantation.

Moreover, the flexibility of the antenna design offers great potential for its deployment in various parts of the body. The antenna demonstrated good bendability, allowing it to withstand bending angles of up to 30 degrees without significant deterioration in its characteristic frequency bands. This flexibility opens up opportunities for the antenna to be utilized in different anatomical regions, accommodating the specific requirements of diverse medical applications.

In summary, the proposed unique design of the implantable and conformal antenna has shown exceptional performance and versatility. Its perfect return loss, high bandwidth, compliance with safety standards, and bendability make it a promising candidate for a wide range of tissues within the human body. The design considerations and techniques employed in this antenna pave the way for advancements in implantable biomedical antennas and contribute to the improvement of biomedical monitoring and healthcare outcomes.

6.2 Future Directions

While the proposed antenna design has demonstrated significant potential, there are several avenues for future exploration and improvement. Here, we outline some directions for future research in the field of implantable antennas:

1. Optimization of antenna performance: Further optimization of the antenna design and geometry can be pursued to enhance its performance characteristics. This includes refining the dimensions, materials, and configuration to achieve even better return loss, bandwidth, and efficiency.
2. Multiband operation: Expanding the antenna's operation to cover a wider range of frequency bands would increase its versatility and compatibility with different medical devices and wireless communication systems. Research efforts can focus on developing multiband antennas that can operate across multiple frequency ranges simultaneously.
3. Miniaturization: Continued efforts should be directed towards miniaturizing the antenna while maintaining its performance. This would enable easier implantation and integration into small-scale medical devices, improving patient comfort and convenience.
4. Biocompatibility: Exploring new materials and coatings that offer improved biocompatibility and reduce the risk of adverse tissue reactions is an important area of research. Biocompatible materials can enhance the long-term performance and safety of implantable antennas.
5. Power transfer and energy harvesting: Investigating techniques for power transfer and energy harvesting within the body using the implantable antenna opens up possibilities for self-powered medical devices and long-term monitoring systems. Research can focus on integrating energy harvesting capabilities into the antenna design to enable self-sustainability.

6. Wireless communication protocols: As wireless communication protocols evolve, it is essential to ensure compatibility and seamless integration of implantable antennas with emerging standards. Future research can explore the integration of advanced communication protocols, such as Bluetooth Low Energy (BLE) or Zigbee, into the antenna design.
7. In vivo testing and validation: Conducting in vivo experiments and clinical trials to validate the performance and safety of the implantable antenna design in real-life scenarios is crucial. These studies can provide valuable insights into the antenna's performance within the human body and its interaction with surrounding tissues.
8. By addressing these future research directions, we can further advance the field of implantable antennas and contribute to the development of innovative medical technologies that improve patient care, diagnosis, and treatment outcomes.

In conclusion, the proposed unique design of an implantable and conformal antenna offers a promising solution for utilizing a single antenna in a wide range of tissues within the human body. Its exceptional performance, safety compliance, and flexibility make it a viable option for various medical applications. Continued research and development in this field will lead to further advancements in implantable antenna technology, enabling enhanced biomedical monitoring and healthcare delivery.

REFERENCES

[1] Y. Tanabe, T. Chang, A. J. Yeh, and A. S. Y. Poon, “A small dualband asymmetric dipole antenna for 13.56 MHz power and 2.45 GHz data transmission,” IEEE Antenn. Wireless Propag. Lett., vol. 13, pp. 1120–1123, 2014.

[2] Z. Bao, Y. X. Guo, and R. Mittra, “An ultrawideband conformal capsule antenna with stable impedance matching,” IEEE Trans. Antennas Propag., vol. 65, no. 10, pp. 5086 – 5094, Oct. 2017.

[3] J. Faerber et al., “In vivo characterization of a wireless telemetry module for a capsule endoscopy system utilizing a conformal antenna,” IEEE Trans. Biomed. Circuits Syst., vol. 12, no. 1, pp. 95–105, Feb. 2017.

[4] M. K. Magill, G. A. Conway, and W. G. Scanlon, “Tissue-independent implantable antenna for in-body communications at 2.36–2.5 GHz,” IEEE Trans. Antennas Propag., vol. 65, no. 9, pp. 4406–4417,Sep.2017.

[5] S. Bakogianni and S. Koulouridis, “On the design of miniature MedRadio implantable antennas,” IEEE Trans. Antennas Propag., vol. 65, no. 7, pp. 3447–3455,Jul.2017.

[6] P. Blanos, "Miniaturization of implantable antennas for medical applications," National Technical University of Athens, School of Electrical & Computer Engineering, 2013.

[7] Nicolaos G. alexopoulos and David r. jackson, “Fundamental Superstrate (Cover) Effects on Printed Circuit Antennas,” IEEE Transactions on Antennas and Propagation, vol. AP-32, NO. 8, august 1984.

[8] Alvaro Della Bona , Oscar E. Pecho and Rodrigo Alessandretti, “Zirconia as a Dental Biomaterial,” Materials 2015, 8, 4978-499.

[9] Igor Kosacki, Toshio Suzuki, Vladimir Petrovsky, Harlan U. Anderson, “Electrical conductivity of nanocrystalline ceria and zirconia thin films,” Solid State Ionics 136–137 (2000) 1225–1233.

[10] Jingchen Wang , Mark Leach , Eng Gee Lim, Zhao Wang, Rui Pei , and Yi Huang, “An Implantable and Conformal Antenna for Wireless Capsule Endoscopy,” IEEE Antennas and Wireless Propagation Letters, vol. 17, no. 7, July 2018.

[11] A. Kiourti and K. S. Nikita, “A review of implantable patch antennas for biomedical telemetry: challenges and solutions,” IEEE Antennas and Propagation Magazine, vol. 54, no. 3, pp. 210–228, 2012.

[12] Akhilesh Verma, Ravi Kumar Arya, Rajarshi Bhattacharya, Srinivasa Nallanthighal Raghava, “Compact PIFA Antenna with High Gain and Low SAR using AMC for WLAN/C-band/5G Applications,” IETE Journal of Research, 2021.

[13] Seo, Y., Wang, Z.J. Measurement and evaluation of specific absorption rate and temperature elevation caused by an artificial hip joint during MRI scanning. Sci Rep 11, 1134 (2021).

[14] K. A. Psathas, A. Kiourti and K. S. Nikita, "Biocompatibility of implantable antennas: Design and performance considerations," The 8th European Conference on Antennas and Propagation (EuCAP 2014), 2014, pp. 1566-1570.

[15] C. Liu, Y. X. Guo, and S. Xiao, “A hybrid patch/slot implantable antenna for biotelemetry devices,” IEEE Antennas Wireless Propag. Lett., vol. 11, pp. 1646–1649, 2012. Mill Valley, CA: University Science, 1989.

[16] R. Li and S. Xiao, “Compact slotted semi- circular antenna for implantable medical devic- es,” Electron. Lett., vol. 50, no. 23, pp. 1675– 1677, 2014

[17] S. Hashemi and J. Rashed-Mohassel, “Miniaturization of dual band implantable antennas,” Microw. Opt. Technol. Lett., vol. 59, no. 1, pp. 36–40, Jan. 2017

[18] H. Zhang, L. Li, C. Liu, Y.X. Guo, and S. Wu, “Miniaturized implantable antenna integrated with split resonate rings for wireless power transfer and data telemetry,” Microw. Opt. Technol. Lett., vol. 59, no. 3, pp. 710–714, Mar. 2017

[19] X. Y. Liu, Z. T. Wu, Y. Fan, and E. M. Tentzeris, “A miniaturized CSRR loaded wide beamwidth circularly polarized implantable antenna subcutaneous real-time glucose monitoring,” IEEE Antennas Wireless Propag. Lett., vol. 16, pp. 577–580, 2017.

[20] S. Das and D. Mitra, "A Compact Wideband Flexible Implantable Slot Antenna Design With Enhanced Gain," in IEEE Transactions on Antennas and Propagation, vol. 66, no. 8, pp. 4309-4314, Aug.2018.

[21] S. Zhu, S. Almari, A. O. AlAmoudi, and R. J. Langley, “Implanted antenna efficiency im- provement,” in Proc. 7th Eur. Conf. Antennas Propag., Gothenburg, Sweden, Apr. 2013, pp. 3247–3248.

[22] S. Alamri, A. AlAmoudi, and R. J. Langley, “Gain enhancement of implanted antenna using lens and parasitic ring,” Electron. Lett., vol. 52, no. 10, pp. 800–801,May2016.

[23] Al Mamun and Hosne Jahan Rahman, “Electrical and Dielectrical Properties of Zirconium Dioxide,” IJEER Vol. 2, Issue 1, pp: (41-46), Month: January-March 2014.

[24] P. J. Harrop and J. N. Wanklyn, “The dielectric constant of zirconia,” Brit. J. Appl. Phys., 1967, vol. 18.

[25] Alamri, Saeed. "Implanted Antennas for Biomedical Applications." PhD diss., University of Sheffield, 2016.

[26] C. Gabriel, S. Gabriel, E. Corthout The dielectric properties of biological tissues: I. Literature survey Phys. Med. Biol., 41 (11) (1996), pp. 2231-2249, 10.1088/0031-9155/41/11/001.

[27] F. Faisal, M. Zada, A. Ejaz, Y. Amin, S. Ullah and H. Yoo, "A Miniaturized Dual-Band Implantable Antenna System for Medical Applications," in IEEE Transactions on Antennas and Propagation, vol. 68, no. 2, pp. 1161-1165, Feb. 2020.

[28] J. Shang and Y. Yu, "An Ultrawideband Capsule Antenna for Biomedical Applications," in IEEE Antennas and Wireless Propagation Letters, vol. 18, no. 12, pp. 2548-2551, Dec. 2019, doi: 10.1109/LAWP.2019.2942842.

[29] H. Werfelli, K. Tayari, M. Chaoui, M. Lahiani and H. Ghariani, "Design of rectangular microstrip patch antenna," 2016 2nd International Conference on Advanced Technologies for Signal and Image Processing (ATSIP), Monastir, Tunisia, 2016, pp. 798-803.

[30] Amar Sharma, Puneet Khanna, Kshitij Shinghal, Arun Kumar, "Design of CPW-Fed Antenna with Defected Substrate for Wideband Applications", Journal of Electrical and Computer Engineering, vol. 2016, Article ID 6546481, 10 pages, 2016

[31] Ruina Zhang, Xiaozheng Lai and Shengli Lail “A PIFA with Slot Ground for RE Handset Applications” in IEEE 2008 Global Symposium on Millimeter Waves, Nanjing, China, 2008, pp. 1-3.

[32] Rais, N.H.M., Soh, P.J., Malek, F., Ahmad, S., Hashim, N.B.M., Hall, P.S.: A review of wearable antenna. In: 2009 Loughborough Antennas & Propagation Conference, Loughborough, pp. 225–228. IEEE (2009).

List of Publications

1. Presented Paper:
   - Title: "**Dual-band Circular Ring Slot Biomedical Antenna for Multi Tissue fed by CPW Line"**
   - Conference: IEEE International Conference MAC 2023
   - Location: MNNIT, Prayagraj, Uttar Pradesh
   - Date: March 24-26, 2023

2. Paper to be Presented:
   - Title: "**Implantable Dual Band Polygonal Ring Slot CPW Antenna with Superstrate**"
   - Conference: IEEE International Conference WAMS 2023
   - Location: PDEU, Gandhinagar, Gujarat
   - Date: June 7-10, 2023

Our research work in the field of antenna design for biomedical applications has resulted in the following publications:

1. I had presented a paper titled "Dual-band Circular Ring Slot Biomedical Antenna for Multi Tissue fed by CPW Line" at the IEEE International Conference MAC 2023, held in MNNIT, Prayagraj, Uttar Pradesh from March 24-26, 2023. The paper focuses on the design and performance of a dual-band antenna capable of efficiently operating in multiple tissues when fed by a coplanar waveguide (CPW) line.

2. I have an upcoming paper presentation at the IEEE International Conference WAMS 2023, to be held in PDEU, Gandhinagar, Gujarat from June 7-10, 2023. The paper, titled "Implantable Dual Band Polygonal Ring Slot CPW Antenna with Superstrate," explores the design and characteristics of an implantable antenna with dual-band capabilities and a polygonal ring slot structure.

These publications contribute to the advancement of antenna technology in the biomedical field, aiming to enhance the performance and functionality of antennas used in various medical applications.