DEVELOPMENT OF IMPLANTABLE ANTENNAS FOR BIOMEDICAL DEVICES

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by

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CERTIFICATE

This is to certify that the thesis entitled **“DEVELOPMENT OF IMPLANTABLE ANTENNAS FOR BIOMEDICAL DEVICES”** to the Delhi Technological University, Delhi for the award of Doctor of Philosophy in Electronics and Communication Engineering is a record of bonafide work carried out by Mr. **RAJIV KUMAR NEHRA** with enrolment number **2K18/PhD/EC/10** under my supervision. The candidate has completed all the statutory requirements of the University and the research in question is his original and genuine work.

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Rajiv Kumar Nehra

कर्ता करे न कर सके, गुरु किए सब होय ।

सात द्वीप नौ खण्ड में, गुरु से बड़ा न कोय ।

A person cannot do all the work done without the blessings of his Guru

In this whole Universe, Nobody is greater than the Guru

मनसा वाचा और कर्मणा, यदि मैने कुछ पाया है ।

मेरा इसमे रंच नही है, सब गुरुवर की माया है ।

If I have got something by heart, by speech or by action,

it is not because of my effort, it is due to the divine power of my Guru

सुख दुख के चक्र में ही घूमती है जिन्दगी, खुशियों में बावरी सी झूमती है जिन्दगी ।

माता-पिता को हर कदम पे पूजते हैं जो, उनको कदम-कदम पे चूमती है जिन्दगी ।।

Life circulates in the wheel of prosperity and sorrow, life oscillates happily

Those who obey their parents then life obeys them on every step

Dedicated

to

My Guru and Parents

for

Love, Respect and Gratitude

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ABBREVIATIONS AND SYMBOLS

Symbol	**Description**
μ_r	Relative Reflective magnetic permeability
ε_r	Relative dielectric permittivity
λ	Wave length
Σ	Conductivity
Γ	Reflection coefficient
$\tan(\delta)$	Loss Tangent
dB	Decibel
L_f	Free Space Loss
L_a	Air Propagation Loss
G_r	Receiver Antenna Gain
No	Noise Power Density
B_r	Bit Rate
G_c	Coding Gain
G_d	Fixing Deterioration
RC	Reflection Coefficient
NaCl	Sodium Chloride
SiO_2	Silicon Dioxide
PCB	Printed Circuit Board
PEC	Perfect Electric Conductor
SMA	Sub Miniature version A
BMD	Bio Medical Device
IMD	Implantable Medical Device
MDS	Magneto Dielectric Substrate
SAR	Specific Absorption Rate
SRR	Split Ring Resonator
CPF	Co Planer Wave Fed
DSS	Defected Slotted Structure
LHM	Left-Handed Material
EBG	Electronic Band Gap
WPT	Wireless Power Transfer
CSRR	Complimentary Split Ring Resonator
MICS	Medical Implant Communication System
FDFT	Finite Element and Finite Difference Time
ARBW	Axial Ratio Bandwidth
ISM	Industrial Scientific, and Medical

IEEE	Institute of Electrical and Electronics Engineers
PIFA	Planer Inverted F Antenna
HFSS	High Frequency Structure Simulator
VNA	Vector Network Analyzer
DGS	Defected Ground Structure
RF	Radio Frequency
CP	Circular Polarization
EM	Electro Magnetic
W/KG	Watt per Kilogram
3-D	Three Dimensional
2-D	Two Dimensional
e	Exponential
RF	Radio Frequency
MSA	Micro Strip Antenna
GSM	Global System for Mobile Communication
GPRS	General Packet Radio Systems
CPW	Coplanar Waveguide
VSWR	Voltage Standing Wave Ratio
P_R	Power Reflected
P_T	Power Transmitted
Ѓ	Reflection Coefficient
D	Directivity
G	Gain

PBG	Photonic Band Gap
EBG	Electronic Band Gap

ABSTRACT

In this thesis, several designed implantable antennas are simulated, fabricated, and tested successfully. To achieve ISM band characteristics with highly compact size, the meandered shaped antenna is expostulated. By considering the weightage of dual band antenna, the proposed design is simulated with serpentine structure of size 12 mm^3. The two ISM bands (lower and upper) with resonating frequencies 0.93 GHz and 2.43 GHz are attained with help of sorting pin and slots on patch surface. In the ISM bands, the impedance bandwidth of 7.7 % and 5.5 % are achieved in lower and higher frequency bands respectively. The acceptable SAR values of 1007.7 and 856.3 are secured in ISM bands at frequencies at 0.93 GHz and 2.43 GHz respectively. To avoid back radiation through ground surface, the ground slots are completely avoided. It has been deeply observed that the designed antenna does not possess ultra-wide band (broad band) status. To increase the impedance bandwidth, magnetodielectric substrates are used. The initial design of serpentine teeth shaped antenna is considered with extremely compact volume of 4.572 mm^3 and resonated at frequency of 2.44 GHz (ISM band). This design of antenna is embedded on roger RT duroid material and got impedance bandwidth 190 MHz only from frequency 2.34 GHz to 2.53 GHz. To further enhance the impedance bandwidth, the magnetodielectric substrates such as MDS1, MDS2, MDS3 having different value of relative permeability and relative permittivity are simulated and got impedance bandwidth of 450 MHz, 350 MHz, and 350 MHz at resonating frequencies 1.78 MHz, 2.01 GHz, and 2.13 GHz respectively. This proposed antenna with MDS materials has shown acceptable value of SAR 979.1, 977.8, and 971.6 respectively. This work is carried out with no use of sorting pin and no ground slots. It has shown excellent performance in terms of size and impedance bandwidth. The circular polarization feature of implantable antenna has a lot of demand. Such antennas are not affected by multipath losses and ensure patients not to sit in rigid posture during data transmission. To achieve CP characteristics, the antenna is designed with increased current path length of serpentine structure. The increased path length of patch surface method is adopted to reduce the resonating frequency and size too. The proposed antenna is carried out with volume 12.29 mm^3 at resonating frequency of 2.41 GHz. This antenna is circularly polarized with axial ratio bandwidth of 80 MHz from 2.45 GHz to 2.53 GHz. In this work, an acceptable value of SAR 901, and gain of -23.45 dB are obtained. The better results are attained with no use of sorting pin, no patch staking techniques, and no metamaterials. A simple square shaped meander design with triangular slots is proposed. The proposed antenna is tested in skin mimicking gel successfully and got results in agreement. In this thesis, multiple antennas are designed with different techniques like spiral, meander, serpentine structure, sorting pin (via through ground) with materials like Rogers RT duroid, and MDS. All designed antennas are fabricated with superstrate layer which avoids direct contact of conducting part of antenna with human tissues. For validation of simulated results, the skin mimicking gel is prepared under specific conditions.

Chapter 1

Introduction

1.1 Introduction

Now a days, human health is the biggest concern due to enormous reasons like bad eating habits, no exercise, drinking alcohol, smoking, and environmental pollution [16]. Many times, hazardous diseases are detected at the later stage of patients that consequently result in loss of human life. High population with low economic growth nations have poor medical facility. Patients have to wait for long hour during medical check-ups [1-2].

With the rapid growth of wireless technology, the biomedical devices (BMDs) are introduced in medical science. These devices are implanted inside human body by means of surgery to get bio-information of internal human body environment [37]. To setup the wireless communication of implantable medical devices with external base receiving station, microwave antenna must be an integral part of BMDs [33, 21]. The block diagram of implantable medical device (IMD) with components is shown in Fig. 1.1.

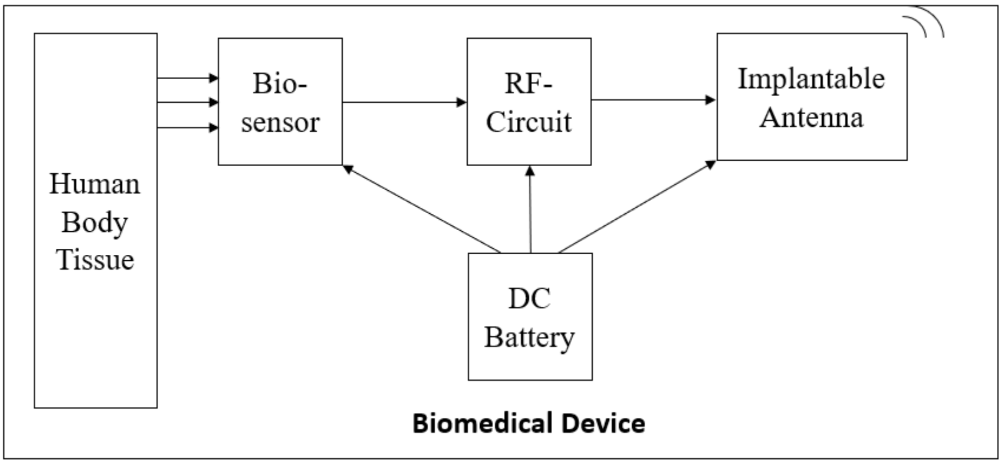


Fig. 1.1 Block Diagram of Implantable Medical Device.

- Bio-Sensors
- Radio Frequency Circuitry
- Implantable Antenna

- DC Battery

Complete details of component use are explained individually.

a). Bio Sensors:

It is a device which converts biological information into electrical signals. It is composed of biological entities like RNA, DNA, Enzymes, Electrochemical transducers and observe certain analytes like antigen, antibody. Bio sensors are used in medical and food industry with large scale. It involves with medical science to detect glucose levels, O_2 level, sugar level, metal detection, pesticides. Based upon category, sensors are of two types i.e., physical sensor and chemical sensor. Any sensor that can response physical properties of medium is known as physical sensor. If sensor senses smell or taste is considered under chemical sensor.

b). Radio Frequency Circuit (RF):

This section of BMDs is used to convert low frequency electrical signals to high frequency strong signals. RF circuit section basically use the concept of oscillator. It takes inputs from biosensor (low frequency signals) and process them into high frequency signals. The RF circuit's output is fed to the implantable antenna. Since the RF circuit devices is integral part of BMDs so to ensure patients safety, low power RF circuit design must be considered.

c). Implantable antenna:

The implantable antenna is used to provide wireless communication between BMDs and external base station. It is the most voluminous part of BMDs. The performance of BMDs depends upon the operation of implantable antenna. In this dissertation, complete study of implantable antennas is described in detail.

d). DC Battery:

To work with electronic circuitry, DC voltage is used. For BMDs, DC battery is necessary for biasing energy. The size and voltage rating of battery are highly concerned for BMD's performance. To make efficient system of BMDs, battery performance must be enhanced to improve life of BMDs [53, 20].

1.2 Essential Parameters of Implantable Antenna

In this section, all essential parameters of implantable antenna have been explained in detail. These parameters reading value show the quality performance of implantable antenna.

1.2.1 Reflection coefficient (RC):

RC defines the reflected wave strength to the incident wave strength of the respective antenna. It is mainly caused by impedance mismatching between transmission line and antenna. For any antenna, -10 dB reflection coefficient or below is accepted as standard value for desired radiations [27]. The concept of reflection coefficient is explained with example below.

Let reflection coefficient is -10 dB,

P_{in} = Input incident power to antenna.

P_{ref} = Reflected power from antenna.

Z_l = load impedance.

Z_O = characteristics impedance.

Γ = The symbol of RC, known as gamma.

$$\Gamma = (Z_l - Z_o)/(Z_l - Z_o) \quad (1.1)$$

$$-10 = 10 \log (P_{ref} / P_{in}) \quad (1.2)$$

$$-1 = \log (P_{ref} / P_{in}) \quad (1.3)$$

$$0.1 = P_{ref} / P_{in} \quad (1.4)$$

$$P_{ref} = 0.1\, P_{in} \quad (1.5)$$

It means 10 % power is reflected w.r.t incident power of antenna.

With this value or less, antenna is acceptable, and signals start radiating through medium successfully. In simple words, reflection coefficient having value -10 dB or less leads to radiate 90 % or more power. Only 10 % or less power is reflected to generator end.

1.2.2 Impedance bandwidth:

It is clearly expressed as the diversity in frequency where antenna shows RC either -10 dB or less [69]. This impedance bandwidth plays important role in biomedical implantable antennas. With high value of impedance bandwidth, large no of channels can be framed for data transmission. The reconstruction of original signals can be easily recovered at external receiver stations. The impedance bandwidth is explained in Fig. 1.2 below.

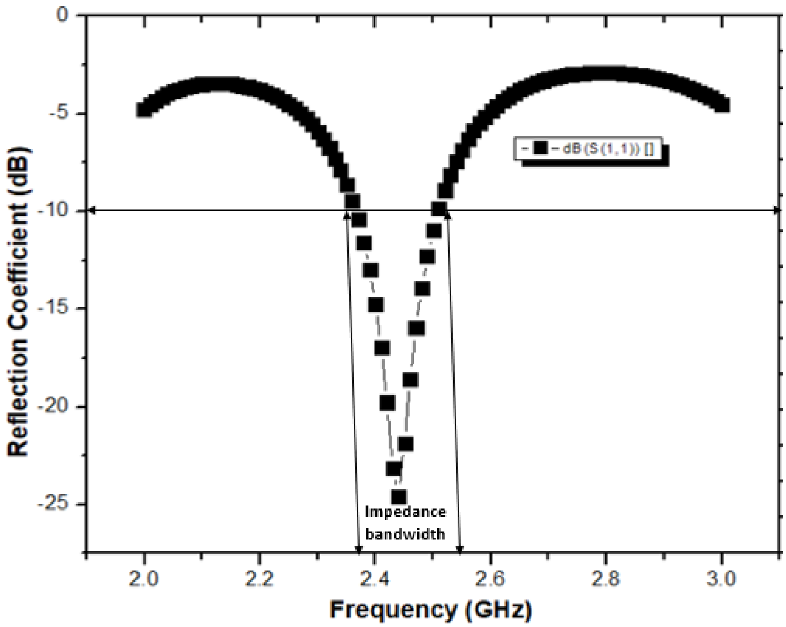


Fig. 1.2 Impedance Bandwidth Graph of Implantable Antenna.

The implantable antenna having -10 dB or less value of reflection coefficient from frequency range 2.37 GHz - 2.5 GHz is presented in Fig. 1.2. So, the frequency range 2.37 GHz - 2.5 GHz i.e., 130 MHz is the impedance bandwidth of this implantable antenna. If any implantable antenna has impedance bandwidth more than 10 % then it is called broadband antenna otherwise it comes under narrowband antenna. Sometimes impedance bandwidth is also known as -10 dB bandwidth because -10 dB reflection coefficient standard is adopted for its calculation. The high value of impedance bandwidth is suitable for high data rates and better link margin.

1.2.3 Circular polarization:

In BMDs, circular polarization (CP) implantable antennas are of very high demand. During the telemetry sessions, the implantable antenna suffers from multiple losses [75]. For linear polarized antenna, patients must sit in rigid posture to avoid losses. With CP characteristics of implantable antenna, the patients can enjoy full mobility during data transmission. In CP antenna, the two-equilateral component of electric field vectors are of equal strength and have phase difference of 90^0.

It is associated with axial ratio bandwidth. High value of axial ratio bandwidth leads to have better CP characteristics of implantable antenna. The axial ratio bandwidth is specified as the frequencies range where an axial ratio bandwidth remains 3 dB or less. So sometimes it is also known as 3 dB bandwidth. The axial ratio bandwidth is shown in Fig. 1.3 below.

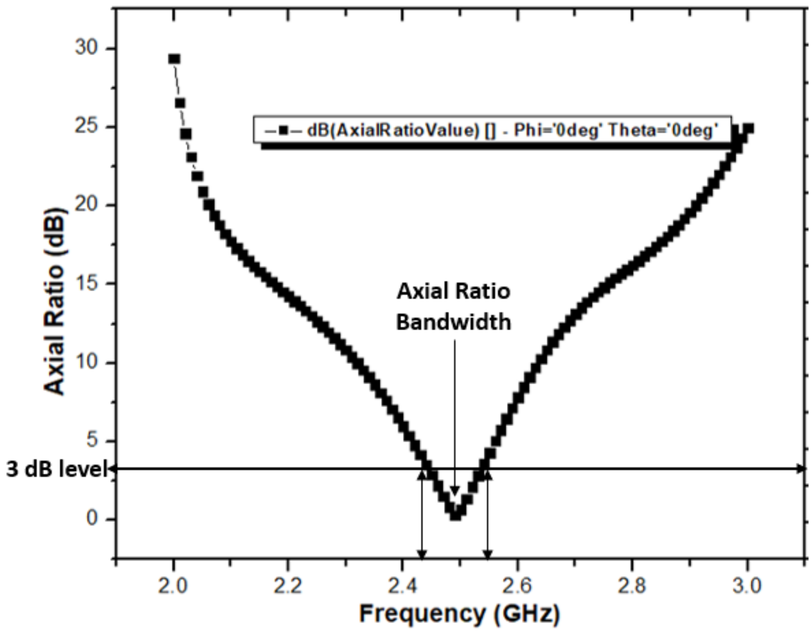


Fig. 1.3 The Axial Ratio Bandwidth of Implantable Antenna.

The implantable antenna shows an axial ratio 3 dB or less value from frequency 2.45 GHz to 2.53 GHz as shown in Fig. 1.3. It means the frequency range 2.45 GHz - 2.53 GHz i.e., 80 MHz is the axial ratio bandwidth of this implantable antenna in which antenna behaves as circularly polarised antenna. More the axial ratio bandwidth leads to have better CP characteristics of implantable antenna for biomedical applications. For BMDs, researchers focus on receiving better CP characteristics of implantable antenna and eventually provide big relief for patients during telemetry sessions.

1.2.4 Specific Absorption Rate (SAR):

SAR is clearly expressed as rate at which heat, or radiation is engrossed when body tissue is exhibited to electromagnetic wave (EMW). In other words, it is the heat hold by human body substance and has unit watt per kilogram (W/KG).

To ensure the patients safety, SAR parameter of implantable antenna is most important is most important concern. Due to absorbing nature of human body tissues during data transmission, the temperature of neighbouring tissues may rise. If rise in temperature of 1^0 to 2^0, this may change the dielectric constant of body tissues and consequently mat cause severe diseases.

By considering all aspects of SAR, IEEE has given two standards. For 1 gram of tissue, the maximum limit of SAR is 1.6 W/KG and for 10 gram of body substance is 2 W/KG [23]. So as per given standard, the implantable antenna must be designed with SAR below 1.6 W/KG or 2 W/KG as 1 gram and 10-gram body substance respectively. The SAR understanding of medical device antenna is shown in Fig. 1.4 below.

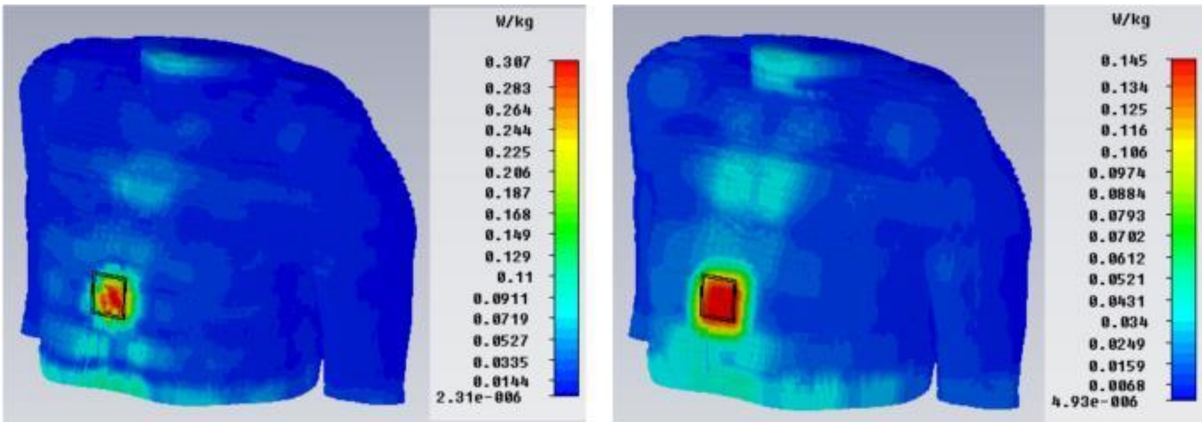


Fig. 1.4 1 Gram/10 Gram SAR Distribution in Human Body [43].

The maximum SAR value is reported 0.387 w/kg and 0.145 w/kg for 1 gram and 10 gram of body substance respectively as shown in Fig. 1.4. The Simulated value of SAR is in acceptable range as per IEEE standards.

This standard is presented for 1 watt input power to implantable antenna. But due to human body environment, the input power of implantable antenna is very low in order of milli watts (mW). So, for input power of 1 milli watt, the standard maximum limit of SAR becomes 1600 W/KG and 2000 W/KG for 1 gram and 10 gram of body tissues respectively.

1.2.5 Directive gain:

Since implantable antenna is integral component of BMDs which is implanted inside human body. Human body itself is of absorbing nature so getting good value of gain is tough task. Moreover, the implantable antenna works with very low signal strength. Consequently, such antennas show negative gain value in desired frequency band. So, antennas with better gain are highly preferred for BMDs.

1.2.6 Link Margin:

To setup the air medium communication between BMDs, and external receiver, the link margin must exceed zero dB. The link margin calculation [66] is given below with all required details.

$$Link\ margin = Link\ C/N_o - Required\ C/N_o \tag{1.6}$$

$$Link\ C/N_o = P_t - L_{feed} - G_t - L_f - L_a + G_r - L_{feed} - N_o \tag{1.7}$$

$$Required\ C/N_o = E_b/N_o + 10\log B_r - G_c + G_d \tag{1.8}$$

Where,

P_t = Transmitter power of antenna,

L_{feed} = Feeding loss,

G_t = Transmitting antenna gain,

L_f = Free space loss,

L_a = Air propagation loss,

G_r = Receiving antenna gain,

N_O = Noise power density,

E_b/ N_O = Ideal phase shift keying (psk),

B_r = Bit rate,

G_c = Coding gain,

G_d = Fixing deterioration.

So, for positive value of link margin Link C/N_O must be greater than Required C/N_O. For positive value of link margin, it can be said that implantable antenna is good candidate to be used for telemetry sessions in BMDs for health care monitoring.

1.3 Essential Requirement of Implantable Antenna

To design implantable antenna, there are some important requirements by considering human body environment.

1.3.1 Biocompatible:

The implantable antenna is of conducting material human body itself is good absorber of heat or radiation. So, conducting material of implantable antenna is in the touch of body organs then it may cause severe health issues. To avoid such issues, implantable antenna is used superstrate and biocompatible material wrapped over the entire structure of antenna. Then implantable antenna does not come in direct contact of human body tissues. There are several superstrate and biocompatible material for implantable antenna like FR4 Epoxy, Roger RT 3210 duroid, ceramic alumina, macor, and Teflon etc. The BMDs are also covered with biocompatible material to avoid any harmful reaction with body organ tissue.

1.3.2 Miniaturization:

The medical device antenna is the most capacious part of BMDs. So, to detract the structure of BMD, the dimensions detracting techniques of medical antenna become very crucial. Highly compact size of implantable antenna with low resonating frequency is preferred. The different techniques have been explored to minimize the implantable antenna structure over the time.

The meandered, spiral with sorting pin, slots on patch, and defects on ground of antenna have been investigated in detail for miniaturization.

1.4 Realistic Environment for Testing of Implantable Antenna Performance

The BMD which is integrated with implantable antenna is implanted inside human body. For simulation and testing, it is tough task to present any dead human body or animal body for validation of implantable antenna. For the simulation purpose of implantable antenna, different human body tissue models like skin, muscle, bone, fat are adopted. Every tissue model has unique properties w.r.t operating frequency.

For validation purpose of implantable antenna, two types of testing are performed i.e., vitro and vivo testing. In vivo model testing, implantable antenna is tested inside of body organs. This technique is quite accurate. Other method is vitro model in which implantable antenna is tested outside of body. In vitro model, gel is prepared having properties equivalent to skin or other human body tissues at specific frequency. The skin mimicking gels are formed under mixing of different percentage of sucrose, NaCl, deionized water, and carbomer [11]. The complete method or procedure to prepare skin gel is described in detail.

For ISM frequency band:

- Take 53 % of sucrose and 47% of deionized water.
- Stirring this solution with magnetic stirrer for 20 minutes.
- Add 0.5 gm carbomer for 40 ml solution (1.25 gm for 100 ml solution).
- Start heating this solution at 80 ^{0}C for one hour.
- Mixture starts solidifying by cooling at room temperature.
- Finally skin mimicking gel is prepared for vitro testing purpose of implantable antenna.

For MICS frequency band:

- Take 56.18 % of sucrose, 41.49 % of deionized water, and 2.33 % of NaCl.
- Stirring this solution with magnetic stirrer for 20 minutes.
- Add 0.5 gm carbomer for 40 ml solution (1.25 gm for 100 ml solution).
- Start heating this solution at 80 ^{0}C for one hour.
- Mixture starts solidifying by cooling at room temperature.
- Finally skin mimicking gel is prepared for vitro testing purpose of implantable antenna.

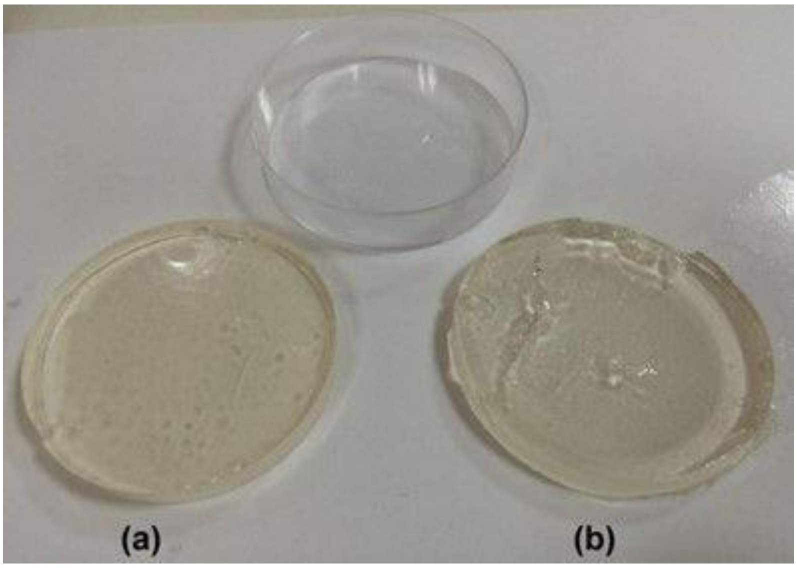


Fig. 1.5 (a) Skin mimicking gel at ISM band. (b) Skin mimicking gel at MICS band [11].

The skin gels at ISM band and MICS band are shown in Fig. 1.5. In this way, this saline solution has same electrical properties as that of actual skin of human body at specific frequency. The electrical properties of body tissues [22] like skin, muscle, and fat for ISM and MICS frequency bands are displayed in the Table 1.1 given below.

Table 1.1 The electric properties of human body tissues in ISM and MICS frequency bands.

S. No	Body tissue	Frequency Band	Dielectric constant	Bulk conductivity (S/m)	Density (kg/m^3)
1	Skin	MICS	49.85	0.67	1100
2	Muscle		57.95	0.81	1040
3	Fat		11.62	0.081	1850
4	Skin	ISM	42.85	1.59	1100
5	Muscle		53.6	1.81	1040
6	Fat		10.82	0.27	1850

1.5 Different Techniques for Performance Enhancement of Implantable Antenna

The implantable antennas experience lossy environment of human body tissues. Moreover, the implantable antennas are fed with low input power to ensure safety of patients. So, getting good performance from implantable antennas is quate big challenge for researchers. Few important techniques to enhance performance of implantable antenna have been discussed in detail.

1.5.1 Fruition of High Permittivity Dielectric Substrate/Superstrate:

The antenna used for medical applications, is integral part of BMDs. So, to decrease the antenna size, high permittivity dielectric substrate is considered. Due to high permittivity, effective wavelength would be minified. Eventually, the resonating frequency will get reduced to lower value. In general, most suitable substrate material for implantable antenna is Roger RT/duroid 3210/3010/6002. This material has dielectric constant of 10.2 and widely used for BMDs.

Some researchers have used much higher permittivity material [53] i.e., MgTa1.5Nb0.5O6 (e_r=28) to reduce the size but consequently the expense of medical device antenna gets higher. So moderate value of dielectric constant substrate material is used for such application.

1.5.2 Increasing the Length of Current Path of Radiator:

For implantable antennas, the way distance of current is to be enlarged on patch surface. This increased current path leads to reduce the inductance of radiator and then eventually the resonating frequency of implantable antenna gets shifted towards lower side. Different structures have been adopted to increase the current path like meandered [40], spiral [40], slotted [64]. Such structures work well to miniaturise the size of implantable antenna. Slots can be implemented on patch or ground surface of antenna with different dimensions and positions.

1.5.3 Using of Planer Inverted F Antenna (PIFA):

In PIFA antenna, the radiating surface and ground plane are grouped to each other with help of sorting pin (conductor). In this way, the path distance of current is increased up to large extent. So, antenna offers high value of inductance and reduces the resonating frequency to its lower side. The impedance matching is achieved by varying position of sorting pin. The impedance of antenna gets decreased if sorting pin moves toward feed line and increase when pin moves away from feed line. The impedance bandwidth depends upon the air gap present between ground and patch. The structure of PIFA antenna is depicted in Fig. 1.6.

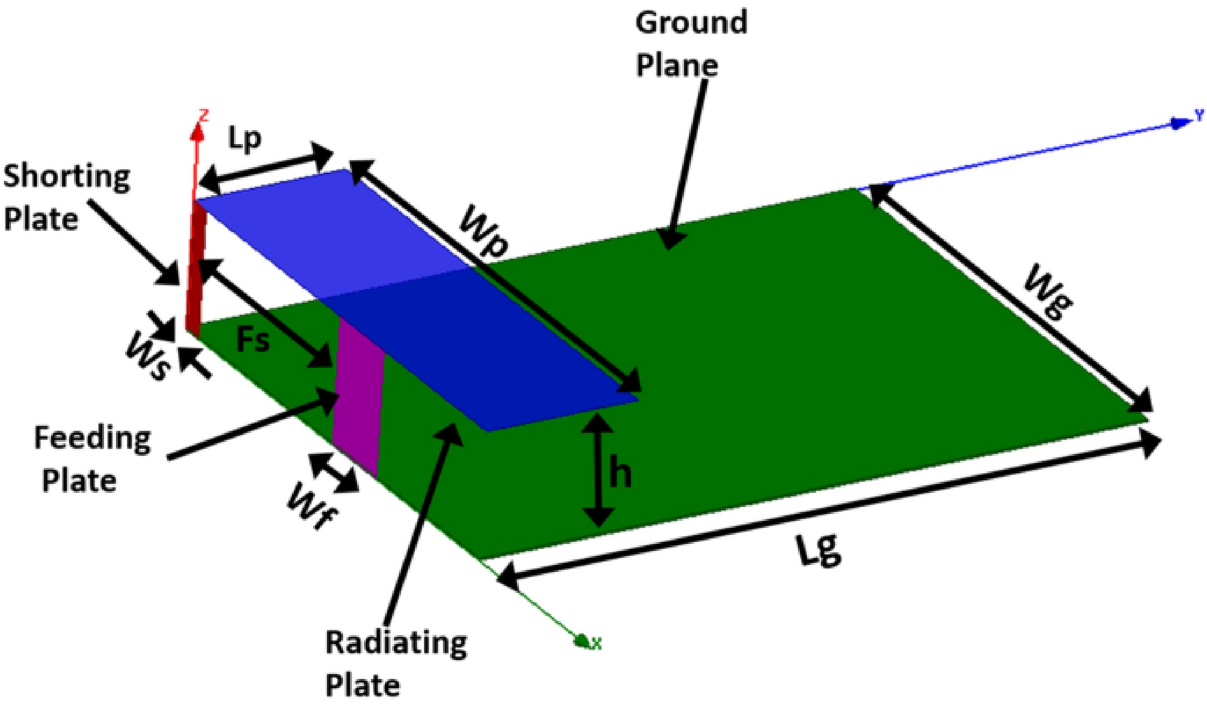


Fig.1.6 The Structure of PIFA Antenna [65].

1.6 Design Guidelines for Implantable Antenna

The complete procedure of designing an implantable antenna is presented in Fig. 1.7. The complete work is divided into nine subsections.

- Select the operating frequency based on biomedical application i.e., ISM & MICS bands.
- Select the dielectric material with relative permittivity.
- Use designing equations of implantable antenna for resonating frequency.
- Design the structure of antenna using Ansys HFSS simulator and apply boundary conditions with excitation.
- Use parametric study with different aspects like feed position, dimensions of structure, body tissues etc.
- Optimise implantable antenna with best simulated results.
- Start fabrication of final designed implantable antenna.

- Testing of antenna parameters using VNA for validation purpose.
- Observe similarity between simulation and fabrication results.

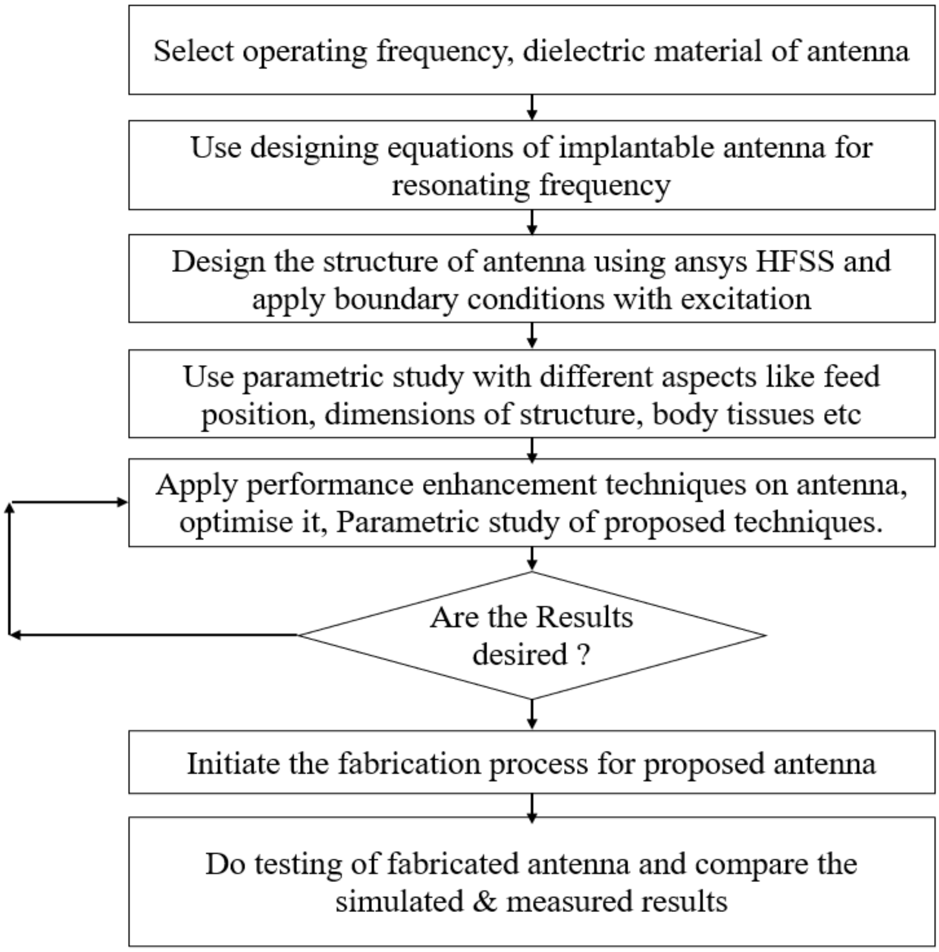


Fig.1.7 The Designing Procedure of Implantable Antennas.

1.7 Motivation and Objectives of Thesis

With the rapid growth of wireless technology, medical science area is great scope of improving the human health by means of Biomedical devices. In today's world, BMDs are working excellent for human health monitoring purpose. The success of BMDs is directly dependent upon the quality of implantable antenna which is back bone to setup wireless communication between implantable medical device and external receiving station. The motivation behind this thesis is to develop such implantable antennas which have excellent performance in terms of compact size, low SAR, high gain, good CP characteristics. Every aspect (cost, size, flexibility, biocompatibility, dual band, radiation) of implantable antenna development is considered with deep investigation and analysis. Some of the challenges for motivation factor have been observed during the entire period of research. All challenges are mentioned below.

- Low profile antenna with extremely compact size.
- Antenna with low SAR within acceptable range of IEEE standard.
- Avoiding of multipath losses during telemetry sessions.
- Wireless power transfer system for implantable antenna.
- Multi band implantable antenna for data and power transmission.

Problem statement:

1. Many researchers have worked on implantable antenna regarding its performance like reflection coefficient, SAR, Gain, and ISM band frequencies. But volume of proposed antennas is not miniaturized. So, strong gap is found based on literature survey. Since antenna is implanted inside human body so size must be as small as possible. This is the first problem statement on which objective is framed.

2. Few researchers have worked on dual band characteristics of implantable antennas. The wireless charging of DC battery of BMD is quite possible only with dual band antenna

characteristics. This approach improvises the life span of DC battery and avoids multiple surgery for battery replacement in future for patients. This is the second problem statement on which objective of thesis is framed.

3. Many researchers have worked on circular polarization of microwave antennas. But implantable antennas are not obtained with this characteristic up to considerable extent. The Circular polarization for implantable antennas is extremely needed for the patient's prospects. During the data transmission, patient can enjoy his/her mobility and multipath losses can be avoided. By considering patient's need, objective of designing circular polarization implantable antenna along with good performance is framed.

4. Based on literature survey, researchers have used complex techniques like patch stacking, metamaterial, passive elements, and large thickness of substrate etc. But this thesis is very much focused on simple techniques like triangular slots, rectangular slots, sorting pin, meander and spiral structure, and small thickness of substrates. With these simple techniques, overall good performance of all designed implantable antennas is achieved. Objective of using magneto dielectric substrate is inspired from this problem statement.

5. Very few researchers have touched the domain of link margin of biomedical antenna. Without link margin analysis, upcoming researchers cannot have idea of BMDs feasibility. Link margin simply ensures the communication establishment of BMDs and external receiver. It also determines the distance of feasible communication between BMDs and external station. This problem statement is highly addressed by putting objective of implantable antenna with rectifier circuit for wireless power transmission in this thesis.

Based on the challenges and problem statements observed during literature survey of this thesis, objectives are framed as given below.

- Design and Analysis of Compact Implantable Antenna for Biomedical Application.
- Design and Analysis of Multiband Implantable Antenna for Biomedical Application.
- Design and analysis of circularly polarised antenna for biomedical application.
- Design and analysis of implantable antenna using magneto dielectric substrate for biomedical antenna.
- Design and analysis of circularly polarised antenna integrated with rectifier circuit for wireless power transfer.

1.8 Organization of Dissertation

The dissertation has been organised in six chapters which are given as:

Chapter 1: In the first chapter, brief introduction of biomedical devices is explained followed by important component of BMDs. Next, the importance of implantable antenna in BMDs is discussed at length. Wireless link is simply established by implantable antennas. Availability of standard frequency bands, important parameters, and requirements of antenna are mentioned in this chapter itself. The implantable antenna testing scenario (vivo and vitro model) is explained with mimicking gel procedures. Different performance enhancement techniques have been highlighted. This chapter gives complete research idea for development of implantable antennas.

Chapter 2: In the second chapter, literature survey of implantable antennas has been discussed at length. The size reduction techniques have been demonstrated from early research days to recent research trends. Great reduction of size in implantable antenna has been studied by involving various efficient techniques like meandered, spiral, sorting pins, and slots etc. The circular polarised antenna and its significance have presented with gradual development of research in this prospect. Low SAR value of implantable antenna with useful techniques are discussed w.r.t international standards. The implantable antenna suffers from lossy human body environment and hence it shows low value of gain. In the end, gain enhancement techniques are focussed for implantable antenna.

Chapter 3: The chapter describes the design of dual band implantable antenna in ISM band. The dual band antenna is designed with 12 mm^3 volume which is least among recent published work. The final design antenna resonates at two bands i.e., 0.93 GHz, 2.43 GHz. In both ISM band, proposed antenna shows 7.7 % and 5.5 % impedance bandwidth. SAR value in both bands is below IEEE standard values (1.6 W/KG) for one gram of body substance. Two ISM bands have been achieved without ground slots of proposed antenna that avoids back radiations. Overall, this is observed that final design antenna shows excellent performance with dual band characteristics.

Chapter 4: In forth chapter, the medical device antenna is implemented in ISM band (2.44 GHz). 1^{st} designed antenna show 190 MHz impedance bandwidth. Further, to enhance the -10 dB bandwidth of 1^{st} designed antenna, magnetodielectric substrate (MDS) materials have been implemented as substrate material with some non-zero positive value of relative permittivity (e_r) and relative permeability (u_r). The impedance bandwidth is improved from 190 MHz to 410 MHz. Then MDS 2 and MDS 3 materials have been used to improve bandwidth from 190 MHz to 350 MHz respectively. The reduced values of resonating frequencies are observed from 2.44 GHz to 1.78 GHz, 2.01 GHz, and 2.13 GHz for all three MDS materials respectively. It means that MDS material worked well to improve impedance bandwidth up to large extent. One more triple ring slotted circularly polarised implantable antenna is explored. In this design, three rings with coaxial feed at circular patch are designed. This design is optimized in ISM band with sufficient impedance bandwidth. Moreover, ground slots are incorporated to attain circular polarization. The proposed antenna exhibits axial ratio bandwidth from 2.38 GHz to 2.67 GHz with acceptable SAR value of 944.2. This proposed antenna is reported with least volume of 9.77 mm^3 w.r.t recent research work.

Chapter 5: In the fifth chapter, the complex fabrication of PIFA, patch stack, and metamaterial antennas is considered. To get advantage over mentioned implantable antennas, simple meandered structure implantable antenna is designed with patch and ground triangular slots. The 1st designed antenna with meander structure is optimised at 2.44 GHz with RC (Γ) of -24.54 dB. The -10 dB bandwidth of 120 MHz with frequency range 2.37 GHz - 2.49 GHz is achieved. To get circular polarisation, four triangular slots are implemented on patch surface. With these slots, antenna has improved impedance bandwidth from 120 MHz to 140 MHz. At last, the circular polarisation is achieved by using similar four triangular slots on ground surface. The proposed antenna now is shown circular polarisation with axial ratio bandwidth of 80 MHz with frequency range 2.45 GHz - 2.53 GHz. The proposed antenna is reported with volume of 12.29 mm^3 and acceptable SAR value of 901 which is quite better among recent research work. A wideband circularly polarised antenna is also considered. A simple spiral structure implantable antenna is designed with sorting pin and superstrate metamaterial of H shaped. The 1st designed antenna with spiral structure is optimised at 2.53 GHz with RC (Γ) of -16.89 dB. The -10 dB bandwidth of 120 MHz from 2.47 GHz to 2.59 GHz is attained. To get circular polarisation, sorting pin is implemented between patch and ground surface. With this sorting pin, antenna has shown circularly polarised with axial ratio bandwidth of 530 MHz with frequency range 2.15 GHz - 2.73 GHz. To further improve the axial ratio bandwidth, H shaped metamaterial is used on superstrate surface. With this implementation of metamaterial, axial ratio bandwidth has been enhanced from 530 MHz to 830 MHz. The proposed antenna is reported with volume of 10.67 mm^3 and acceptable SAR value of 952.7 which is quite better among recent research work.

Chapter 6: In the end, the sixth chapter consists of the overall concluding remarks and future aspect of the thesis. The thesis described about designing of circular microstrip patch antenna with circular rings, meandered, spiral, MDS and PIFA antenna to achieve high impedance bandwidth, high gain, circular polarisation in ISM band with compact size. These antennas can be used as implantable antenna for biomedical application.

In this way, this thesis will discuss size reduction, bandwidth, circular polarisation, low SAR, and gain enhancement using slots, PIFA, MDS, spiral, and meandered shapes.

Chapter 2

Literature Survey of Implantable Antennas

Literature Survey of Medical Device Antennas

In this section of chapter, complete history of medical antennas related to its performance has been discussed in detail. From early days to recent time, implantable antennas are very much improved in context of size, multi band availability, impedance bandwidth, gain, SAR, and link margin. The history of implantable antennas is sequentially presented with different performance areas given below.

2.1 Literature Survey of Size Reduction of Implantable Antennas

In 2004, an implantable PIFA antenna [29] was proposed in comparison with microstrip antenna by J. Kim et al. With help of sorting pin and spiral shaped radiating surface, miniaturisation was achieved. The suggested antenna was designed with size of 6144 mm^3 and 5.95 % impedance bandwidth. The SAR value for spiral PIFA antenna shows 209 w/kg with 7.656 mW input power. In this research work, proposed antenna was simulated and characterised in different human body phantom like chest, head etc. To reduce the size of implantable antenna, researchers kept on working hard by involving various techniques over the decades. In 2008, pie shaped double L strips PIFA antenna was proposed by C. M lee el al [34] in MICS band with volume of 643 mm^3. 80 MHz (362 MHz to 442 MHz) impedance bandwidth had been achieved and results are validated with skin mimicking gel at MICS frequency band. In these years from 2004 to 2008, considerable reduction of implantable antenna had been analysed. W. C. liu et al [48] proposed stacked PIFA implantable antenna in 2009. A hook shaped slots were implemented on patch surfaces to bring down the dimensions of medical device antenna significantly. The final suggested antenna was designed with volume of 121.6 mm^3 and covering impedance bandwidth of 122 MHz including 402 MHz to 405 MHz (MICS) band. Besides sorting pins, three-layer patch stacking concept was introduced by W.C. liu et al. With the implementation of special shaped (Hook) slots on radiating patch, wide impedance bandwidth was obtained. Initially Split Ring Resonator (SRR) shaped design was adopted to have negative permeability in 1999. Then left-handed material (LHM) was introduced to possess negative value of permittivity and permeability. In recent time of 2009, electronic band gap (EBG) and SRR in planer microstrip line was utilised to have negatives value of permittivity and permeability. But size of EBG structure depended upon permittivity of substrate that is resulted into alteration of transmission line dimensions. In this research work. SRR and CSRR shaped structure was used on patch and ground surface respectively. In 2010, Tsung-Fu Chien el al [6] proposed mono pole implantable antenna with coplanar waveguide feed. This antenna was presented without superstrate which caused miniaturisation. Microwave dielectric ceramic substrate was taken into consideration with high value of dielectric constant and quality factor. The suggested antenna depicted good impedance bandwidth of 130 MHz (33.5 %) in MICS band with RC (Γ) of -25 dB at resonating frequency of 402 MHz. The implantable antenna may have some bad reaction with human body tissue if it touches with human body substance. But in this literature, better stability of reflection coefficient, impedance bandwidth, and gain has been observed over 60 days. In absence of superstrate, the comprehensive thickness of final designed antenna is decreased to half value. Hence the proposed antenna achieved low profile and miniaturisation. A stable characteristic of proposed antenna with loading of high dielectric substrate (ceramic) is suitable for biomedical devices. In 2011, J. Ha el al [19] had published research work based on zeroth order resonance. The proposed antenna was designed with 15.9 mm x 12.9 mm x 1.6 mm (328.176 mm^3) with FR 4 epoxy substrate having dielectric 4.4 with 0.8 mm thickness. By introducing two chip inductors, negative epsilon had been observed in MICS band. These chip inductors are quite insensitive to human body electrical properties. This becomes the biggest advantage of proposed antenna to deliver stable performance. The input power of 11.8 mW is delivered to proposed antenna with SAR 1.54 w/kg which is as per American standard. The antenna is insensitive to permittivity variation of human body tissues. In 2012, Asimina Kiourti el al [30] has submitted implantable antenna for head implantable medical devices. A circular shaped antenna was designed to avoid sharp and abrupt edges. The Rogers rt/duroid substrate is utilised for designing purpose. The final suggested antenna has volume of 203.472 mm^3 having two patch stacking arrangement with thickness of substrate 0.6 mm each. To get biocompatibility, superstrate material same as substrate is used. The four different frequency bands (MICS, ISM) are received at resonating frequencies of 402 MHz, 433 MHz, 868 MHz, and 915 MHz. The directive gains and local SAR of these four resonating frequencies have been analysed in detail. The link margin analysis for all resonating frequencies is explained in detail for existing communication system. The finite element and finite difference time (FTFD) domain method is adopted in contrasting stage of antennas designs. In 2012, Changrong Liu el al [40] proposed implantable antenna with single fed miniaturisation in MICS band. Ground surface of proposed antenna was introduced with meander shaped slots and six open slots. Consequently, great reduction of size was achieved in MICS band with sides 10 mm x 16 mm x 1.27 mm (203.2 mm^3). To increase the current path on radiating surface, two patch stacking approach has been implemented along with sorting pin between ground surface and patch surface. With this structure, the recommended antenna has been attained with 22.8 % impedance bandwidth in MICS band and gain value of -30.5 dB. The SAR value is received with 609.2 w/kg. To guarantee the protection of patients, a biocompatible coating of implantable antenna has been provided.

In 2015, Rupan Das et al [9] has proposed implantable antenna for leadless pacemaker system. The wireless power transfer (WPT) technique is also proposed. The BMD works well with wireless power transfer system. Multiple surgery to install new battery in BMDs are avoided and get the continuous monitoring system of human health. The spiral shaped technique to length the current path is adopted in final suggested antenna design. Designing of final antenna is executed on flexible substrate which is wrapped in cylindrical shaped BMDs. The polyamide material is utilised as substrate and superstrate having electrical properties like dielectric constant and loss tangent (tan(δ)) 4.3 and 0.004 respectively. The proposed antenna is designed with volume of 20.5 mm x 30 mm x 0.05 mm (30.75 mm^3). This research paper has reported the least possible volume of biomedical implantable antenna among recent published work. In comparison of previous implantable antennas, the proposed antenna has been achieved excellent miniaturisation at MICS frequency band. In this paper [4], Sajid M. Asif et al proposed wireless power transfer method for pacemaker BMDs. Wide band numerical method has been studied in detail for proposed conformal antenna. For the patient's safety, long last performance of battery in BMDs, effectiveness communication link between external receiver station and implanted medical devices, importance of wireless power transfer system plays significant role in RF communication link. In BMDs like pacemaker, lead and battery creates huge drawbacks for patients. Lead may mackle the blood vein that results into infection, pneumothorax, and tricuspid valve insufficiency. Moreover, DC battery has lifetime validity issue. As per the statistics available in 2018, every 14^{th} patient of pacemaker installed in chest body part may suffer with infection. Almost 20 % patients of having pacemakers cause death due to such infections. So, this research paper demonstrates the designing of conformal implantable antenna using complimentary split ring resonator (CSRR) metamaterial at 2.45 GHz resonating frequency in ISM band. The radius of conformal antenna is taken 3 mm with total antenna thickness 0.289 mm. The CSRR shaped conformal antenna is wrapped on cylinder. The adopted hybrid technique in proposed numerical method can detract the cost of antenna including pacemaker.

In research paper [77], Yudi Zhang et al presented implantable antenna with highly miniaturised size of 88.09 mm^3. The proposed antenna is resonated in ISM band at 915 MHz frequency. The reference design of implantable antenna is simulated with centre slot near to feed point. Then this antenna is followed by implementing a sorting pin with radius 0.25 mm. This sorting pin has reduced the resonating frequency of antenna around 1.5 GHz with low impedance matching. Then diverse symmetric slots on radiating surface are used to increase the current path that is resulted into a highly miniaturised antenna at resonating frequency of 915 MHz with impedance bandwidth from 866 MHz to 978 MHz. With the help of sorting pin and diverse slots, proposed antenna shows circular polarisation and almost 20% axial ratio bandwidth has been achieved. These diverse slots brought two orthogonal modes on radiating surface. The skin mimicking gel is prepared by ingredients of water, salt, and sugar with definite proportions. In this research paper [28], rectangular implantable antenna is designed with dimensions of 24 mm x 22 mm x 0.07 (37 mm^3). The proposed design of antenna possesses polyimide as substrate with dielectric constant, loss tangent 3.5 and 0.008 respectively. In proposed antenna, split ring resonator (SRR), slots, and coplanar wave fed (CPW) on patch surface are implemented. The proposed antenna shows excellent S_{11} of -22.2 dB at resonating frequency 2.6 GHz with impedance bandwidth of 400 MHz in frequency range 2.41 GHz - 2.81 GHz. The proposed antenna is simulated in air and muscle (vitro model) medium respectively. The gain value of proposed antenna degrades when muscle mimicking gel is used as medium. The gain is reduced from 2.62 dB to -19.7 dB in muscle medium. The gain is reduced up to large extent because of lossy medium of human body environment. In 2019, Zhihao Luan et al [51] has explained the significance of magneto dielectric substrate (MDS) for implantable antennas. The human body absorbs more energy if operating frequency is higher. So, it is advised to researchers to design implantable antenna at ISM band of frequency from 902 MHz to 928 MHz. There were many proposed methodologies to reduce the size of implantable antennas such meandered, spiral shape, slots on patch and ground. But in this literature, magneto dielectric substrate is explored in detail for performance enhancement of medical device antennas. The electrical properties of human body substances are varied w.r.t different operating frequencies. Due to this behaviour of body tissues, limited bandwidth antenna suffers from various losses and performance of antenna does not remain stable. The magneto dielectric substrate has high value (> 1) of relative permittivity and relative permeability. These materials miniaturise antenna size without affecting bandwidth. In MDS, magnetic particles are compounded with dielectric substrate using material synthesis techniques. The MDS provides desired reactive impedance characteristics. The proposed antenna with MDS properties of relative permittivity 13, relative permeability 20.7, dielectric loss tangent 0.17 and magnetic loss tangent 0.12, is designed with dimensions 4 mm x 12 mm x 0.274 mm (13.152 mm^3). The suggested antenna exhibits bandwidth of 252 MHz from 810 MHz to 1062 MHz. The final suggested antenna is produced and tested in muscle (meat) and achieved almost similar impedance bandwidth. In this communication [74], triple band highly miniaturised implantable antenna is proposed. The designed antenna is having size of 7 mm x 6 mm x 0.5 mm (21 mm^3). The compact dimension of antenna has been achieved with meandered shaped patch, open end ground slots, and sorting pin between ground and patch plane. The proposed antenna exhibits three resonating frequencies at 915 MHz, 1.9 GHz, and 2.45 GHz with -10 dB bandwidth of 8.7 %, 8.2 %, and 7.3 % respectively. The link margin study at various bit rate has been studied followed by parametric study on every aspect of proposed antenna. The devices integrated with suggested antenna is simulated in various human body tissues like scalp, heart, colon, stomach, and large intestine. In 2021, the least size of implantable antenna is suggested by Muhammad Jada et al [73]. The final designed antenna is fabricated with dimensions 3 mm x 4 mm x 0.5 mm (6 mm^3) on rogers rt duroid substrate. The performance of proposed antenna is tested with impedance bandwidth of 21.88 % and 15.46 % in presence and absence of device respectively. The implantable antenna with least volume is designed at 2.4 GHz frequency with gain -25.9 db and SAR of 270.28 w/kg for one gram of body substance. The recommended antenna is excellent choice to be used in pacemaker system. In 2021, Muhammad Yousuf et al [71] demonstrated ultra-miniaturised antenna with size of 7 mm x 7 mm x 0.2 mm (9.8 mm^3). The rogers ULTRALAM is used as substrate/superstrate. With sorting pin, and open-ended cur slots, compact size of proposed antenna has been achieved. The link budget analysis 1 Mbps data rate can be transmitted over 15-meter distance between external station and BMD. The antenna is placed in leg tissue with deep implantation and received SAR value of 350.81 w/kg. The medical device antenna is simulated in different human tissues heterogeneity. In 2022, Feng Yang et al [15] published tiny and compact proposed antenna that is worked in ISM band. The total volume of proposed antenna is reported with 4.5 mm^3. With best of my wisdom, proposed antenna is available with least volume. This antenna is optimised with defected slotted structure (DSS). Almost 22 % impedance bandwidth and -24.9 dB gain have been achieved from final design. The application of such compact size antenna is useful for cardiac pacemaker. The complete BMD is designed along with detailed study of link margin analysis. In this way, it is well said that researchers have put huge effort to reduce size of implantable antenna from 6144 mm^3 to 4.5 mm^3 from year 2004 to 2022 respectively. In these years, various size reduction techniques have been explored. In recent time, researchers have been achieved great size reduction but some other parameters like dual band, circular polarisation, high gain, and low SAR must be considered meanwhile.

2.2 Literature Survey of Gain of Implantable Antennas

The directive gain is the important concern for any microwave antenna. It reflects the radiation efficiency and quality of communication link between external receiving station and BMDs. The directive gain of any antenna is described as the radiation intensity in definite direction to the radiation intensity averaged in all coordinates of antenna. If an antenna emits maximum radiation in one direction, then it is called directivity of antenna. For directional antennas, the gain value is always higher because it radiates more radiation in particular direction. But for omnidirectional antennas, gain value is uniform because of equal distribution of radiation in all directions. For any ordinary antenna which operates in air medium, shows positive value of gain like 2 dB of dipole antenna. More value of gain ensures the better radiation of antenna for particular application. For BMDs, the implantable antenna must have high value of gain to get better radiation property. There have been experienced some challenges in context of gain for the implantable antennas. Since such antennas are implanted inside human body tissues. The human body tissues have absorbing nature of radiation. Eventually, it acts as lossy medium for radiation. Moreover, the BMDs operates at low power levels like mW etc. Due to low signal strength, and lossy nature of tissues, the implantable antennas have poor gain value. The detailed literature survey of gain for implantable antennas have been discussed in this section.

In 2016, S. Alamri et al [3] worked-on gain enhancement of implantable antenna with glass hemispherical lens and parasitic ring on superstrate surface. The final antenna is designed with FR 4 epoxy substrate of size 34 mm x 30 mm x 0.8 mm (816 mm^3). The concept of coupling electromagnetic (EM) wave with external object. In this paper, coupling of EM wave is carried out with parasitic ring 28 mm radius and width of 3 mm which is printed on layer of felt. The gain value is enhanced by 2.12 dB as compared to antenna without parasitic ring. When antenna is integrated with hemispheric lens on top surface of skin, the gain value is increase to 8.5 dB compared to antenna alone. At 2.45 GHz, the final designed antenna with ring, and lens is exhibited gain value of -9 dB. In 2013, Ching Lung Yang et al [70] studied the novel antenna for dental implants. The recommended antenna is analysed in medical radio band. The Archimedean spiral and Hilbert based curve; 3D folded implantable antenna is implanted on ceramic denture (ZrO_2). The final designed antenna is simulated in modified teeth model. The antenna has volume of 514.5 mm^3 with simulation gain of -3.8 dB and measured gain of -6.78 dB. In 2018, Soumyadeep Das et [10] proposed dual ring slotted antenna in ISM band. In this paper, various techniques for gain enhancement like printed grid surface and combination of parasitic ring [3] have been studied in detail. But these techniques lead to increase size of implantable antennas. So, to serve the purpose of improved gain, the ground metamaterial structure has been analysed in 2 x 2 array with unit cell. The 3 dB of gain improvement has been reported in ISM band without disturbing impedance bandwidth of ring slotted antenna. The proposed antenna is tested on Kapton polyimide material with dielectric constant 2.91 and loss tangent 0.005. The rogers 6010 material is used as superstrate for biocompatibility purpose. At 2.45 GHz ISM band frequency, -9 dB gain has been noticed with 57 % impedance bandwidth. In 2020, metamaterial loaded medical antenna is suggested by Muhammad Jada et al [72]. The final design antenna is designed with size of 10.67 mm^3. The H shaped metamaterial cell is implemented on superstrate surface with 2 x 2 array. The metamaterial loaded antenna has two bands having resonating frequency at 915 MHz and 2.45 GHz with gain value -17.1 dB and -9.81 dB respectively. With implementation of metamaterial, the compact size of antenna, circular polarisation, good impedance bandwidth, better gain value has been achieved. In 2022, A new study has been reported by Ducdung Nguyen et al. [59] to enhance circular polarisation and gain with help of defected ground structure (DGS) and holey superstrate. Many techniques like printed grid surface, parasitic ring, patch stacking, and metamaterial have been discussed before. But in this paper, DGS technique has been implemented on ground surface which eventually improved impedance bandwidth and circular polarisation. To enhance gain value, the holey superstrate with different radius of drilling holes is installed. To control the electric field in desired phase, the effective permittivity of superstrate must be managed by disturbing the structure. This work is carried out by creating different radius holes on superstrate. Finally, antenna is ameliorated with gain value from -17.5 dB to -14.3 dB. The proposed antenna is presented with volume of 8 mm^3, circular polarisation, impedance bandwidth of 33 %, and low SAR value at resonating frequency of 2.4 GHz. In this way, researchers keep on publishing their work by introducing various techniques like DGS, metamaterial, parasitic rings, printed grid surface, and holey superstrate etc. The excellent work has been surveyed in the field of gain of implantable antenna.

2.3 Literature Survey of Circular Polarization of Implantable Antennas

In BMDs, the input feeding power is low to ensure patient safety. The human body is a good heat (radiation) absorber which eventually degrades the radiation efficiency of implantable antenna. If antenna is designed with linear polarisation, then it suffers from multiple path losses. So, to avoid multiple path losses, and patient mobility during telemetry sessions, the circular polarisation behaviour is much needed in BMDs. In this section, literature survey of circular polarised antenna has been discussed in detail.

In 2014, Changrong Liu et al. [42] presented cylindrical shaped implantable antenna with volume of 361.89 mm^3 in ISM band. The multilayer helical antenna is simulated on rogers 3010 substrate. With this structure of antenna, an axial ratio bandwidth has been realized from 2 GHz to 2.8 GHz. The parametric study of radius, and turning angle of open loops is explained at length. In 2015, Changrong Liu et al. [44] presented one more research paper with circular polarisation. The microstrip patch antenna with volume of 127 mm^3 is presented and tested in vivo model specially implanted inside rat dead body. This testing work is carried out in collaboration of Singapore Institute for Neurotechnology, Centre for Life Sciences, National University of Singapore. The circular polarisation of proposed antenna is achieved using multiple slots on patch surface. It shows CP behaviour with axial ratio bandwidth of frequency range 2.44 GHz - 2.418 GHz (1.63 %). In 2017, Rongqiang Li et al. [38] submitted research work of annular ring microstrip antenna. The antenna is brought with CP behaviour with annular ring and Z shaped slots on radiating surface. The axial ratio bandwidth has been received from 2.419 GHz to 2.48 GHz (2.49 %). The entire ISM band is covered by proposed antenna. Traditionally, realization of circular polarisation of implantable antenna is achieved by using asymmetrical slits [57], diagonally symmetrical slotted patch [56, 58], and capacitive loaded [30] . In 2018, wide band circularly polarised antenna was proposed by Yudi zhang et al. [77]. The proposed antenna is turned into circular polarised antenna by using sorting pin in between radiating and ground plane. By optimising the positions of sorting pin or via and U shaped slots, the 3 dB bandwidth has been received with 19.7 % in lower ISM band. To lengthen the current path, initially L shaped slots were introduced then followed by sorting pin and U-shaped slots on radiating surface. A good wide band CP characteristic has been obtained in desired band.

In [68] paper, Li Jie Xu et al. introduced implantable antenna with volume of 91.9 mm^3. Traditional technique of cross slots has been implemented on patch surface. The crossed slots with arc have achieved axial ratio bandwidth of 18.3 % with frequency range 2.18 GHz - 2.62 GHz. The proposed antenna is resonated at 2.45 GHz with -20.3 dB gain value. In 2022, Abdenasser Lamkaddem et al. [32] presented implantable antenna with compact size of 5.2 mm X 5.6 mm X 0.25 mm (7.28 mm^3). In this paper, author has not used complex techniques like sorting pin. The U-shaped structure of slot has been introduced along with meander shaped antenna. The electrical length of antenna has been increased without altering mechanical size. With this U shaped slot, 17.2 % axial ratio bandwidth has been achieved from 850 MHz to 1010 MHz.

Recently, an excellent research work has been proposed by Daibin Din et al. in [24] paper. In this paper, volume of 85.37956 mm^3 is reported with 3 dB axial ratio bandwidth of 28.7 %. Initially modified square ring was introduced followed by mitered cross on radiator surface. Using only square and mitered slots on patch, almost 30 % impedance bandwidth has been received in ISM band. Without using sorting pin, this research work has made efficient with good value of -10 dB and 3 dB bandwidth. In this way, it is generalised that CP characteristics of implantable antenna is achieved with help of sorting pins, diagonal slots, special shaped slots on patch and ground surface. This parameter becomes one of the most important parameters for BMDs to provide minimum losses in communication link.

2.4 Literature Survey of Multiband Implantable Antennas

In BMDs, the multiband antenna has great significance to get data transmission and wireless power transfer. In one frequency band, bio information in terms of data can be transmitted through implantable antenna. In other band, the DC battery of BMDs can be charged wirelessly which avoids replacement of DC battery regularly and increase the life span of medical devices. Due to multiband antenna, multiple surgery can be avoided for battery replacement. In this field, many research papers have been proposed by authors.

In 2012, Changrong Lie et al. [5] proposed dual band antenna in ISM band with volume of 691.515 mm^3. With help of two spiral resonators on patch surface and sorting pin, the impedance bandwidth in ISM bands (lower and upper) from 393 MHz to 447 MHz (13%) and from 2.34 GHz to 2.48 GHz (4.4%) respectively. In the same year, Li Jie Xu [67] had presented dual band antenna with comparatively small volume of 487.8 mm^3. The dual bands had been achieved with open end slots on ground surface of 52.6 % and 4.4 % impedance bandwidth of lower and upper ISM bands respectively. In 2016, Novel differential fed implantable antenna was proposed by Yijun Liu et al [50]. The dual band is achieved with volume of 642.62 mm^3 from 389 MHz to 419 MHz and 2395 MHz to 2563 MHz respectively. In 2020, Farooq Faisal et al [14] had published research work of dual band (ISM) with smallest volume of 9.8 mm^3 so far. With this small size of proposed antenna, hexagonal and T shaped slots are implemented on radiating surface along with open end slots on ground plane and sorting pin. In lower ISM band, 107.5 MHz impedance bandwidth has been received and in upper ISM (2.4 GHz - 2.48

GHz) 560 MHz impedance bandwidth has been attained successfully. In this paper, highly miniaturised size antenna is proposed with sufficient bandwidth of dual ISM band using only slots and sorting pin.

2.5 Literature Survey of Rectenna System for Biomedical Devices

Rectenna is the inevitable system component to provide wire power transfer to BMDs. The rectenna is the component of BMDs which increases the life span of device and avoids multiple surgery for battery replacement. In this section, literature survey of rectenna system has been explained in detail from past years to recent time.

In 2017, Alice Yi-Szu Jou et al [25] proposed rectenna using global foundries 45-nm CMOS SOI technology. The rectenna system has given 1.1 volt of DC energy in lower ISM band (0.95 GHz). In this paper, slots antenna is chosen to reduce ohmic losses over wired antenna. The rectenna has occupied area of 620 um X 700 um. In 2022, Vikrant Kaim et al [26] proposed multiple input and multiple output (MIMO) system rectenna for wireless power transfer at ISM band frequency 2.45 GHz and 5.8 GHz. The designing of rectifier is successfully completed in ADS software with better efficiency.

In this way, the detailed study of miniaturisation, circular polarisation, dual band, and rectenna system of implantable antennas is surveyed successfully.

2.6 Conclusion of Literature Survey

The literature survey has been carried out for last more than 15 years in the field of implantable antennas. Complete development and improvement in size miniaturization, multi band performance, circular polarization, SAR reduction, direction gain, and rectenna system for wireless power transfer has been discussed at length. The size miniaturization of implantable antennas is achieved using meander, serpentine, and spiral shaped radiating patch surface for the reduction of resonating frequency. For the multiband characteristics, sorting pin (via) and open-end slots, and slots on patch surface are highly recommended to get the desired impedance matching. It is closely observed that the high gain value in implantable antennas is extremely a big challenge for researchers due to lossy environment of human body and low feed power to such antennas. The literature survey has revealed some techniques to improve directive gain of implantable antennas. Using glass lens and parasitic ring on upper surface of skin, metamaterials, and dipole with folded meandered line. The circular polarization characteristics are achieved with help of reactive impedance surfaces, sorting pins, and metamaterials. The high impedance bandwidth of implantable antenna has been obtained using special material named magnetodielectric substrate having magnetic particle composition with dielectric substance. Such materials used to reduce the quality factor and hence improve impedance bandwidth up to large extent. Some rectenna systems are also described with highly efficient rectifier circuits. So, literature survey covers every aspect of implantable antenna for biomedical applications.

Chapter 3

Compact Dual-Band Medical Device Implantable Antenna for Biomedical Application

3.1 Introduction

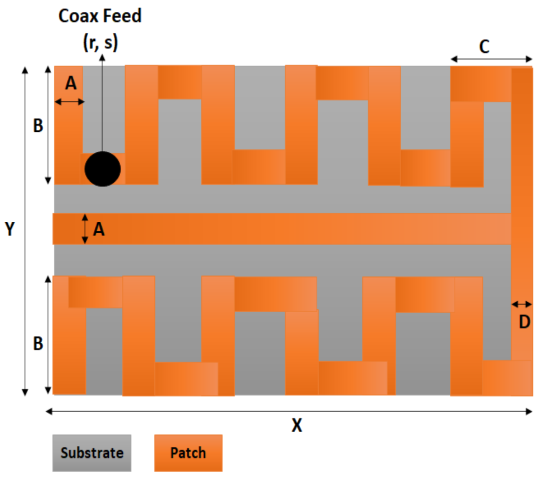
Now a days, human well-being is the biggest disquietude for research community. Due to bad health habits, most of the people are suffering from multiple diseases and consequently cause premature death. To ensure the good human health, the biomedical devices are growing day by day. It is quite possible to diagnose any patient in advance using BMDs. With invention of BMDs, patient can save time rather than waiting in a long queue and long hours. The biomedical devices are very much successful with dual band antennas. In dual band medical antenna, data and power can be transferred through wireless communication link. In one band, data telemetry is established and in other band, DC battery can be charged up by means of wireless power transfer. In this section, detailed study of two frequency band medical implantable antenna is introduced.

3.2 Designing and Parametric Analysis of Proposed Antenna

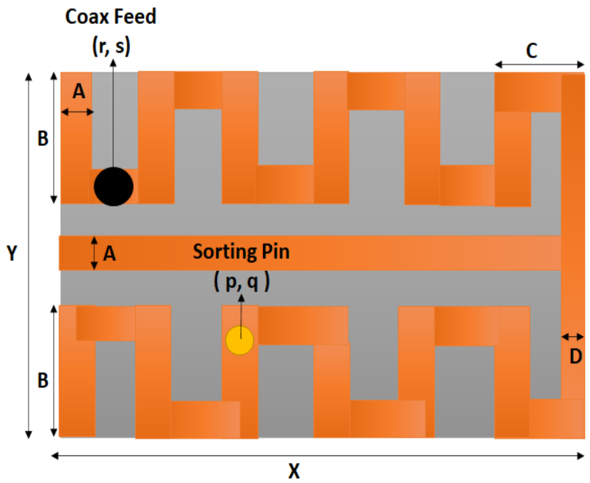
In this section, the sequential flow of proposed antenna design and parametric study of every aspect like effect of penetration depth, performance of antenna in various body substances, and effect of different substrate materials of proposed antenna are discussed at length.

3.2.1 Designing of Proposed Implantable Antenna:

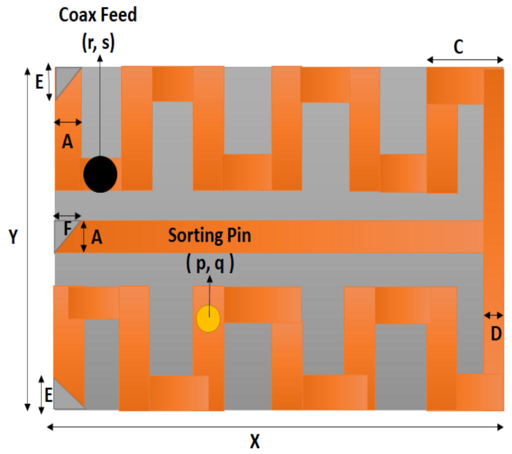
With adoption of meandered shaped technique, a zig zag shaped implantable antenna is designed with size of 6 mm x 4 mm x 0.5 mm (12 mm^3). The two symmetric (zig zag) shapes along with centre strip line has been designed successfully. The substrate Rogers 6010 material that has dielectric constant or e_r of 10.2 and loss tangent 0.0023, has considered for proposed antenna. The thickness of substrate and superstrate is taken as 0.25 mm each. The substrate and superstrate are having same material as Rogers RT duroid 6010. The superstrate has objective to avoid direct touch of conducting part of antenna with human body tissues. The proposed antenna structure is mentioned in Fig 3.1.



(a)



(b)



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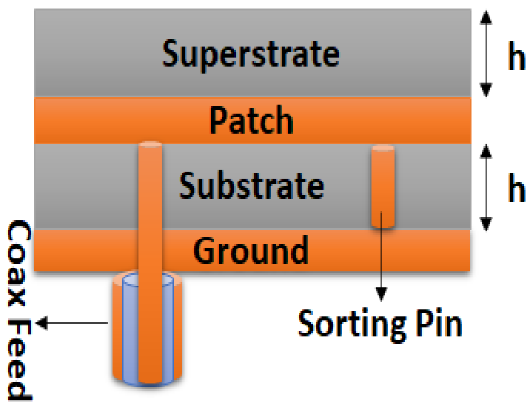

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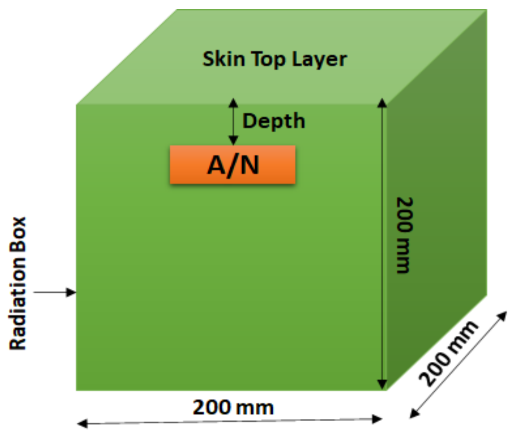
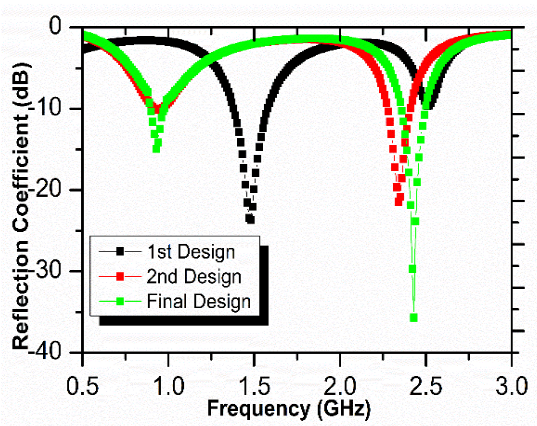




(e) (f)

Fig. 3.1 The designing steps of final antennas. (a) reference antenna design with coax feed. (b) reference antenna design with cylindrical pin (via). (c) The final designed medical antenna with three slots along y axis. (d) side view of the final design antenna with feed excitation and via pin. (e) position of the final designed antenna in the skin box with 3.5 mm depth. (f) s11 parameters of all designed antennas.

The material specifications used in this research work is reflected in table 3.1 having complete details of electrical parameters.

Table 3.1 Material used in proposed antenna specification.

Material/substrate used	**Relative permittivity (e_r)**	**Relative permeability (u_r)**	**Dielectric Loss tangent**	**Bulk conductivity**
Rogers RT duroid 6010	10.2	1	0.0023	0

The reference antenna shown in Fig 3.1 (a) is optimised at position r, s of coaxial feed. The width and length of conducting strips are shown in Table 3.2. The dimension of coax feed cylinders is considered to match 50-ohm impedance of SMA connector. The reference designed antenna is resonated at 1.48 GHz with S11 parameter of -23.65 dB. The -10 dB bandwidth of 12.94 % has been achieved with frequency range 1.39 GHz - 1.57 GHz.

But 1.48 GHz resonating frequency is not included in standard ISM band for medical applications. So, to achieve resonating frequency in standard ISM bands, sorting pin has been used in reference design shown in Fig 3.1 (b) and it is optimised at definite position (p, q). The radius of sorting pin is selected as 0.2 mm to match impedance. With the inclusion of sorting pin at 0.2 mm radius, antenna has shown twin bands at resonating frequency of 0.94 GHz and

2.34 GHz respectively. In lower ISM band, 3.2 % impedance bandwidth has been received and in higher ISM band, it is attained with 5.26 %. Both resonating frequencies have obtained reflection coefficient of -10.2 dB and -21.44 dB respectively shown in Fig 3.1 (f). The higher ISM band is still not covered in standard band ranging from 2.4 GHz to 2.48 GHz. To get existing band in standard ISM bands, three diagonal slots have been introduced along the vertical axis shown in Fig 3.1 (c). The size of three slots is perfectly represented in Fig 3.1 (c) and Table 3.2. With these three slots, two resonating frequencies are occurred at 0.93 GHz and 2.43 GHz with RC (Γ) -14.14 dB and -35.70 dB respectively shown in Fig 3.1 (f). In this final proposed antenna, the -10 dB bandwidth of 7.77 % from 0.9 GHz to 0.97 GHz is received in lower ISM band. In upper ISM band, 5.5 % impedance or -10 dB bandwidth ranging from 2.36 GHz to 2.49 GHz is attained with excellent impedance matching. The superstrate as roger rt duroid 6010 is selected to reduce absorption of EM wave by antenna and provide mechanical strength. To get the accomplishment of final design antenna in human tissues, the final antenna is located at 3.5 mm penetration depth of skin model from the top surface shown in Fig 3.1 (e). The skin model box is simulated in HFSS software having electrical properties of relative permittivity 42.9 and bulk conductivity 1.56 siemens per meter [11]. The dimension of skin substance model is 200 mm x 200 mm x 200 mm shown in Fig 3.1 (e). The parameters value of final design antenna is shown in Table 3.2.

Table 3.2 Designed Parameters of Final Design Antenna.

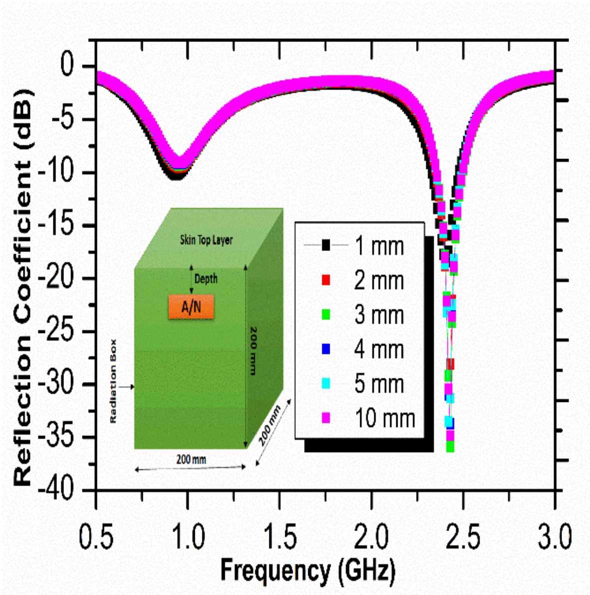
Parameter	**Value of parameter (mm)**
A	0.5
B	1.5
C	1

D	0.25
X	6
Y	4
H	0.25
E	0.4
F	0.45
R	0.75
S	2.75
P	2.75
Q	1

3.2.2 Parametric Study of Final Design Antenna:

a). Performance of Final Design Antenna w.r.t Penetration Depth in Skin Tissue:

In this section, different depth of penetration has been simulated in skin model. The depth is varied from 1 mm to 10 mm from top surface of skin phantom model. The performance in terms of S11 parameters at different depth of penetration of final antenna is depicted in Fig 3.2 (a). From this Fig 3.2 (a), proposed antenna has attained almost similar performance in both ISM bands and no major alteration has been received.



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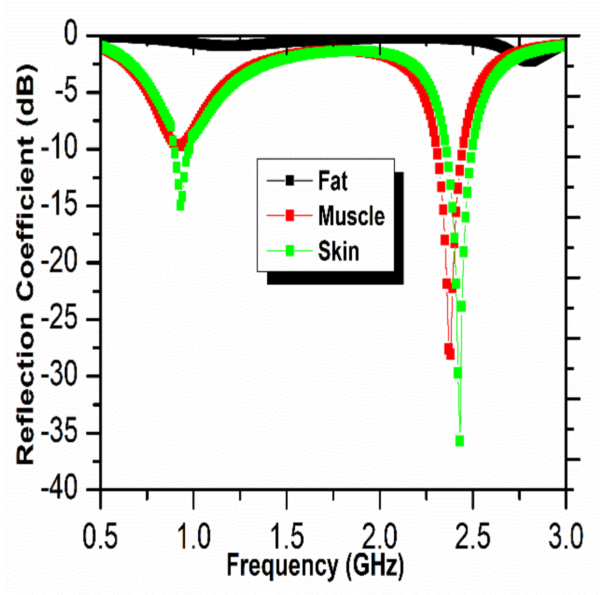

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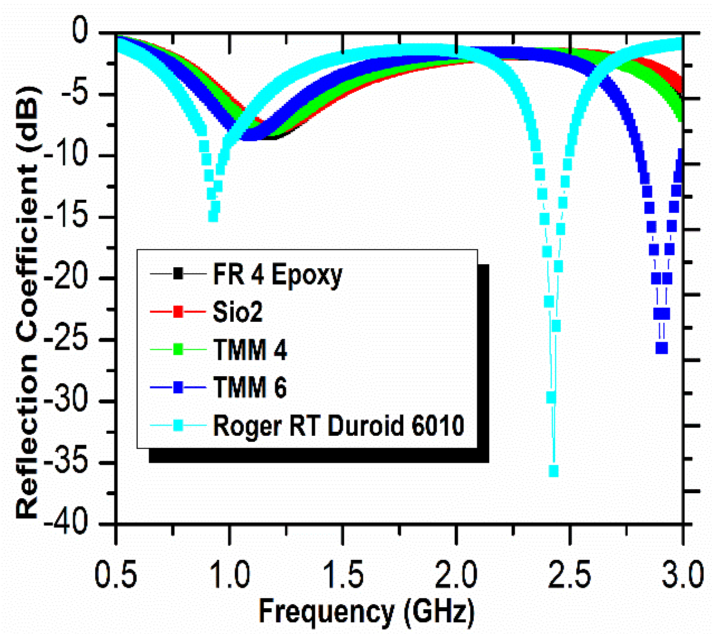


(c)

Fig. 3.2 (a) The analysis of S_{11} in different depth of penetration of final design antenna. (b) the analysis of S_{11} in different human body tissues of final design antenna. (c) the analysis of S_{11} in different substrate/superstrate materials of final design antenna.

b). Performance of Proposed Antenna in Different Physical Body Tissues:

The final design implantable antenna is also simulated in various body tissues with help of vitro model in HFSS. In the fat body tissue, the proposed antenna has vanished its impedance matching badly and did not radiate in either of ISM bands. In muscle phantom model, the proposed antenna has vanished in underneath ISM band due to RC (Γ) which is below -10 dB shown in Fig. 3.2 (b). But in higher ISM band, good impedance matching is secured at 2.4 GHz. So, muscle tissue performance is rejected because of having only single band. At last, skin model is implemented for proposed antenna. The proposed antenna has shown excellent performance in dual band.

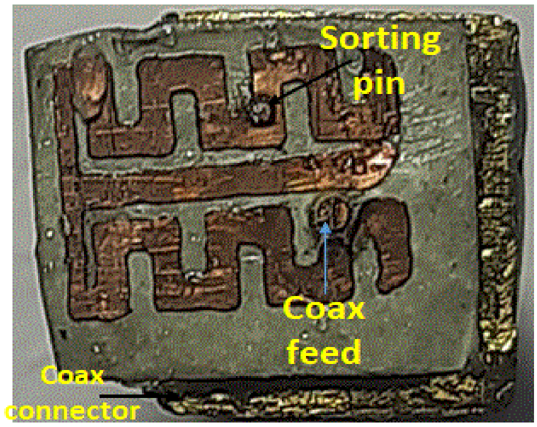
c). Analysis of Final Design Antenna with Various Substrate Materials:

The substrate material is provided mechanical robust and physical strength for implantable antennas. The proposed antenna is simulated with various materials like FR 4 Epoxy, SiO_2, TMM 4, TMM 6, Roger RT duroid 6010. Firstly, the FR 4 Epoxy substrate is used as dielectric material for proposed antenna design because of its low cost. But the proposed antenna design has lost its impedance matching in both ISM bands as shown in Fig 3.2 (c). Then next material what is simulated to test antenna performance is Silicon Dioxide (SiO_2). This substrate has dielectric constant of 3.8. The lower ISM band is disappeared, and higher ISM band is shifted to higher frequency which is not included in desired ISM band range. The TMM 4 and TMM 6 materials are also introduced as substrate for final antenna design. In both substrates, lower ISM band has shown S11 below -10 dB, and upper ISM band is shifted higher undesired frequency range greater than 2.5 GHz. At last, Rogers RT duroid 6010 is selected as best suitable material for proposed design.

3.3 Measurement and Result Discussion

To calibrate the performance of final designed antenna, the vitro model is embraced in this research work. The skin mimicking gel is prepared under specific condition. The skin gel is formed by mixing 53 % sucrose, 47 % deionised water, and 0.5 gram/40 ml solution and then followed by heating this solution at 80^0 for one hour. This mimicking gel has electrical properties equivalent to theorical value of simulation phantom model as shown in Fig. 3.3 (a). The final design antenna is fabricated by photolithography technique. The fabricated antenna and measurement build up is depicted in Fig 3.3 below.

(a)



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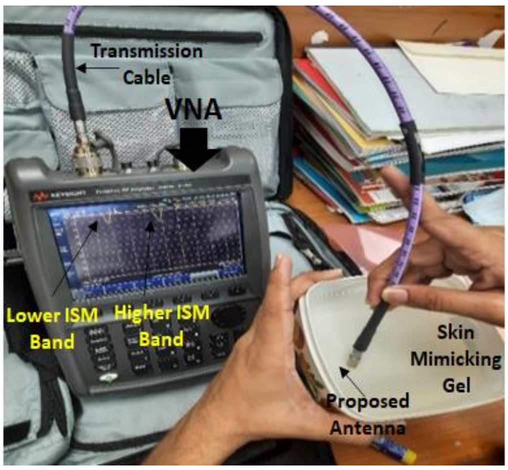

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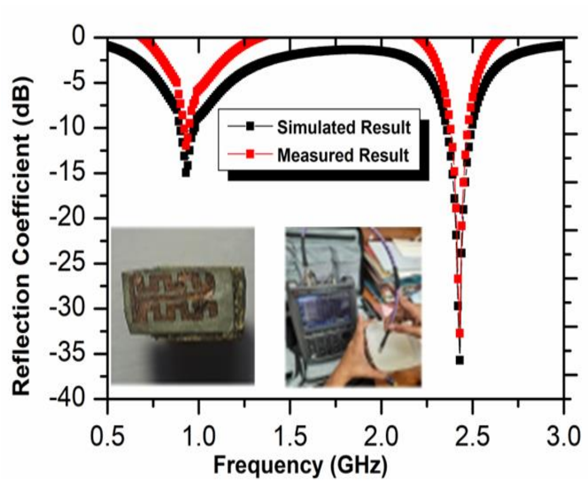

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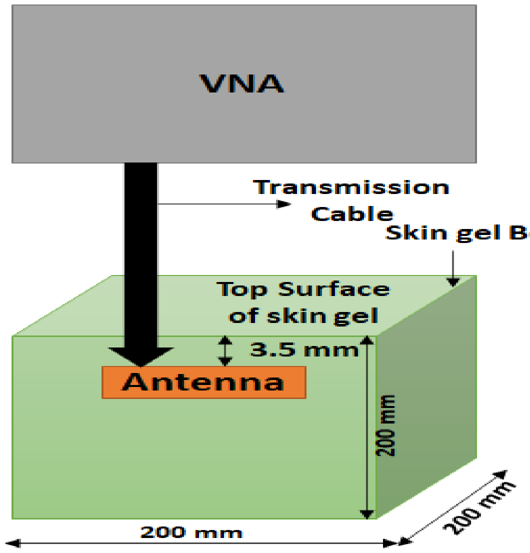
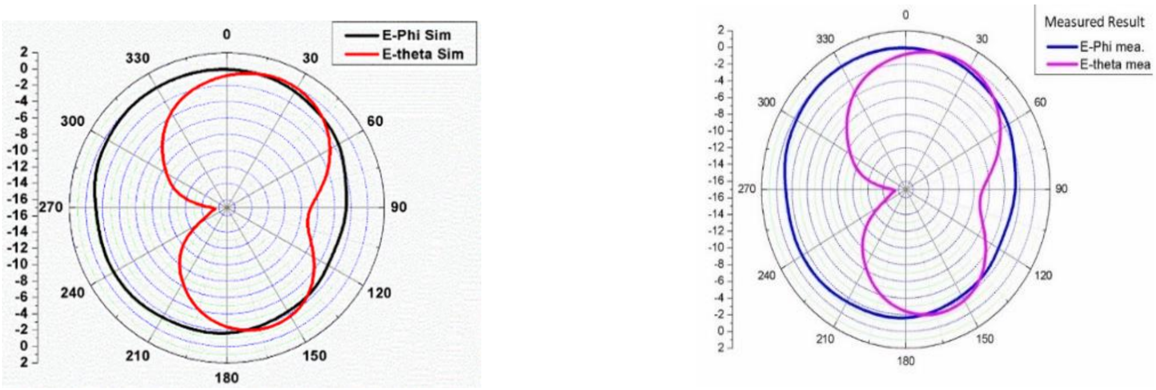


(e)

Fig. 3.3 (a) The saline solution gel at 2.43 GHz. (b) fabricated suggested medical device antenna. (c) Testing setup in the microwave lab. (d) S11 of simulated and fabricated antenna. (e) Prototype model of antenna measurement setups.

The final design antenna is dipped inside of saline solution gel at 3.5 mm depth as shown in Fig 3.3 (c). The vector network analyser (VNA) and the practice of using 50-ohm SMA connector is implemented to validate the simulated results of final design antenna. The sorting pin is developed by making a drilling hole in printed circuit board (PCB) with radius of 0.2 mm. The slots are developed on patch surface using etching selected structure and position in fluoride solutions. Finally, the simulation and testing results of S_{11} have received in agreement shown in Fig 3.3 (d). The measured -10 dB bandwidth is reported with frequency range 0.92 GHz - 0.94 GHz and 2.38 GHz - 2.47 GHz respectively. The slight variation in simulation and measurement results are occurred due poor soldering techniques, imperfection on radiating surface, and glue gel use on patch to fix superstrate material.

The proposed antenna is tested for gain measurement where simulation and measured results are shown in good comparison as depicted in Fig 3.4.



(a) (b)

Fig. 3.4 (a) The simulated value of gain at resonating frequency 2.43 GHz. (b) The measured value of gain of final designed antenna at 2.43 GHz.

It is clearly shown that the final recommended antenna has simulated with gain value of -28.68 dB at 2.43 GHz as presented in Fig 3.4. The simulated and tested gain values are in almost analogous values. The negative value of gain shows that the input feeding power has low strength in order of mW and human body itself has lossy and absorbing nature of radiation. But this value of gain is sufficient to setup wireless communication link between medical device and external device.

The specific absorption rate for any electronic device is the highly concerned parameter for human health. The SAR value is described with absorption of radiation by human body. The low SAR value is always preferred over high value. As per IEEE standard of 1999 and 2005, the maximum SAR value must not exceed 1.6 w/kg for 1 gram of body substance and 2 w/kg for 10 gram of body substance respectively. The SAR analysis and simulated values are shown in Fig 3.5 below.

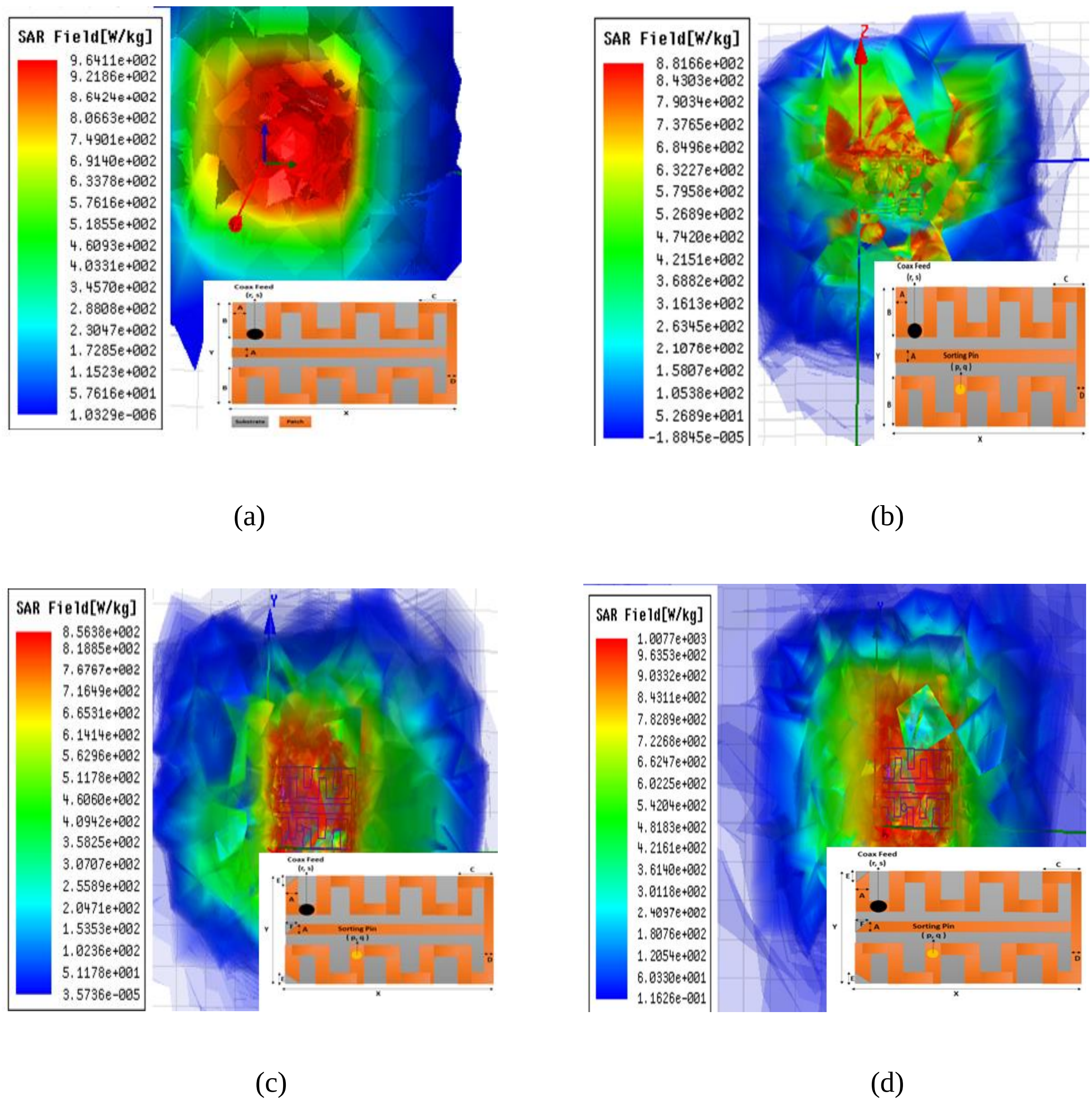


Fig. 3.5 (a) SAR value of reference antenna design at frequency of 1.48 GHz. (b) SAR value of reference antenna with sorting pin at 2.34 GHz. (c) SAR value of final design antenna at 2.43 GHz. (d) SAR value of final design antenna at 0.93 GHz.

The tabular form of SAR analysis of all designed antennas is given in Table 3.3 below.

Table 3.3 SAR values for all designed antennas with input power.

Antenna	**SAR value**	**Max input power (mW)**
Reference Antenna	964.1	1.65

Reference Antenna with Sorting pin	881.6	1.81
Proposed antenna at 2.43 GHz	856.3	1.87
Proposed antenna at 0.95 GHz	1007.7	1.58

The final design antenna at resonating frequency of 0.95 GHz and 2.43 GHz has maximum allowed input power is 1.58 mW and 1.87 mW as displayed in Table 3.3. The more input power is led to produce high radiation.

After the complete discussion of simulation and testing results of proposed antenna, the comparison has been presented to show the novelty of research work w.r.t recent published work which is shown in Table 3.4.

Table 3.4 The comparison table of proposed antenna with neoteric papers.

Reference	f_r (GHz)	SAR	Ground Slot	Via	Volume (mm^3)	Gain (dB)	Bandwidth %	**Improvement of proposed work over previously published work**
[23]	0.402, 0.915, 2.45	665, 837, 759	Yes	Yes	52.5	-40, -32, -22	15, 9.9, 4.2	**Size reduction: 77.14%, No ground slot, Gain improvement by almost 10 dB in lower ISM band**
[41]	0.92	-	No	Yes	486.4	-	11	**Size reduction: 97.53%**
[50]	2.46	213	No	No	127	-20.4	10.2	**Size reduction: 90.55%**
[12]	0.402, 2.4	832, 690	No	Yes	642.62	-36, -27	7.4, 6.6	**Size reduction: 98.13%**
[11]	2.45	649	Yes	Yes	91.9	-20.3	18.3	**Size reduction: 86.94%, No ground slot**
[79]	0.402 2.4	318 292	No	Yes	691.51	-30 ---	12.58 5.8	**Size reduction: 98.26%**
[80]	0.92 2.45	725 833	Yes	No	60	-29.33 -21	--- 123	**Size reduction: 80%, Gain improvement in lower ISM band by almost 8 dB.**
This work	**0.93, 2.43**	**1007.7, 856.3**	**No**	**Yes**	**12**	**-21.65, -28.28**	**7.7, 5.5**	

The Table 3.4 has reflected the information that the final antenna has least volume among all recent published research papers. Moreover, SAR value of proposed antenna is in acceptable limits as per IEEE standard. With this much of small size of implantable antenna, a better gain value is extremely difficult to achieve. But the proposed work has good value of directive gain with highly miniaturized size. This final design of antenna is offered with impedance bandwidth of 7.7 % in lower ISM band and 5.5 % in higher ISM band. There are no ground slots used in proposed research work. Due to this, spurious radiation can be overcome and suppress the back lobe radiation towards ground plane of antenna.

3.4 Conclusion

A miniaturised implantable antenna with zig zag shape is successfully simulated and studied detail analysis on every aspect of dimensions. The compact size antenna is designed with volume of 12 mm^3 only which is under low profile and dimensions. The parametric study reveals that proposed antenna shows almost same performance in skin model box irrespective of depth of penetration from top surface. Based upon parametric study, the skin tissue and Roger RT duroid 6010 are handpicked for best results in ISM bands. The final design of proposed antenna is fabricated using photolithography technique. The vitro model has been furnished as skin mimicking gel solution. The proposed antenna is tested in gel solution at depth of 3.5 mm and shows good acceptance between simulated and tested performance. At resonating frequency of 0.93 GHz and 2.43 GHz, the measured gain values have shown similar results as compared to simulation results. Both ISM bands have been received SAR value 1007.7 and 856.3 respectively. At last, it well concluded that the recommended antenna is excellent choice to be replicated in biomedical devices for allotted ISM bands.

3.5 Limitation

In this chapter, serpentine structure is used to reduce the resonating frequency. To get the dual band characteristics, a sorting pin is optimized in between patch and ground surface. Objective of designing of dual band antenna is successfully attained. But this design is limited with narrow impedance bandwidth of 7.7 % and 5.5 % in lower and upper ISM bands respectively. This percentage of proposed antenna comes under narrow band.

To get wide band characteristics, chapter 4 has presented implantable antenna with teeth structure. To enhance the impedance bandwidth of initial teeth shaped square design, magnetodielectric substrates such as MDS1, MDS2, MDS3 materials are implemented.

3.5 Future Scope

For the future point of view, the proposed antenna needs to be operated in wide impedance bandwidth which can work under broadband category. Moreover, implantable antenna needs to be circular polarised in desired ISM bands to avoid multipath losses. The implantable antenna can carry forward to design rectenna system for wireless power transfer system that will promote long battery and BMDs life span.

Chapter 4

Compact Implantable Antenna using Magnetodielectric Substrate & Compact Triple Ring Slotted Circular Polarized Antenna

4.1 Introduction

In the last chapter, the twin band antenna has proposed by adopting meandered structure and sorting pin to receive performance in ISM bands, acceptable SAR values, and gain. But the proposed implantable antenna is limited to achieve broad impedance bandwidth and circular polarisation. The large impedance bandwidth makes huge attention for researchers. The large bandwidth leads to have several multiple channels. From these multiple channels, the bio information can be transmitted through wireless link to external station. Usually, most of research work keep on publishing with some standard dielectric substrate like FR 4 epoxy, Rogers family, TMM family etc. But recently, the material with relative permeability greater than one, are used to get better performance of implantable antennas. The magnetic properties of particles along with dielectric substrate make change in effective impedance which cause better impedance matching. Consequently, better results have been obtaining. The circular polarisation characteristics play most important role in medical devices. The implantable antenna with this characteristic can avoid multiple path losses. It provides facility to patient to enjoy freedom of mobility during transmission of data through BMDs to external stations. In this chapter, the technique of magnetodielectric substrate has been discussed in detail. Using this technique, great level of miniaturisation has been attained for implantable antenna. The analysis of ring-shaped slots has been investigated. The implementation of metamaterial and ground slots techniques have been explored to achieve circular polarisation and compact size.

4.2 Design of Proposed Antenna and Parametric Study

In this section, the gradual designing of suggested implantable antenna has been examined at length. After the final design of proposed antenna, different combination of magneto dielectric substrates in terms of e_r and u_r are investigated. The achievement regarding RC (Γ), -10 dB bandwidth, gain, and SAR has been explored for all designed proposed antennas.

4.2.1 Design of Proposed Antenna:

A square shaped dielectric substrate is considered with dimension 6 mm x 6 mm. Then to provide physical strength to antenna, substrate is selected with height of 0.127 mm. Hence the size of final design antenna is 6 mm x 6 mm x 0.127 mm (4.572 mm^3). This is reported as the least size implantable antenna so far. To increase current path of patch surface, teeth shaped serpentine path is designed. Every tooth that is coming out from rectangular strips has 0.5 mm dimension in square shape. The design of proposed antenna is shown in Fig. 4.1. The designed implantable antenna is simulated with Rogers 6010 substrate having e_r 10.2 and loss tangent 0.0023.

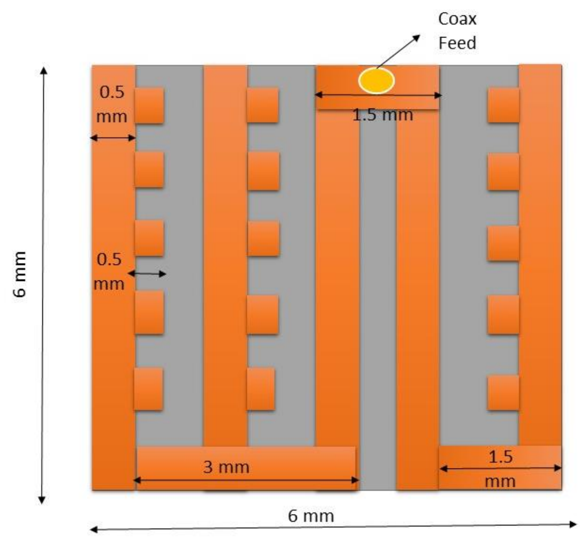


Fig. 4.1 Design and Dimensions of Final Implantable Antenna.

The designed implantable antenna is fed with coax feed with outer and inner diameter of 0.935 mm and 0.28 mm respectively. To simulate the performance of proposed antenna, the vitro model is adopted as skin box in HFSS. The skin box simulation set up is presented by Fig 4.2.

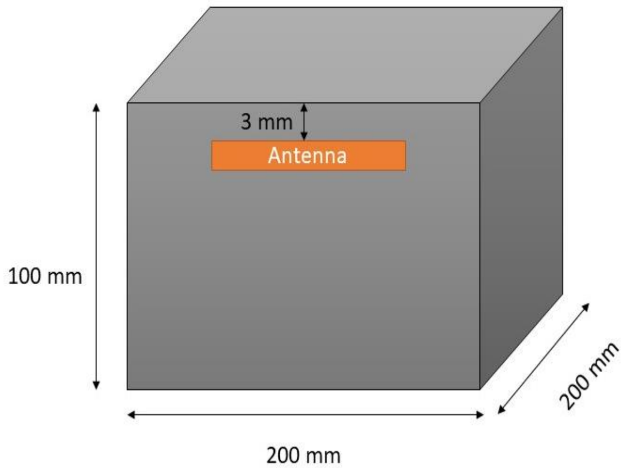


Fig. 4.2 The Implantable Antenna in skin box at 3 mm depth from top layer.

The simulation model of skin tissue box has size of 200 mm x 200 mm x 100 mm. The medical device antenna is situated at 3 mm depth below the top layer of skin phantom box. The electrical characteristics of skin tissues are depending upon operating frequency. So, at 2.45 GHz, the electrical properties of skin are taken from [11]. The different magneto dielectric substrates are simulated with same teeth shaped patch structure. The magneto dielectric substrates are reflected with their properties in Table 4.1.

Table 4.1 Characteristics of magneto dielectric substrates used in research work.

Material	**Relative permittivity (e_r)**	**Relative permeability (u_r)**	**e_r * u_r**	**e_r/u_r Ratio**
Rogers RT duroid 6010	10.2	1	10.2	Greater than 1
MDS 1	1.591	6.4	10.2	Less than 1
MDS 2	3.19	3.19	10.2	Equal to 1
MDS 3	4.516	2.258	10.2	Greater than 1

The reference antenna is optimised in ISM band with substrate of roger rt duroid 6010. There are three magneto dielectric substrate having relative permeability greater than one. Such substrates have enhanced magnetic properties. All magneto dielectric substrates are chosen to have same product of e_r and u_r as shown in Table 4.1. The magneto dielectric substrates are selected in three ways by considering the ratio of relative permittivity and relative permeability shown in Table 4.1. The achievement of final design of antenna is explored with all such combination of magneto dielectric substrates. All research work is carried on simulation tool HFSS. The designing specification of proposed antenna is reflected in table 4.2 below.

Table 4.2 The designing specification of proposed antenna.

Length	6 mm	Thickness	0.127 mm
width	6 mm	Conducting Strip width	0.5 mm

4.2.2 Performance of Proposed Design with Different MDS Materials:

The accomplishment of final design of medical device antenna is analysed regarding RC (Γ), gain, and SAR. In this section, detailed results of proposed design are studied successfully.

a). Reflection Coefficient:

The reflection coefficient or S11 parameter show the ability of any antenna w.r.t impedance matching at given frequency. How much power is transmitted through medium, is simply presented by this parameter. The Rogers RT duroid 6010 substrate has reflection coefficient value of -12.05 dB at resonating frequency of 2.44 GHz. The impedance bandwidth has been obtained 190 MHz with frequency range 2.34 GHz - 2.53 GHz. This bandwidth is sufficient to transmit bio information like glucose monitoring, O_2 level, blood pressure, sugar etc. But when

BMDs are expected to transmit videos signals with very high rate then more impedance bandwidth is required. So, impedance bandwidth needs to be enhanced. After using MDS 1 material as substrate, then the reduction of resonating frequency is placed from 2.44 GHz to 1.78 GHz shown in Fig. 4.3. The -10 dB bandwidth has been improved from 190 MHz to 410 MHz. It is lied from 1.59 GHz to 2 GHz. The reflection coefficient has been improved from -12.05 dB to -31.24 dB. The reflection coefficient for all substrates has been presented in Fig 4.3.

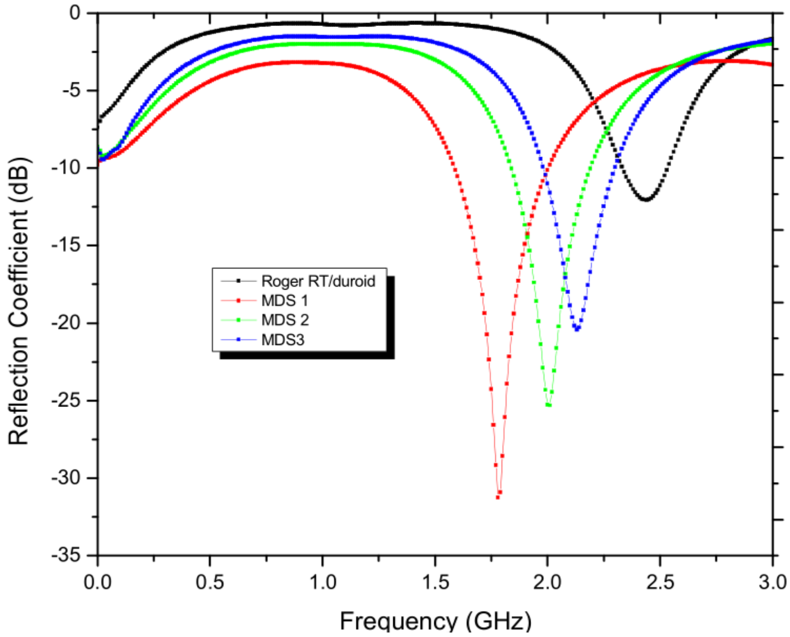
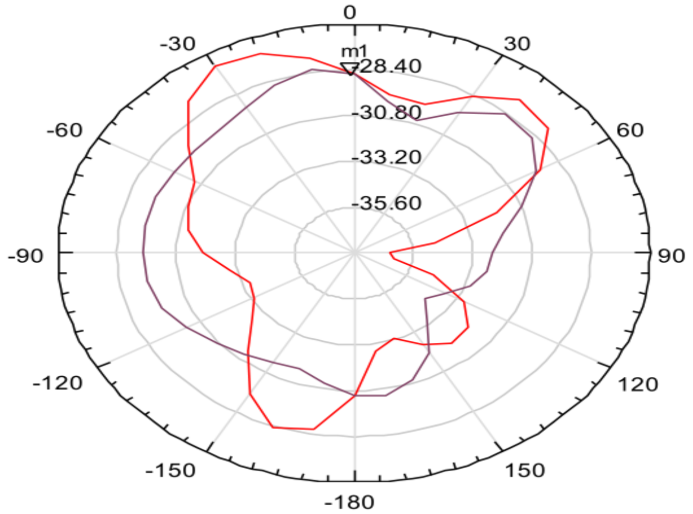


Fig. 4.3 S_{11} of Final Design Antenna with MDS materials.

The MDS 2 material has been achieved reflection coefficient of -25.30 dB at resonating frequency at 2.01 GHz. With this material, the 350 MHz impedance bandwidth has been received from 1.84 GHz to 2.19 GHz. In comparison of Rogers material, the 160 MHz more bandwidth has been enhanced by MDS 2 material. At last, the MDS 3 material is simulated for final antenna design. With this substrate material, the reflection coefficient of -20.39 dB has been attained at resonating frequency at 2.13 GHz. The bandwidth is improved from 190 MHz (Rogers rt duroid) to 300 MHz from 1.99 GHz to 2.29 GHz. It is come to an end that all MDS materials have improved the impedance bandwidth and reflection coefficient or impedance matching up to great extent.

b). Directive Gain:

Usually, the directive gain of medical device antenna gets little value due to weak signal strength and lossy environment of human body. In this paper, the gain from reference antenna having Rogers rt duroid material, is obtained -28.59 dB at 2.44 resonating frequency presented in Fig 4.4 (a).



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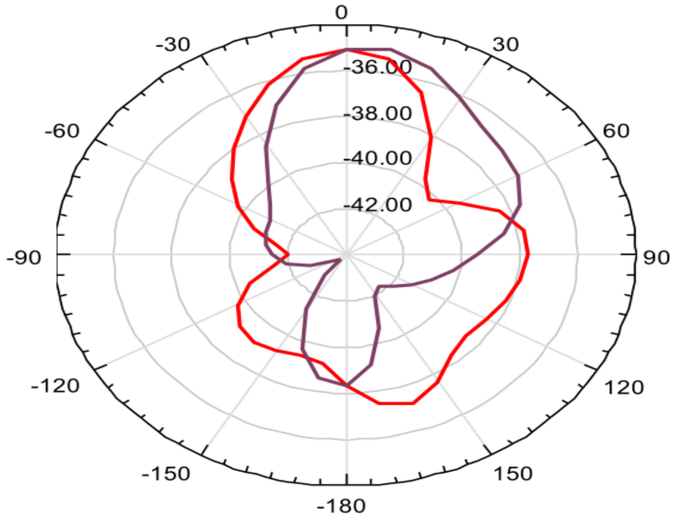

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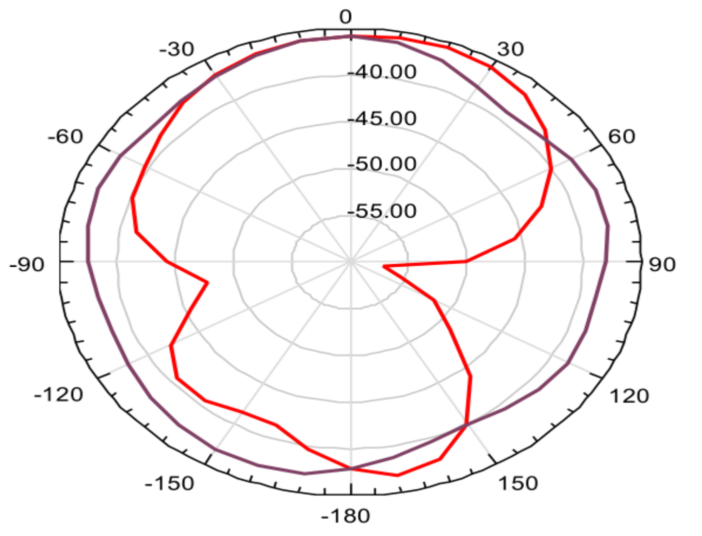

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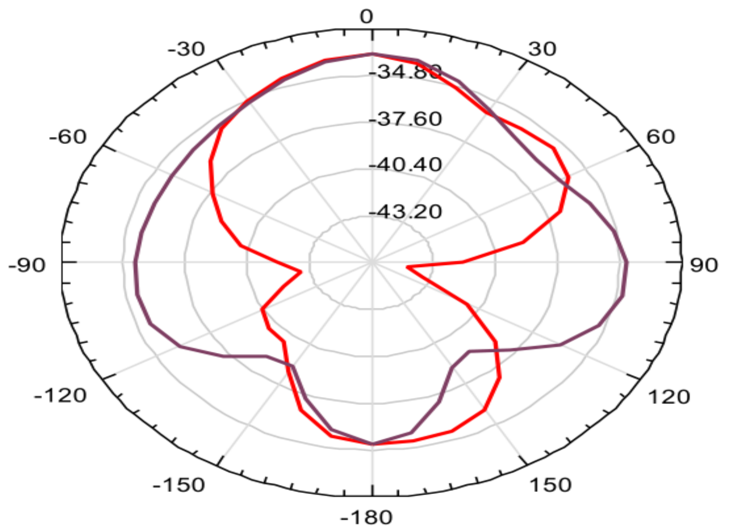


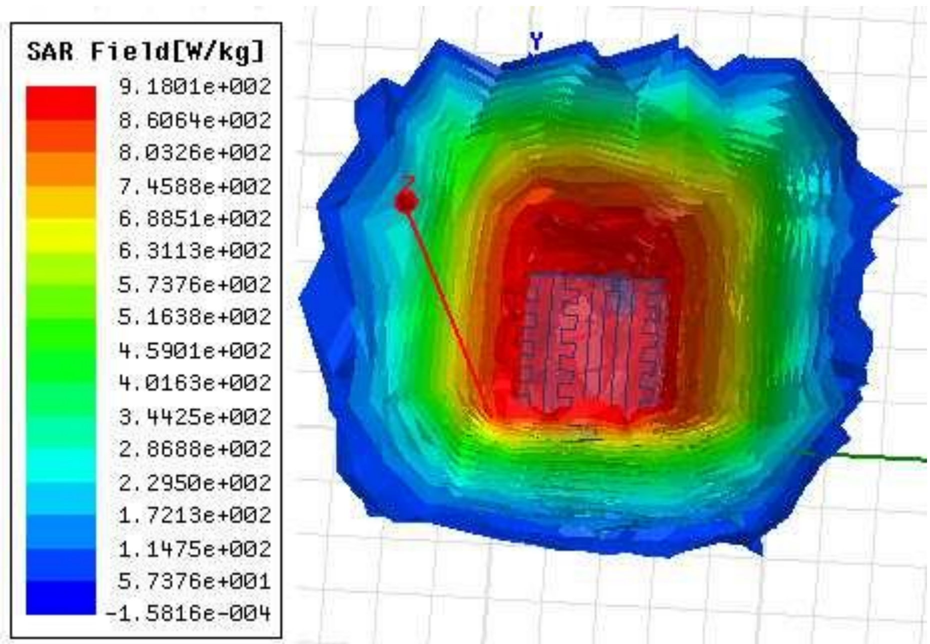
(d)

Fig. 4.4 (a) Directive gain of final design antenna at 2.44 GHz with Rogers RT duroid Substrate. (b) Gain value of proposed antenna with MDS 1 material at 1.78 GHz. (c) Gain value of proposed antenna with MDS 2 material at 2.01 GHz. (d) Gain value of proposed antenna with MDS 3 material at 2.13 GHz.

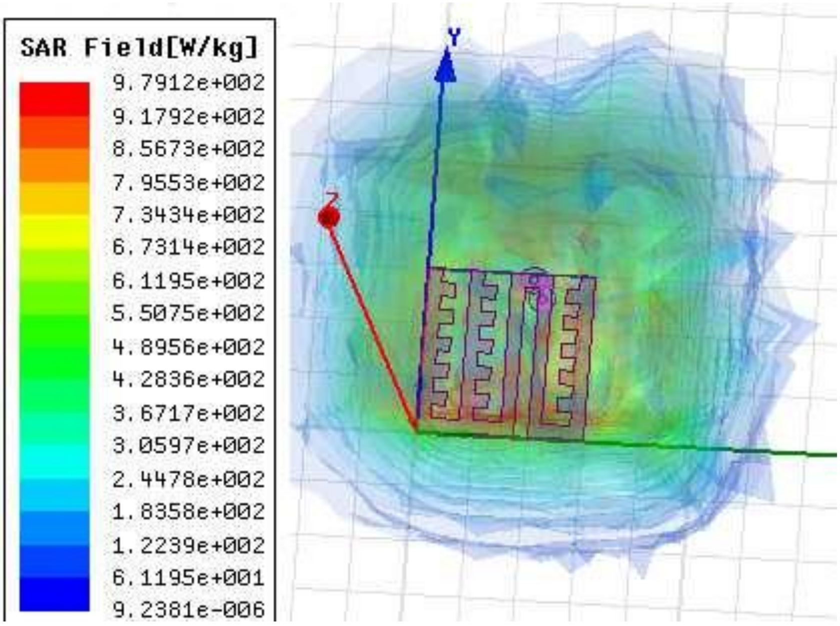
When MDS 1 material is simulated then gain has been achieved -35.08 dB at resonating frequency 1.78 GHz as shown in Fig. 4.4 (b). Almost 7 dB gain has been reduced. In MDS 2 material, gain has been observed -35.75 dB at resonating frequency of 2.01 GHz as shown in Fig. 4.4 (c). In comparison of Rogers rt material, the MDS 2 material has been received gain degraded by almost 7 dB gain value. Similarly, MDS 3 material is simulated with gain value of -33.48 dB at 2.13 frequency as shown in Fig. 4.4 (d). From all materials, it is noted that the magneto dielectric substrates have not worked well to attain improved gain values.

c). Evaluation of Specific Absorption Rate:

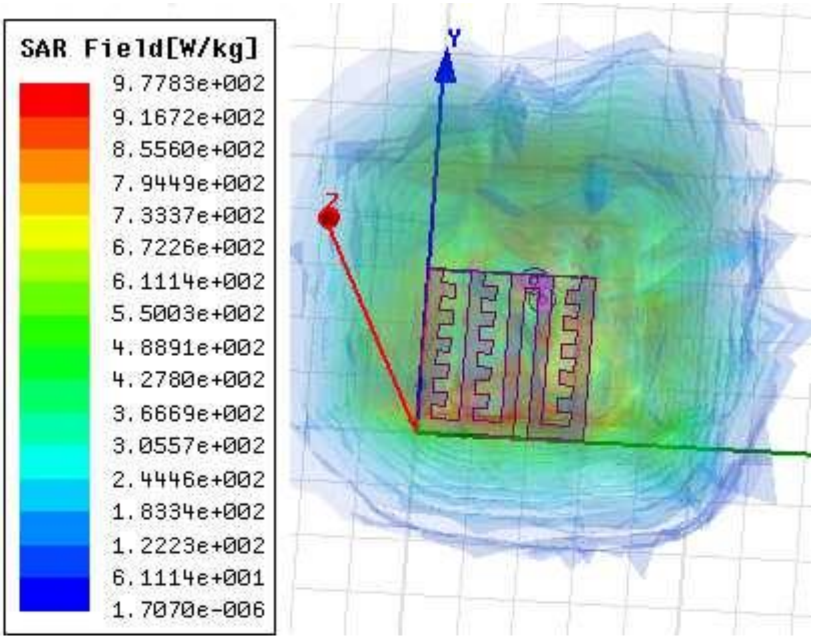
For all BMDs, human health and patient safety is the prime concern. The SAR value is standard parameter which ensures safety for human body tissue. The two standards have been proposed by American and European society in 1999 and 2005 respectively. For 1 gram and 10 gram of body tissues, the SAR value must not exceed 1.6 w/kg and 2 w/kg respectively. The researchers must design biomedical devices or implantable antenna which has SAR value less than standard value. If someone makes designing the implantable antenna having more value than SAR standard, will not be any use in medical industries. In this paper, all MDS materials are simulated with SAR values. The SAR value of every individual material used in this research work, is in acceptable range which is shown in Fig. 4.5.



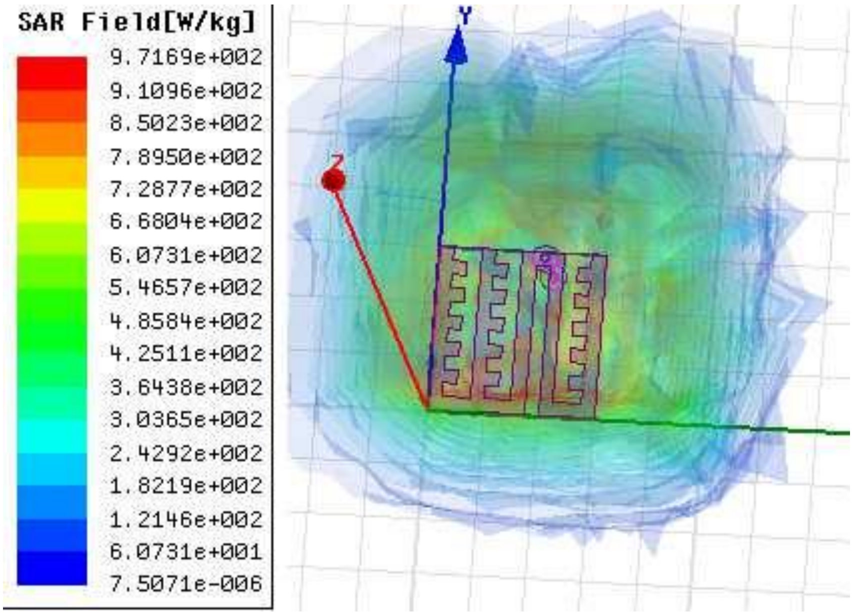
(a)


SAR Field[W/kg]
9.7912e+002
9.1792e+002
8.5673e+002
7.9553e+002
7.3434e+002
6.7314e+002
6.1195e+002
5.5075e+002
4.8956e+002
4.2836e+002
3.6717e+002
3.0597e+002
2.4478e+002
1.8358e+002
1.2239e+002
6.1195e+001
9.2381e-006
Y
Z

(b)


SAR Field[W/kg]
9.7783e+002
9.1672e+002
8.5560e+002
7.9449e+002
7.3337e+002
6.7226e+002
6.1114e+002
5.5003e+002
4.8891e+002
4.2780e+002
3.6669e+002
3.0557e+002
2.4446e+002
1.8334e+002
1.2223e+002
6.1114e+001
1.7070e-006
Y
Z

(c)



(d)

Fig. 4.5 (a) SAR value of proposed medical antenna with Rogers material at 2.44 GHz. (b) SAR value of proposed antenna with MDS 1 material at 1.78 GHz. (c) SAR value of proposed antenna with MDS 2 material at 2.01 GHz. (d) SAR value of proposed antenna with MDS 3 material at 2.13 GHz.

The reference antenna with Rogers material is resonated at 2.44 GHz. At this frequency, the reference antenna has been attained SAR value 918 in Fig. 4.5 (a) which is less than threshold level of standard SAR. The MDS 1 material has obtained SAR value of 979 which is slightly higher than Rogers material in Fig. 4.5 (b). But this value too is under considerable range. The MDS 2 and MDS 3 materials have been attained SAR value of 977.58 and 971.6 respectively in Fig. 4.5 (c) and (d). Some readers may be confused in SAR standard like 1.6 w/kg or 2 w/kg which is quite less than received SAR value like 918, 979, 977.58, and 971.6. All received values of SAR from magneto dielectric substrates are calculated for one mW input power. So, SAR value in terms of mW input power standard, is referenced as 1600 or 2000 for one gram and ten-gram body tissue respectively.

The SAR numbers received from magneto dielectric substrates are mentioned in Table 4.3 with the maximum allowable input power given below.

Table 4.3. SAR numbers and maximum input power for all presented work.

Proposed implantable antenna	SAR value (w/kg)	Max input power (mW) for 1 gram
reference Antenna with Rogers RT duroid 6010	918	1.74
MDS 1	979.1	1.63
MDS 2	977.8	1.63
MDS 3	971.6	1.64

From this Table 4.3, it is reported that the reference antenna with Rogers material has highest incoming power of 1.74 mW value to feed antenna. The maximum input power is resulted into better radiation properties.

4.3 Comparison of Proposed Work with Recent Published Papers

In this section, the final design medical antenna is juxtaposed with the recent released research papers.

Table 4.4. Comparison of proposed work with recent research papers.

Reference Paper	Size of antenna or volume (mm^3)	Resonating Frequency (GHz)	Bandwidth (MHz)	Gain (dB)	SAR/ one gram	Substrate used	Improvement of proposed work over previously published work [16],[31],[60] respectively
[16]	1680	0.402	80.2	-41.03	-	Roger 3210	-
[31]	34.96	2.45	6.92 %	-27.19	-	Roger 5880	-
[60]	12.8	2.45	290	-14	-	Ultralam	-
Proposed work	**4.572**	**2.44**	**190**	**-28.59**	**918**	**Roger 6010**	**Size reduction: 99.72%, Bandwidth improvement: 136.9%, 18.75%, -34.48%**
Proposed work	**4.572**	**1.78**	**410**	**-35.04**	**979.1**	**MDS 1**	**Size reduction: 99.72%, Bandwidth improvement: 411%,156.25%, 41.37%**
Proposed work	**4.572**	**2.01**	**350**	**-35.75**	**977.8**	**MDS 2**	**Size reduction: 99.72%, Bandwidth improvement: 336.4%, 118.75%, 20.68%**
Proposed work	**4.572**	**2.13**	**350**	**-33.48**	**971.6**	**MDS 3**	**Size reduction: 99.72%, Bandwidth improvement: 336.4%, 118.75%, 20.68%**

The final implantable antenna has least volume of 4.572 mm^3 among mentioned research papers as presented in Table 4.4. This proposed implantable antenna has reported with excellent bandwidth of 190 MHz with highly miniaturised size. The MDS materials have been explored with different permittivity and permeability. The resonating frequency of reference antenna is switched to lower frequency band. Hence size is further reduced using MDS materials. All materials used in this research work, have attained acceptable value of SAR. The gain value is little compromised although got excellent impedance bandwidth and size reduction.

4.4 Conclusion

The implantable antenna for BMD is analysed with various substrate materials including Rogers, magneto dielectric etc. With replacement of Rogers rt duroid to magneto dielectric substrate, impedance bandwidth has been enhanced to 410 MHz. The acceptable range of SAR values are achieved too for 1 gram tissue standard. This research work is simulated without having sorting pin, ground slots, patch slots, or patch stacking complex techniques. The least volume of proposed antenna has been attained with simple teeth shaped radiator design. The recommended work has best execution in terms of size reduction, and impedance bandwidth for health monitoring biomedical device system.

4.5 Limitation

This work is reported with least volume of 4.572 mm^3. But this proposed antenna is not subjected to Circular polarization. To avail the facility of moving to and fro during data transmission, the antenna must be designed with CP characteristics. This chapter deals with CP characteristics of implantable antenna in its 2nd part given below.

4.6 Introduction to CP Antenna

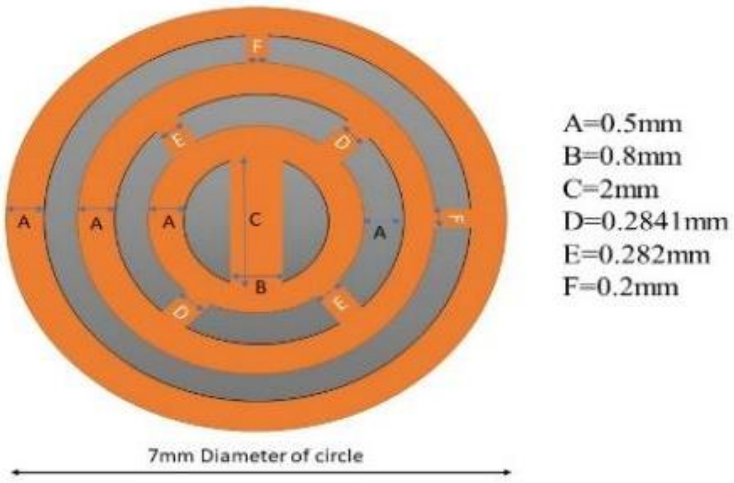
In the above proposed implantable antenna, the impedance bandwidth and miniaturisation have been attained with excellent performance. But this research work is limited to attain circular polarisation in desired ISM band. The CP characteristics of the implantable antenna plays inevitable role for patients during data transmission. With CP characteristics, the implantable antenna simply averts losses due to multiple paths of radiations. So, to achieve CP characteristics, one more proposed implantable antenna has been designed using cylindrical structure. Every minute detail and performance of proposed implantable antenna has been discussed at length.

4.7 Proposed Antenna Designing Steps:

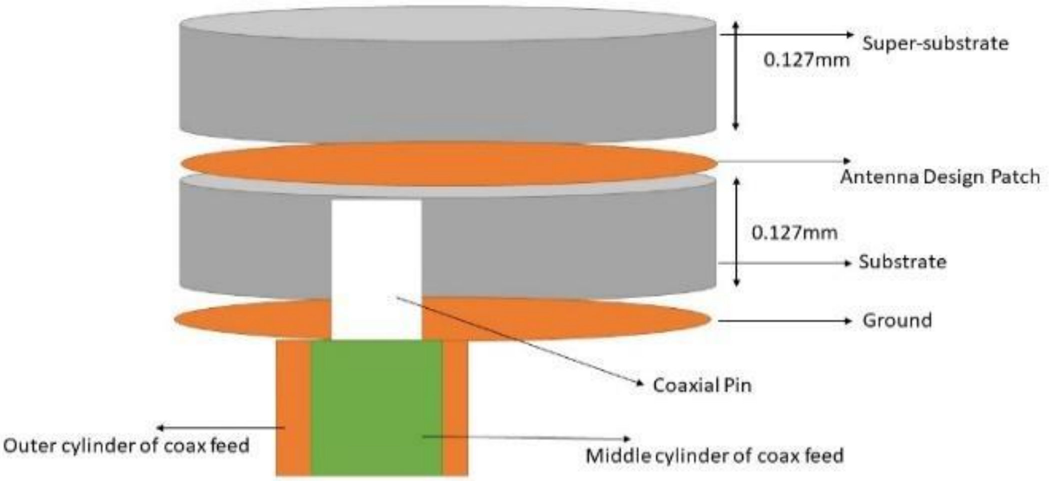
In this segment, the development of final design of suggested antenna has been discussed in detail. Moreover, the parametric study of every dimension of antenna design has been explored. The execution of recommended antenna has been reported regarding S_{11}, 3 dB bandwidth, SAR, and gain value.

4.7.1 Design and Analysis of Final Design Antenna:

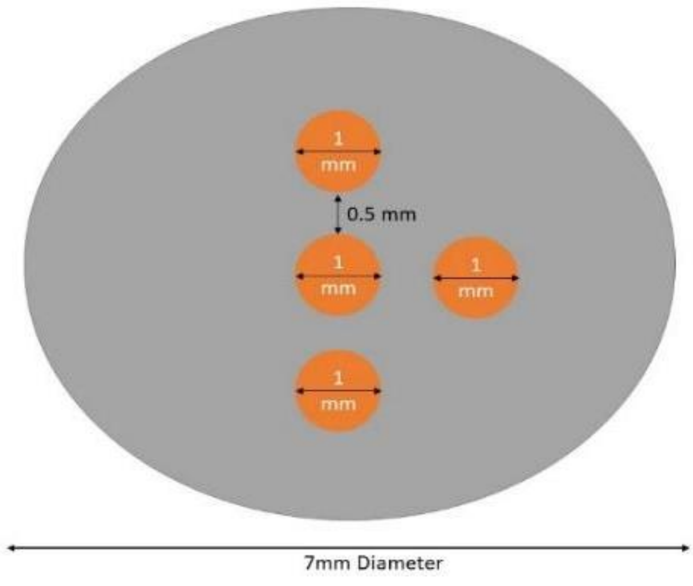
To design implantable antenna with CP characteristics, is the most important intention from scientist and researchers. With this property, complete mobility to patients during telemetry sessions can be ensured. So first, cylindrical shaped substrate of Rogers rt duroid is taken as reference. The substrate has e_r of 10.2 and tan(δ) of 0.0023. The substrate thickness has taken with 0.127 mm. The cylindrical structure has considered with radius of 3.5 mm. On the radiating surface, three circular rings have been designed with 0.5 mm width each. The outermost ring has 3.5 mm radius from outside boundaries. The middle ring has dimension of 2.5 mm radius. The smallest ring is designed on inner side of patch with radius of 1.5 mm. A rectangular strip of 2mm length and 0.8 mm width is used inside of smallest ring. Then to increase the current path on radiating surface, six rectangular strips of different dimensions have been used. With help of these six rectangular strips (D, E, F), the three rings are sorted together. To avoid spurious radiation back to antenna and contact with body tissues, the superstrate with same as substrate material is used having stratum of 0.127 mm. So, the size of final design antenna is of $3.14*3.5^2*0.254$ (9.77 mm^3). To excite the proposed antenna, coaxial feed is provided to match impedance of 50 ohm. The outer, middle, and inner diameter of coax feed connector are given as 0.935mm, 0.4 mm, and 0.28 mm respectively. The design of suggested antenna has been displayed in Fig 4.6 below.



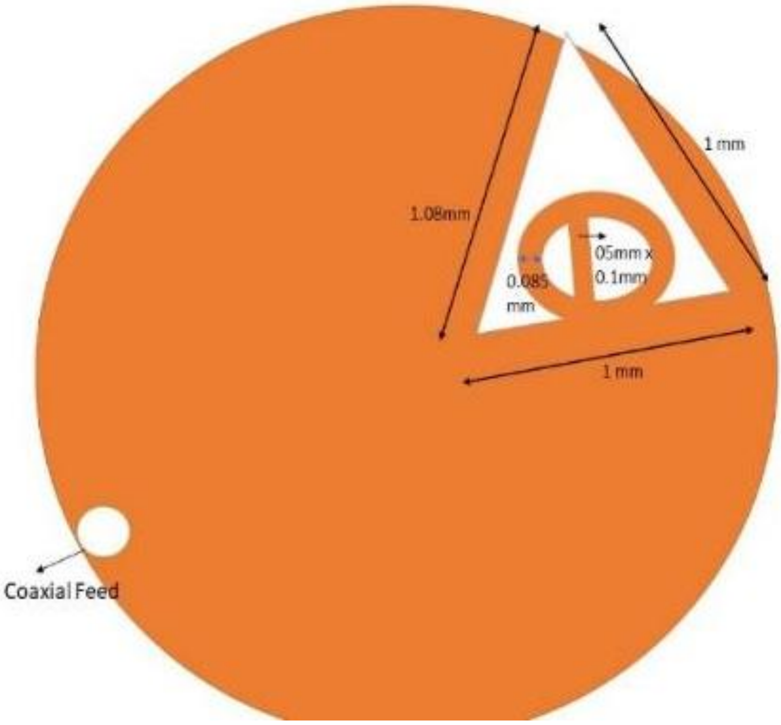
(a)


Super-substrate
0.127mm
Antenna Design Patch
0.127mm
Substrate
Ground
Coaxial Pin
Outer cylinder of coax feed
Middle cylinder of coax feed

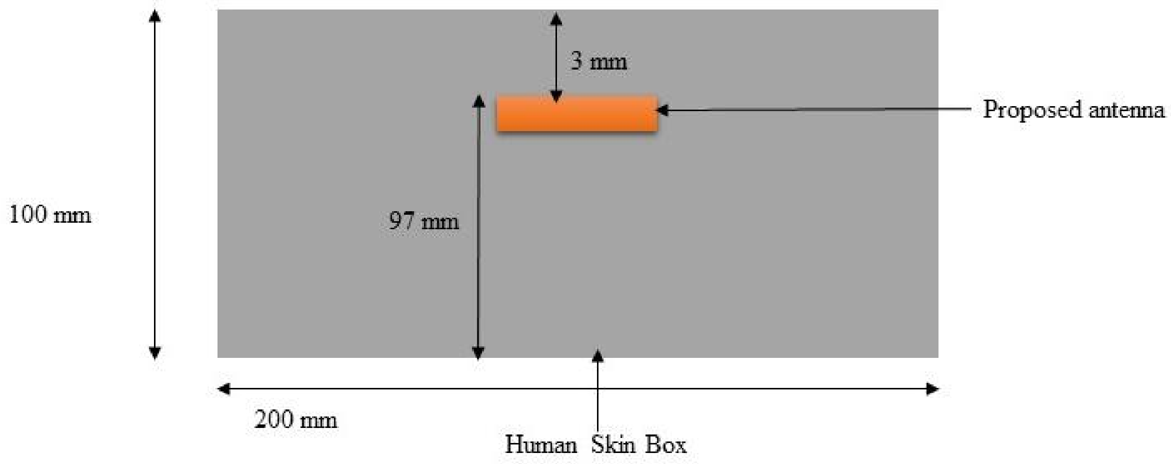
(b)


1 mm
0.5 mm
1 mm
1 mm
1 mm
7mm Diameter

(c)



(d)



(e)

Fig. 4.6 (a) Design of reference antenna of radiating plane. (b) The side profile of final design antenna. (c) The circular shaped metamaterial unit on superstrate surface with dimension. (d) The ground slots of final proposed implantable antenna. (e) Placement of proposed antenna in skin box with 3 mm depth of penetration.

In Fig 4.6 (b), the side profile of suggested medical antenna is shown with thickness of substrate/superstrate. To validate the execution of implantable antenna in tissue, the vitro model is adopted with skin model of dimension 200 mm x 200 mm x 100 mm shown in Fig 4.6 (e). The proposed antenna is placed at 3 mm depth below the top layer of skin tissue phantom. The skin box has electrical properties in ISM band at frequency of 2.45 GHz. The properties of skin at 2.45 GHz frequency have been taken from [11] with dielectric constant 42.8, and bulk conductivity 1.593 siemens per meter. The complete simulation has been carried out in simulation tool of HFSS. To attain the better execution in terms of CP characteristics, impedance bandwidth, and reflection coefficient, the metamaterial, ground slots have been implemented which is shown in Fig 4.6 (c) and 4.6 (d) respectively.

The material specification and designing parameters used in this proposed work are presented in table 4.5 and table 4.6 respectively.

Table 4.5 The material specification of proposed antenna.

Material/substrate used	**Relative permittivity (e_r)**	**Relative permeability (u_r)**	**Dielectric Loss tangent**	**Bulk conductivity**
Rogers RT duroid 6010	10.2	1	0.0023	0

Table 4.6 The designing parameters of proposed antenna.

Variable	**Value (mm)**	**Variable**	**Value (mm)**
A	0.5	D	0.2841
B	0.8	E	0.282
C	2	F	0.2

Diameter	7	Thickness	0.127

4.8 Results and Discussion of Proposed Implantable Antenna

In this section, the proposed antenna with all designs has been analysed in detail. The various parameters like S11, SAR, Axial ratio, and Bandwidth of proposed implantable antenna have been studied successfully.

4.8.1 Reflection Coefficient:

To match impedance of antenna with SMA connector, the reflection coefficient in dB must be either -10 dB or below. This -10 dB S11 parameter ensures the 90 % power transmission through transmission line to antenna and only 10 % power is reflected to source end. So, S11 has value of -10 dB or less, reflects the better impedance matching. The reference antenna shown in Fig 4.6 (a) has three rings with width of 0.5 mm each, shows reflection coefficient of -14 dB at resonating frequency of 2.43 GHz. The -10 dB bandwidth is obtained with frequency range 2.37 GHz - 2.49 GHz (120 MHz). To further improve the impedance matching, the metamaterial with four circles of 0.5 mm radius is implemented on superstrate shown in Fig 4.6 (c). Due to this metamaterial, the RC (Γ) is enhanced from -14 dB to -32.5 dB. The resonating frequency is slightly switched from 2.43 GHz to 2.48 GHz which is still in standard ISM band. After metamaterial, the ground slot of triangular shaped structure of almost 1 mm size has been implemented. One ring is also designed with perfect electric conductor (PEC) in that ground slot shown in Fig 4.6 (d). The S_{11} is attained with value of -38.4 dB at resonating frequency of 2.39 GHz. The complete reflection coefficient for all designed antennas is appeared in Fig 4.7.

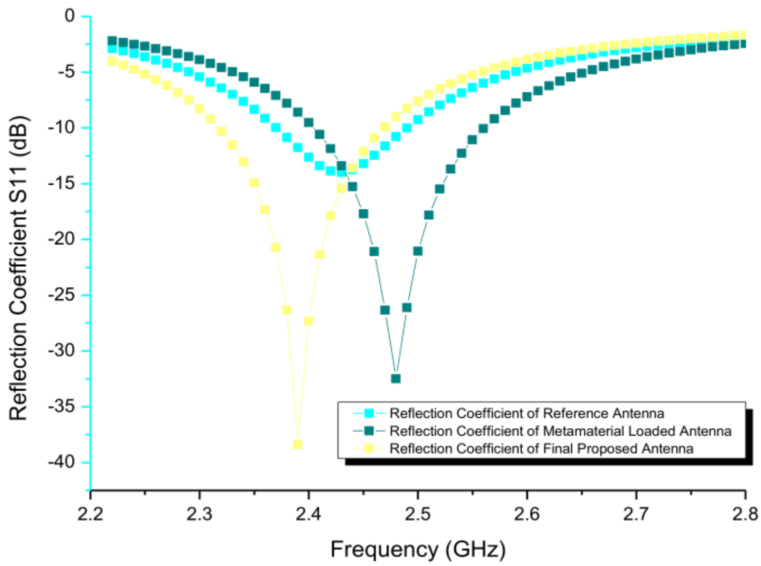


Fig. 4.7 RC (Γ) of all Proposed Antennas.

4.8.2 Axial Ratio of Designed Antennas:

It is termed as the ratio of radiation strength of major lobe to minor lobe. If antenna is circularly polarised, then the major and minor lobe have equal strength of radiation. Then their ratio becomes one and 0 dB. The frequency range below 3 dB threshold of axial ratio is known as 3 dB bandwidth or axial ratio bandwidth. The reference designed antenna shown in Fig 4.6 (a), is depicted axial ratio more than 3 dB in entire frequency range. This is resulted into linear polarised antenna. To achieve CP characteristics, the reference antenna is implemented with four metamaterial circles on superstrate surface. Due to this metamaterial circular structure, the axial ratio has been achieved near to 3 dB in frequency spectrum with frequency range 2.2 GHz - 2.8 GHz. But antenna is still in linear polarisation. After the imposition of triangular slots on ground along with ring (PEC), the proposed implantable antenna is exhibited circular polarisation having axial ratio than 3 dB with frequency range 2.38 GHz - 2.67 GHz. In this frequency range, the proposed antenna is behaved with CP characteristics. In this frequency range, the operation of antenna is performed with excellent suppression of multipath losses. The patient needs not to sit in rigid posture. He/she can entertain with mobility of moving to and fro during data transmission. The axial ratio performance of all designed antennas is presented in Fig 4.8 below.

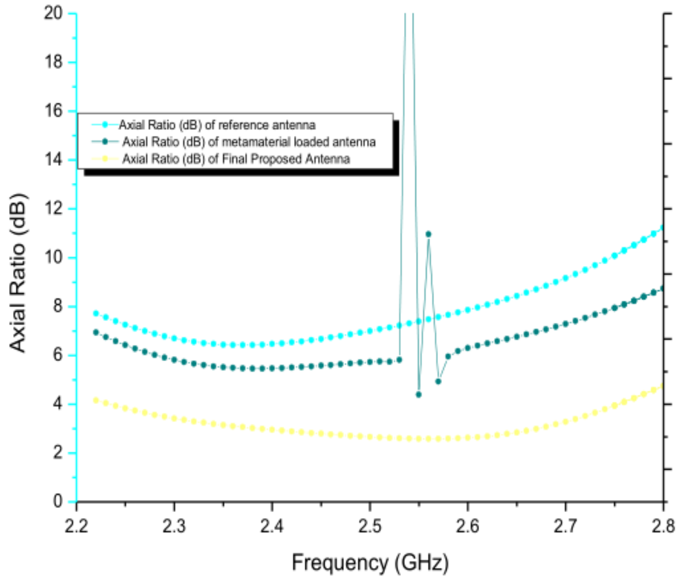


Fig. 4.8 The 3 dB Bandwidth Performance of Proposed Antennas.

4.8.3 Gain of Designed Antennas:

Getting good value of directive gain from implantable antennas, is very tough due to lossy ambiance of human body organs, absorbing capabilities of tissues, low signal strength to implantable antennas, small biasing energy. So, improvement in gain becomes great scope for researchers to work ahead in BMDs. In this paper, the reference antenna with three circular rings has attained gain of -25.7 dB at 2.43 GHz indicated in Fig 4.9 below.

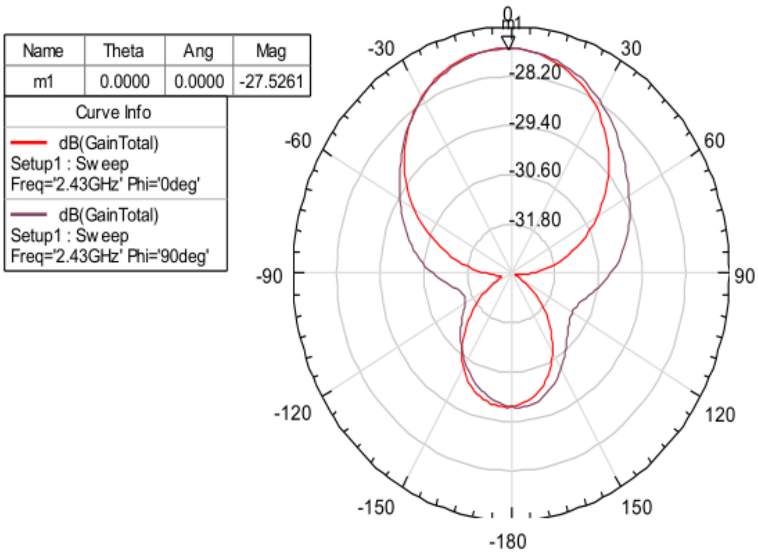


Fig. 4.9 The gain value of Reference antenna at 2.43 GHz.

To further improve the gain value, the reference antenna is loaded with metamaterial of circular shaped of 0.5 mm radius. With this metamaterial structure, the gain of implantable antenna has been improved to -26.1 dB at resonating frequency of 2.48 GHz. Almost 1.5 dB gain has been improved with metamaterial. The gain value of metamaterial loaded antenna is presented in Fig 4.10.

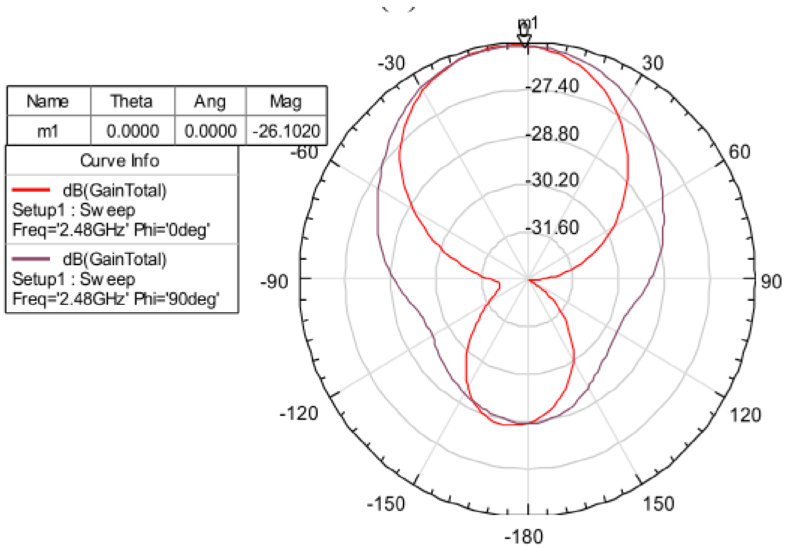


Fig. 4.10 The gain of metamaterial loaded antenna at 2.48 GHz.

The final design medical antenna with ground plane slots of triangular shaped along with circular ring inside, is simulated successfully. The directive gain of the proposed implantable antenna is reported with -27.05 dB at 2.39 GHz which is depicted in Fig 4.11 below. Almost 0.46 dB gain has been enhanced.

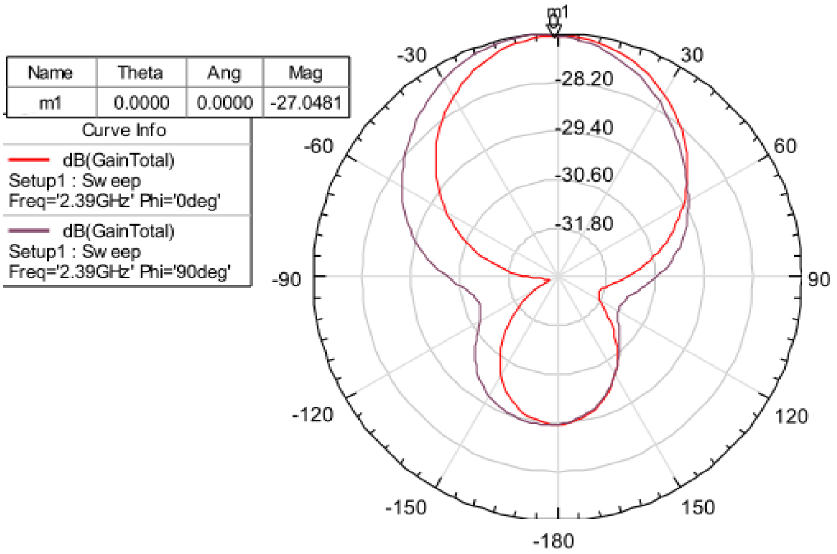
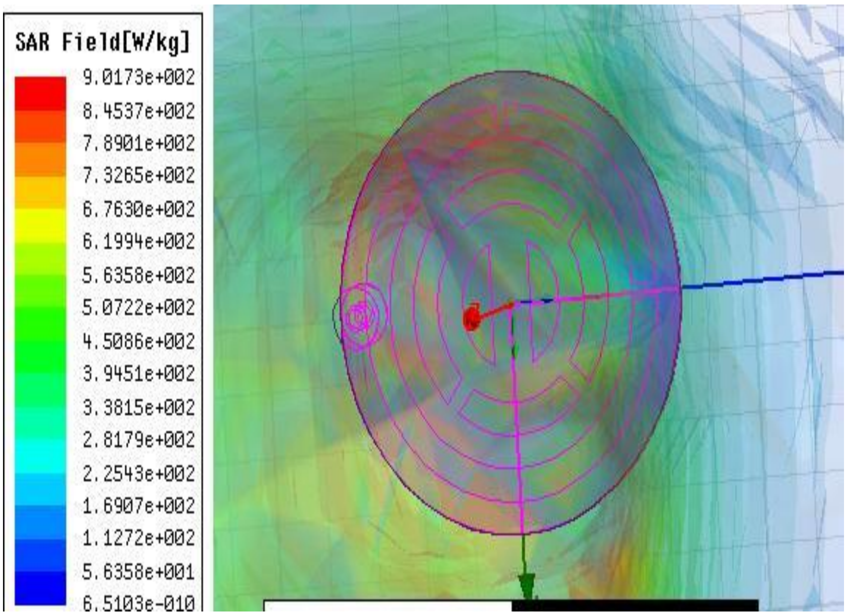


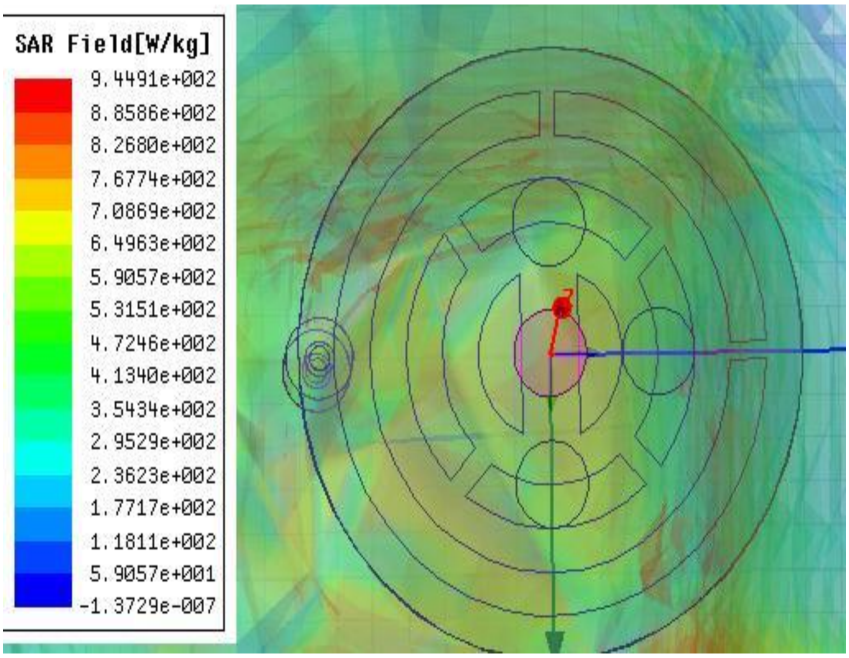
Fig. 4.11 The directive gain of proposed antenna at 2.39 GHz.

4.8.4 Evaluation of SAR of Designed Antennas:

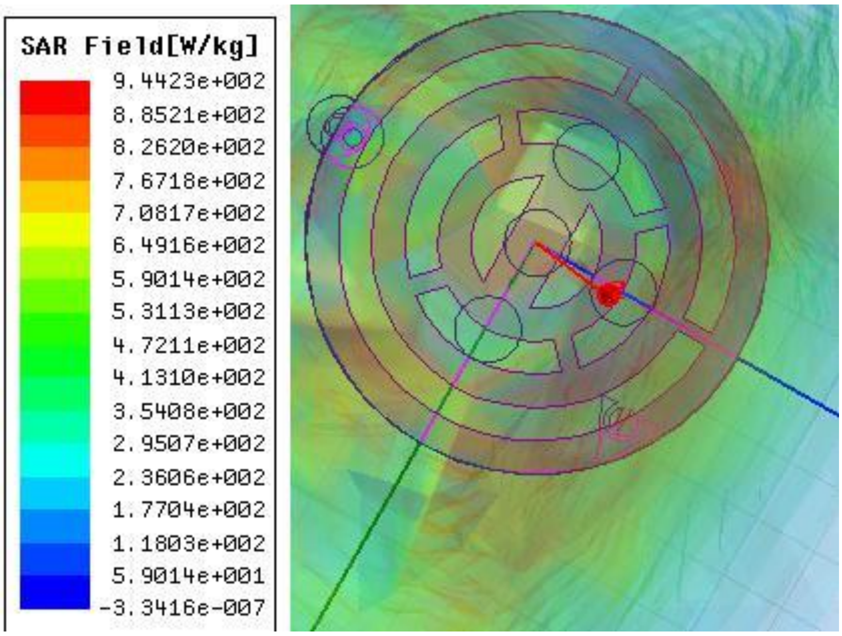
For the safety of patients, the SAR value of implantable antenna should not cross the threshold level. If any antenna crosses this barrier, then the temperature of body organ may rise to 1^0 or 2^0 C which leads to cause severe diseases like cancer. So, designing of implantable antenna can only be successful if it shows SAR value within threshold levels. The SAR value may be reduced by decreasing conductivity or electric field. This may be resulted into gain reduction. But gain value can be enhanced various techniques like metamaterial, patch stacking. The reference antenna is shown with SAR value in Fig 4.12 (a). The reference antenna has been achieved with SAR value of 901.7.


SAR Field[W/kg]
9.0173e+002
8.4537e+002
7.8901e+002
7.3265e+002
6.7630e+002
6.1994e+002
5.6358e+002
5.0722e+002
4.5086e+002
3.9451e+002
3.3815e+002
2.8179e+002
2.2543e+002
1.6907e+002
1.1272e+002
5.6358e+001
6.5103e-010

(a)


SAR Field[W/kg]
9.4491e+002
8.8586e+002
8.2680e+002
7.6774e+002
7.0869e+002
6.4963e+002
5.9057e+002
5.3151e+002
4.7246e+002
4.1340e+002
3.5434e+002
2.9529e+002
2.3623e+002
1.7717e+002
1.1811e+002
5.9057e+001
-1.3729e-007

(b)



(c)

Fig. 4.12 The specific absorption rate for (a) reference antenna at 2.43 GHz. (b) metamaterial loaded antenna at 2.48 GHz. (c) final design medical antenna at 2.39 GHz.

After loading of metamaterial on superstrate surface, the SAR value has been obtained 944.9 which is still within acceptable limits shown in Fig 4.12 (b). Al last, the final medical antenna has been simulated with SAR value of 944.2 at resonating frequency of 2.39 GHz shown in Fig 4.12 (c). From all three designs of proposed antennas, the SAR value are under threshold level which is quite safe for any patient. The SAR analysis of designed medical antennas including the maximum input power is calculated in Table 4.7.

Table 4.7. The SAR value and maximum input power for designed antennas.

Antenna used	Max SAR for 1 gram tissue	Maximum allowed power (mW)
Reference with three Rings	901.7	1.77
Reference with metamaterial	944.9	1.69

Final Proposed antenna	944.2	1.69

From the Table 4.7, it is concluded that the reference antenna is fed with maximum input power of 1.77 mW. Then metamaterial loaded antenna and final proposed implantable antenna are fed with 1.69 mW power each.

4.9 Comparison of Proposed Research Work

In this section, the comparison Table 4.8 has been presented for proposed implantable antenna. The comparison is taken place with all recent published papers.

Table 4.8 Comparison table of final design antenna with recent research work.

Reference Paper	Volume (mm^3)	Resonating Frequency (GHz)	Bandwidth (%)	Gain (dBi)	SAR for 1 gram	CP	**Improvement of proposed work over previously published work**
[3]	816	2.45	6.2	-9	-	No	**Size reduction: 98.8%, CP performance achieved, BW improved by 0.26%.**
[35]	20.06	0.402	35	-23.7	219	No	**Size reduction: 51.29 %, CP performance achieved.**
[46]	153.67	0.915	3.8	-29	-	Yes	**Size reduction: 93.64%, BW improved: 2.66%**
Proposed Work	**9.77**	**2.39**	**6.46**	**-27**	**944.2**	**Yes**	

From this table 4.8, it is evident that the final design antenna has least volume with good impedance bandwidth of 6.46 %. Among all recent papers, the proposed antenna is possessing CP characteristics. The excellent performance of final proposed antenna has been achieved without using complex techniques like sorting pin. The absence of sorting pin in final design as taken advantage regarding fabrication of antenna.

4.10 Conclusion of Proposed Research Work

The designing of implantable antennas is complex task due to compact size, difficult techniques like sorting pin, patch stacking. This paper is dealt with simple ring-shaped design with small volume of 9.77 mm^3. No sorting pin has been used in patch and ground surface which is resulted a simple antenna for fabrication purpose. The challenge of fabrication process is beautifully entertained due to absent of sorting pin or via. With this very small size, proposed antenna shows fine performance of reflection coefficient of -38.6 dB at resonating frequency of 2.39 GHz. The SAR value is exhibited of value 944.2 k/kg. Moreover, the final design of proposed antenna has attained CP characteristics from 2.38 GHz to 2.67 GHz. By considering execution in every aspect, it is said that the final design antenna is the best choice biomedical applications.

4.11 Limitation

This research work is not fabricated and tested in microwave lab. So, validation of this work is not ensured. Consequently, chapter 5 deals with CP characteristics along with fabrication and testing of proposed antenna in microwave lab and hence validation of proposed work is ensured.

Chapter 5

Compact CP Implantable Antennas using Slots & Metamaterials

5.1 Introduction

In the last two chapters, the dual band implantable antenna with sorting pin and meandered path of patch, magneto dielectric substrate based implantable antenna, and ring-shaped antenna have been retracted in detail. In 3rd chapter, the proposed antenna is not circularly polarised hence cannot be used for multiple path losses. In the 4th chapter, the two proposed antennas are presented. First antenna is designed with Rogers' material and then with MDS materials. High bandwidth has been achieved but antenna is not having CP characteristics. So, to attain CP characteristics, the 2nd proposed antenna of chapter 4 is explored in every aspect. But this antenna is limited with simulation work only. To validate the actual performance of implantable antenna, fabrication needs to be done. In this chapter, two proposed antennas are explained in detail. Both antennas are possessed with CP characteristics including performance parameters like S11, SAR, gain, and link margin. The proposed antennas are followed with given procedures.

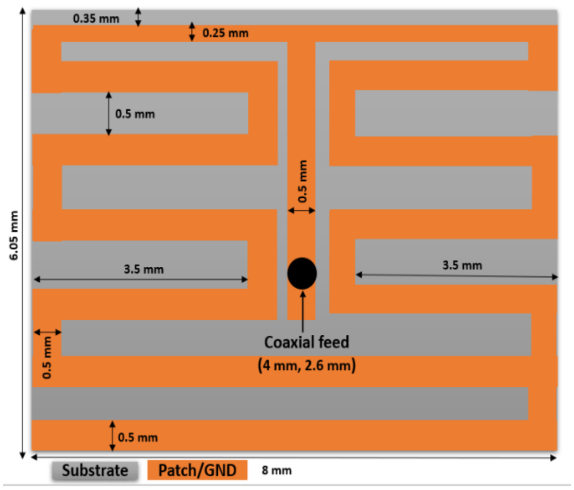
- Select design of antenna with calculated dimensions.
- Optimise the design to match impedance with transmission line.
- Apply recent techniques to improve simulation outcomes.
- Analysis of proposed antenna.
- Fabricate the proposed antenna using photolithography.
- Prepare vitro model by making skin mimicking gel.
- Testing of proposed fabricated antenna using VNA and anechoic chamber.

5.2 Designing of Final Design Antenna with Step Wise Development.

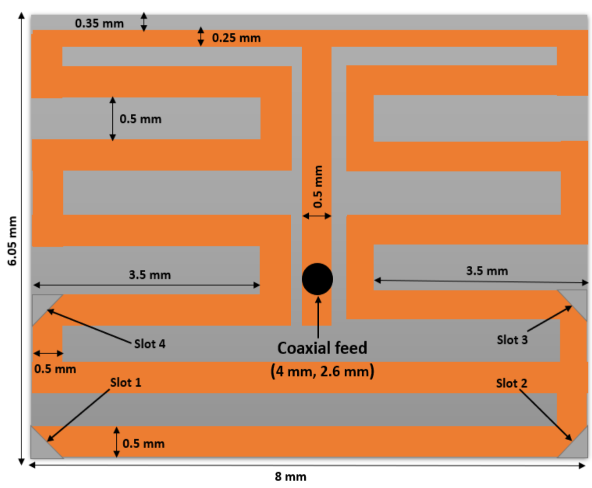
In this section, the designing of implantable antenna is discussed with geometry. The proposed antenna is simulated by working on step wise development in terms of S11, Axial ratio, Gain etc.

5.2.1. Final Antenna Design:

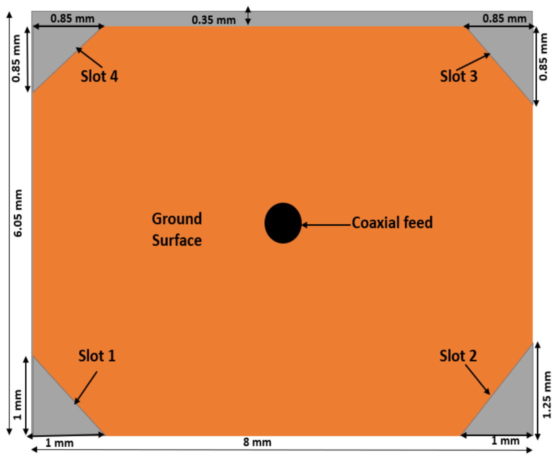
In beginning, the size of antenna is taken with length 8 mm and width 6.05 mm. Roger rt duroid substrate is considered for proposed antenna with e_r 10.2 and tan(δ) 0.0023. This substrate is selected with standard thickness of 0.127 mm. For size reduction, meandered structure is adopted as radiating patch. The superstrate is also used on patch surface with same material of substrate and same thickness. This superstrate is utilised to avoid direct touch of conducting surface of antenna with human body tissues. The proposed implantable antenna is designed with volume of 12.29 mm^3. The proposed antenna is displayed in Fig 5.1.



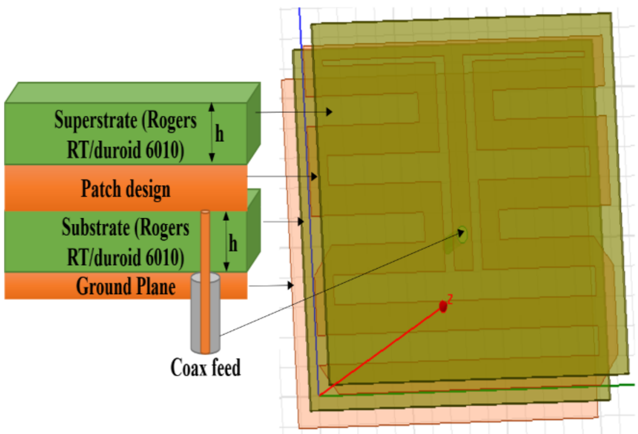
(a)


0.35 mm
0.25 mm
0.5 mm
0.5 mm
6.05 mm
3.5 mm
3.5 mm
Slot 4
Slot 3
Coaxial feed
(4 mm, 2.6 mm)
0.5 mm
Slot 1
Slot 2
0.5 mm
8 mm

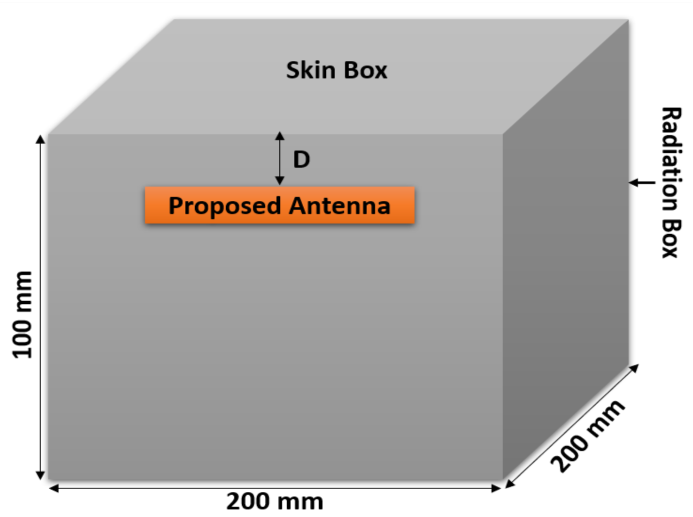
(b)


0.85 mm
0.35 mm
0.85 mm
0.85 mm
Slot 4
Slot 3
0.85 mm
6.05 mm
Ground
Surface
Coaxial feed
Slot 1
Slot 2
1 mm
1.25 mm
1 mm
8 mm
1 mm

(c)


Superstrate (Rogers
RT/duroid 6010)
h
Patch design
Substrate (Rogers
RT/duroid 6010)
h
Ground Plane
Coax feed

(d)



(e)

Fig. 5.1 (a) Patch design of reference antenna with dimensions. (b) Patch design of reference antenna with four slots. (c) Ground surface of antenna with four slots. (d) Isometric view of final design antenna. (e) Dimension of skin box with antenna depth of penetration.

The human body environment is setup by using skin box for simulation purpose. The skin tissue replica box has size of dimensions 200 mm x 200 mm x 100 mm as shown in Fig 5.1 (e). The skin box assigned in HFSS has electrical properties of dielectric constant 42.8 and bulk conductivity 1.593 siemens per meter [11]. The final design antenna is placed at 2.746 mm below from the top layer of skin tissue box. The material specification and designing specification of proposed antenna are shown in table 5.1 and table 5.2 respectively.

Table 5.1 The material specification of proposed antenna

Material/substrate used	**Relative permittivity (e_r)**	**Relative permeability (u_r)**	**Dielectric Loss tangent**	**Bulk conductivity**
Rogers RT duroid 6010	10.2	1	0.0023	0

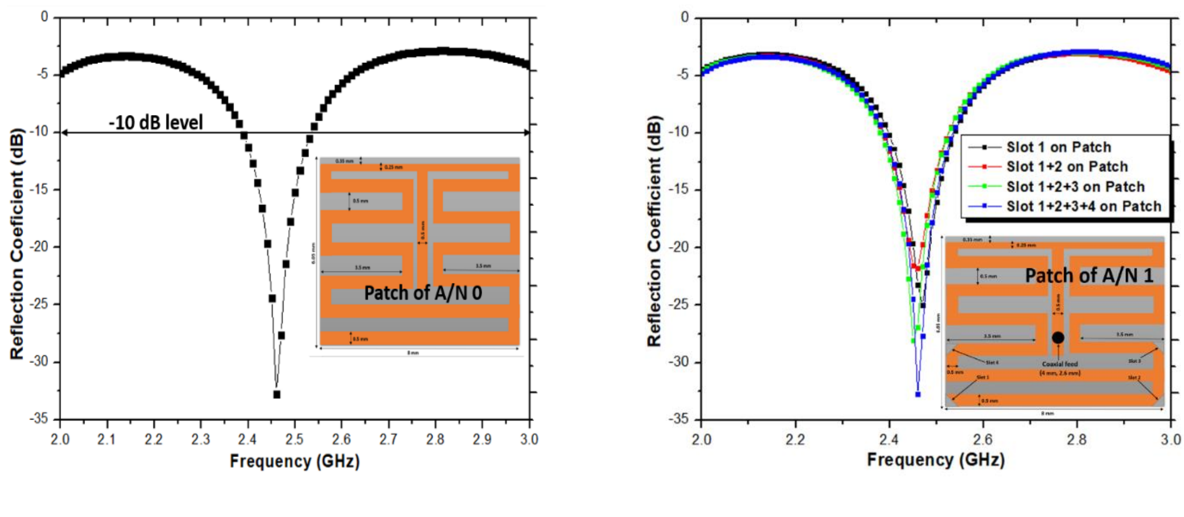
Table 5.2 The designing parameters of proposed antenna.

Variable	Value (mm)	Variable	Value (mm)
Length	8	Thickness	0.127
width	6.05	Feed positions	(4, 2.6,0.127)
Width of conducting strip	0.5		

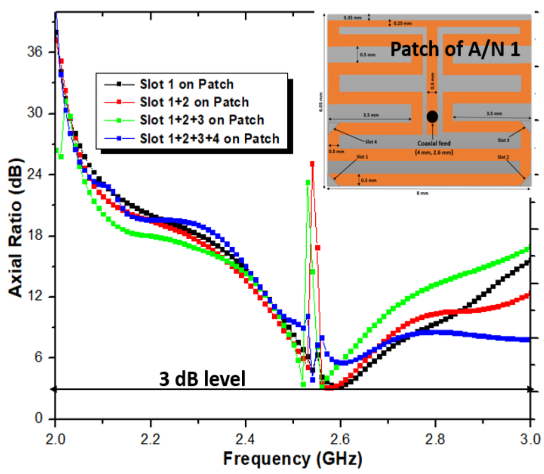
5.2.2 Designing Sequence of Proposed Antenna:

In this part, the final design of medical antenna is formed with sequential approach given in following steps.

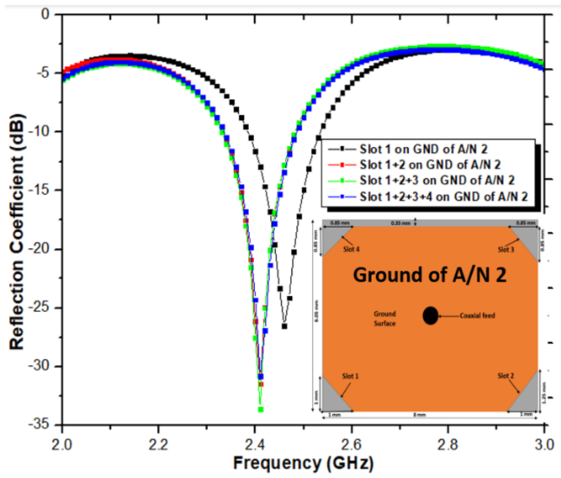
a). Designing of reference antenna (A/N 0): The reference antenna is designed with dimension of 8mm and 6.05 mm. The height of substrate and superstrate is taken 0.254 mm. The radiator size of this antenna is presented Fig. 5.1 (a). To excite the antenna, the coax feed is used at specific position (4, 2.6,0.127). At this specific position, the impedance of antenna is matched well at 2.44 GHz shown in Fig 5.2 (a).



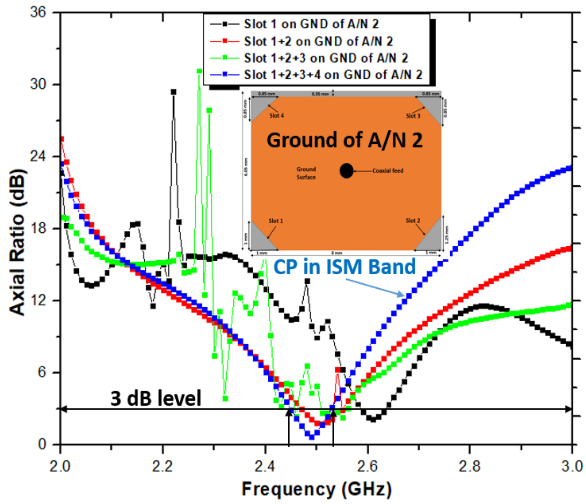
(a) (b)



(c)



(d)



(e)

Fig. 5.2 (a) The reflection coefficient of reference antenna (A/N 0) at 2.44 GHz. (b) The study of Reflection coefficient of reference antenna with four traingular slots (A/N 1) on patch surface. (c) The analysis of axial ratio of reference antenna with four traingular slots (A/N 1) on patch surface. (d) The analysis of reflection coefficient of antenna with ground traingular slots (A/N 2). (e) The analysis of axial ratio curve of final proposed antenna with ground slots (A/N 2).

This designed antenna has impedance bandwidth of 120 MHz frequency range 2.37 GHz - 2.47 GHz. At resonating frequency 2.44 GHz, the S11 parameter has been attained with value of -24.54 dB.

This reference design of antenna has linear polarisation. To work on CP characteristics, this antenna is further modified with slots on patch surface.

b). Designing of antenna (A/N 1): To enhance the bandwidth of A/N O, four triangular slots of phase angle 45^0 are implemented on patch surface. This is termed as A/N 1 which is pointed in Fig 5.1 (b). The analysis of every slot has been displayed in Fig 5.2 (b) in terms of reflection coefficient. The impedance bandwidth has been improved from 120 MHz to 130 MHz after adding 1st slot on patch surface demonstrated in Fig. 5.2 (b). This antenna is optimised at 2.47 GHz. The slight change has been observed after using 2nd and 3rd slots for S_{11} and f_r although in ISM band itself. Finally, 4th slot has been introduced which consequently received impedance bandwidth of 140 MHz from 2.39 GHz to 2.53 GHz at f_r of 2.46 GHz. Considerable improvement of reflection coefficient has been resulted with value of -32.74 dB. This antenna (A/N 1) is almost acquired CP characteristics shown in Fig. 5.2 (c). But there is still scope of this antenna to perform as CP.

c). Designing of antenna (A/N 2): The A/N 1 shows fair execution in terms of S_{11} and bandwidth. But it limited to attain CP characteristics. So, to attain CP performance of antenna, the A/N 1 has crammed with triangular spots on ground surface depicted in Fig 5.1 (c). There are four triangular slots imposed on ground surface. Every slot's effect has been analysed in detail with reflection coefficient, bandwidth, and axial ratio. The first slot on ground surface is resulted the bandwidth almost unaltered in comparison of A/N 1. But this slot has been achieved axial ratio below 3 dB from 2.59 GHz to 2.63 GHz shown in Fig 5.2 (e). So, in this frequency band, antenna is turned into CP but not in standard ISM band. To bring this antenna in standard ISM band, 2nd triangular slot has been incorporated. With this 2nd slot, the axial ratio having less than 3 dB is observed from 2.47 GHz to 2.53 GHz shown in Fig 5.2 (e). The operating frequency is switched to 2.41 GHz with S_{11} of -31.48 dB. To cover complete ISM band, 3rd and 4th slot have been incorporated on ground surface. With these slots, the antenna

(A/N 2) has been attained reflection coefficient of -29.53 dB at resonating frequency 2.41 GHz as shown in Fig 5.2 (d). The -10 dB bandwidth of 140 MHz is attained with frequency range 2.34 GHz - 2.48 GHz. The 3 dB bandwidth of 80 MHz has been observed with frequency range 2.45 GHz - 2.53 GHz shown in Fig 5.2 (e).

5.3 Simulation Results and Parametric Study of Proposed Antenna

In this segment, the simulation outcomes have been elaborated regarding S_{11}, RC (Γ), 3 dB bandwidth, gain, SAR, and surface current density. The parametric study of recommended antenna design is also discussed by analysing different substrates with different thickness.

5.3.1 Simulation Results:

a) CP characteristics of proposed antennas.

The reference antenna (A/N 0) is designed with linear polarisation. The A/N 0 has been modified by introducing slots on patch antenna. With help of these patch slots, the A/N 1 is remained in linear polarisation phase. After adding four slots of ground surface, the A/N 2 has been achieved with CP characteristics with frequency range 2.45 GHz - 2.53 GHz by observing axial ratio. The axial ratio of all three proposed antennas is shown in Fig 5.3. below.

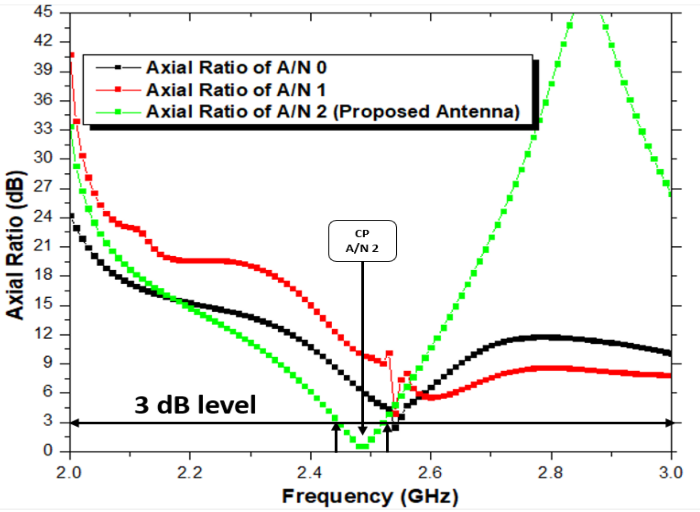
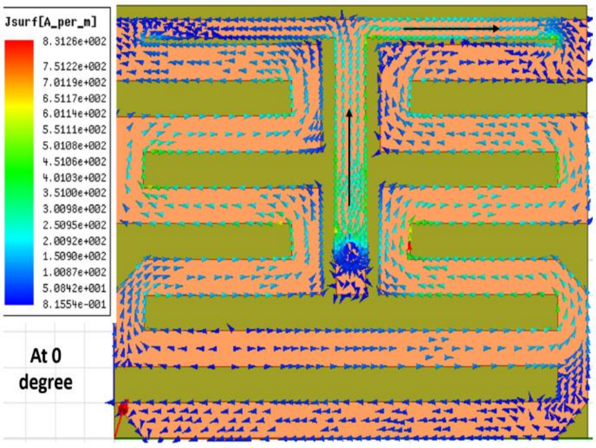
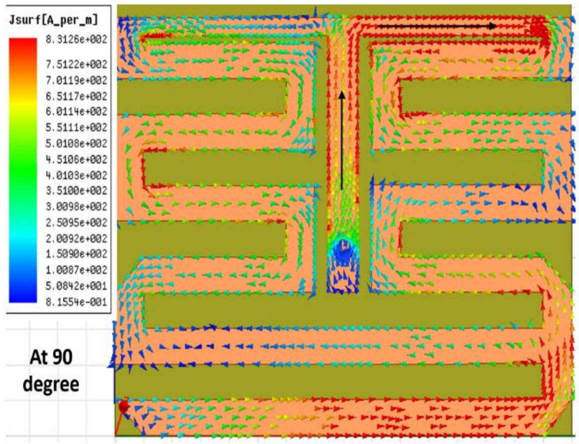


Fig. 5.3 The axial ratio curve of all designed antennas.

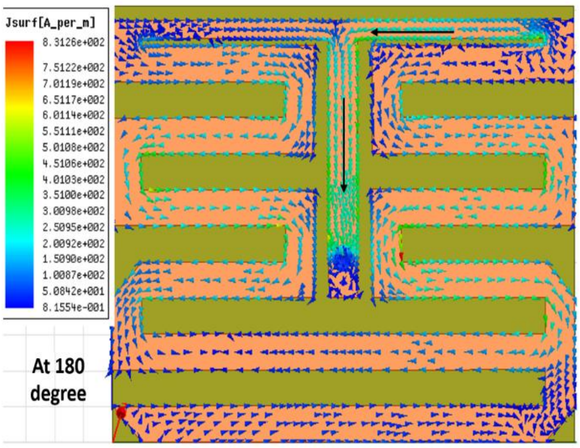
The final proposed antenna (A/N 2) is explored with surface current density at resonating frequency of 2.41 GHz shown in Fig 5.4. The maximum current density is obtained with value 831.2 a/m.



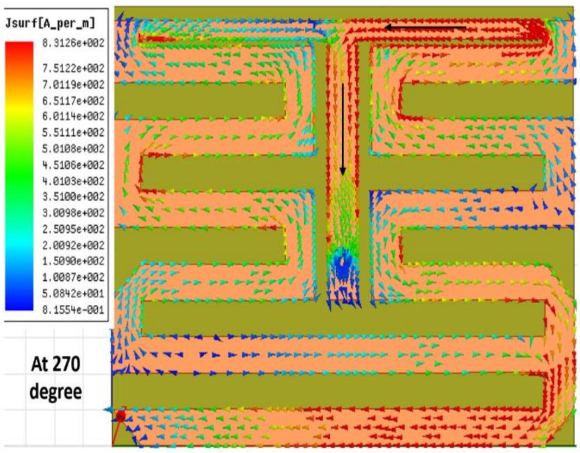
(a)



(b)



(c)



(d)

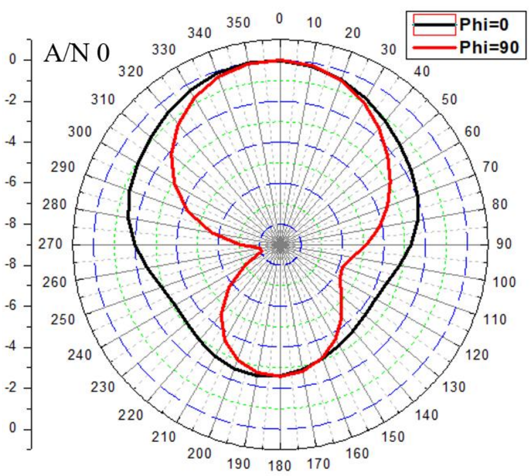
Fig. 5.4 (a) The surface current density at phase angle 0^0 final proposed antenna at 2.41 GHz. (b) At pahse angle 90^0. (c) at phase angle 180^0. (d) At phase angle 270^0.

At all given phase angles, the current density of propsoed antenna at resonating frequency is exhibited with same strength of 831.2 a/m. The equal and opposite direction of surface current density has been received at phase angle of 0^0 and 180^0. Similar results have been resulted for phase angle 90^0 and 270^0 respectively.

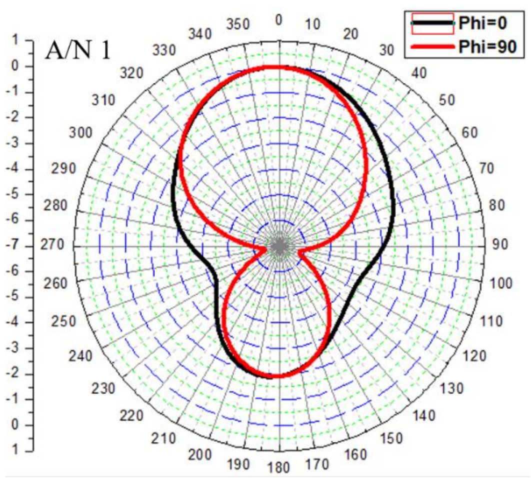
b) Gain characteristics of proposed antennas.

The gain parameter of implantable antenna is offered with negative value due to several reasons. The input power strength of implantable antenna is fed with low value due to patient safety. The human body is of absorbing nature which is led to damp radiation. So, achieving good gain is challenge for researchers in this field.

The A/N 0 is simulated with gain value of -25.67 dB. To further improve the gain value, four slots on patch surface (A/N 1) have been added. This antenna (A/N 1) has been improved gain value to -24.37 dB. At last, the final designed proposed antenna is exhibited with gain of -23.45 dB. Overall, 2.22 dB gain has been improved by incorporating slots on patch and ground surface. All gain values are presented in Fig 5.5.



(a)



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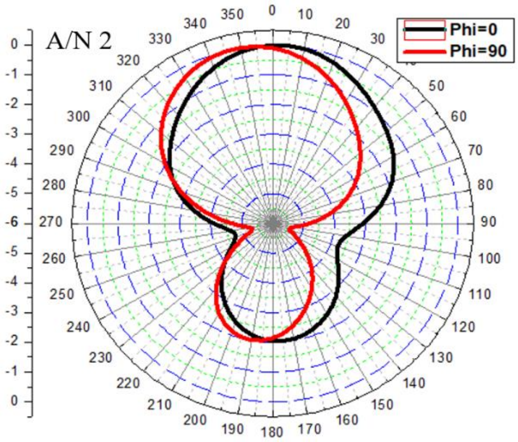


(c)

Fig. 5.5 (a) Directive gain of A/N 0 at 2.44 GHz. (b) Directive gain of A/N 1 at 2.47 GHz. (c) Directive gain of A/N 2 at 2.41 GHz.

c) SAR evaluation of proposed antennas.

The SAR value of any implantable antenna is the most important concern for the patient point of view. If any device exceeds SAR value from standard limit, then patient may undergo with severe issues. The reference antenna (A/N 0) is simulated with SAR value of 911 w/kg. This value is acceptable for medical devices. After adding four slots on patch (A/N 1), the SAR value is received with 916 w/kg. To further reduce the value of SAR, four triangular slots are introduced on ground surface (A/N 2). Now SAR value is reduced from 916 w/kg to 901 w/kg. All SAR analysis for designed antennas have been shown in Fig 5.6.

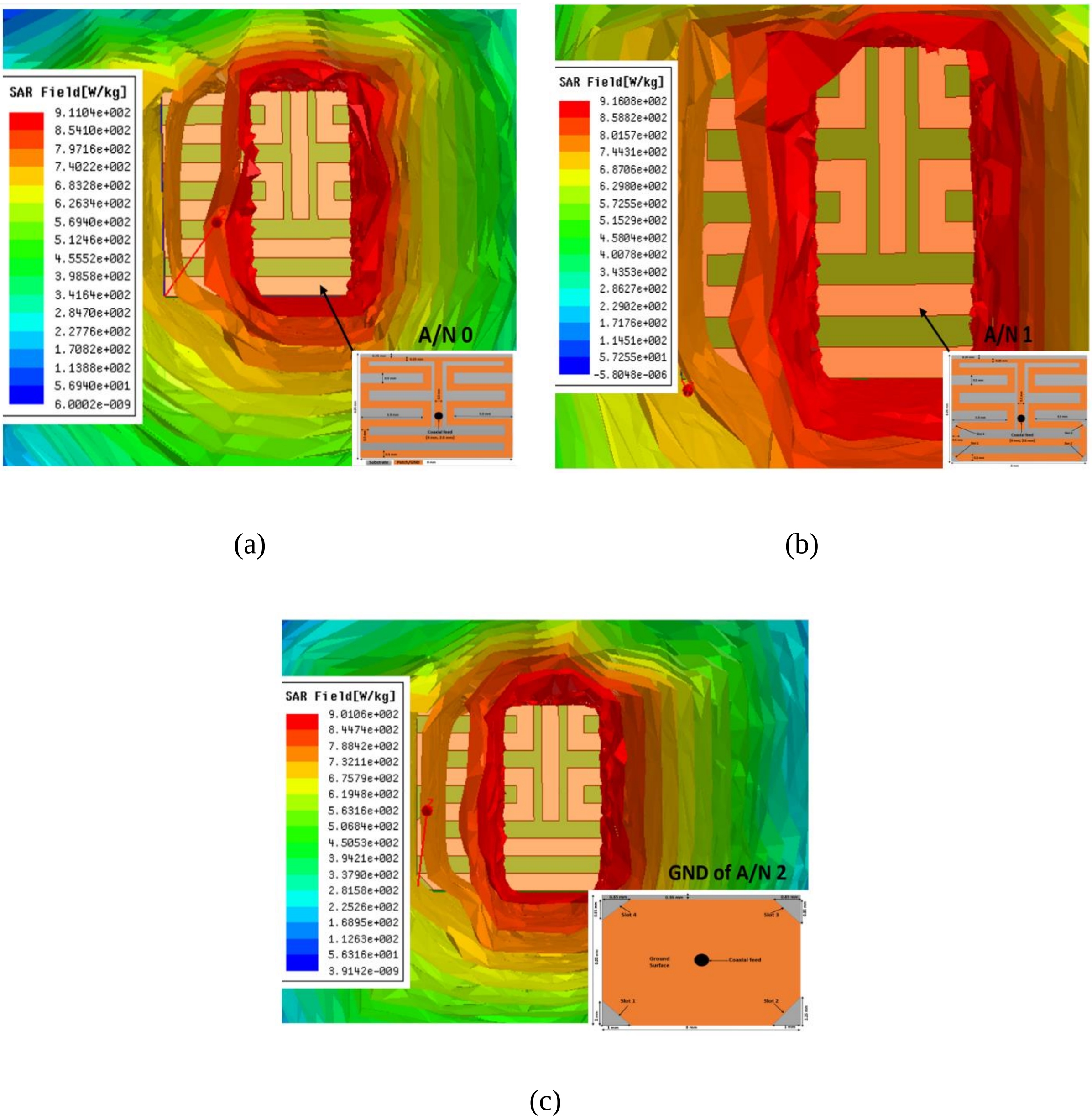


Fig. 5.6 (a) SAR evaluation of reference antenna (A/N 0) at 2.44 GHz. (b) SAR evaluation of antenna (A/N 1) at 2.46 GHz. (c) SAR evaluation of recommended Antenna (A/N 2) at 2.41 GHz.

The designed antennas are studied in terms of SAR performance inside skin body tissues at depth of 2.746 mm. The maximum input power for implantable antennas along with SAR merit are presented in Table 5.3.

Table 5.3 The SAR evaluating along with maximum input power of designed antennas.

S No	Designed antenna	Average SAR	Max allowable power (mW)
1	A/N 0	911	1.75
2	A/N 1	916	1.46
3	A/N 2 (Proposed antenna)	901	1.78

From the Table 5.3, the final designed proposed implantable antenna (A/N 2) has shown SAR 901 which has 1.78 mW input power for radiation purpose. The large value of input power is resulted a high radiation efficiency.

d) Impedance bandwidth of proposed antennas.

The impedance bandwidth of reference antenna (A/N 0) has been attained with 120 MHz from 2.37 GHz to 2.49 GHz. Then this antenna is further altered by introducing four slots on patch. This antenna (A/N 1) has improved bandwidth by 20 MHz as compared to A/N 0. Finally, the recommended medical antenna is simulated with 140 MHz bandwidth with frequency range 2.34 GHz - 2.48 GHz. All impedance bandwidth for proposed antennas have been explored in detail in Fig 5.7.

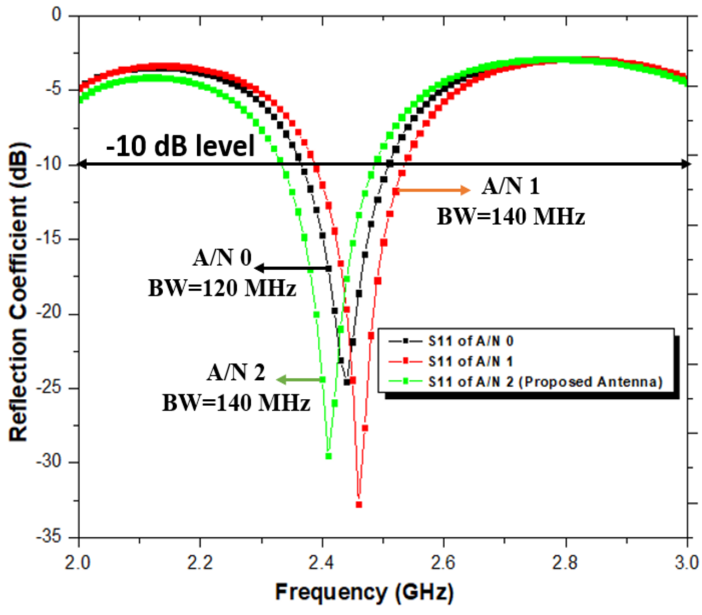


Fig. 5.7 The Reflection Coefficient and Bandwidth for All Designed Antennas.

5.3.2 Parametric Study of Proposed Implantable Antenna:

a). Effect on performance of proposed antenna based on substrate/superstrate thickness:

The achievement of final design antenna is deeply explored on various thickness of substrate. The used substrate i.e., Rogers rt duroid 3010 is available with thickness of 0.127 mm, 0.254 mm, 0.381 mm, 0.508 mm, and 0.787 mm. At thickness of 0.254 mm, the proposed antenna has resonated at 2.01 GHz with RC (Γ) of -17.67 dB. At this thickness, the proposed antenna does not exhibit CP characteristics in ISM band. But the impedance bandwidth of antenna has been improved with large extent of 230 MHz with frequency range 2.31 GHz - 2.54 GHz. By increasing the height of substrate and superstrate, the volume of suggested antenna is enlarged up to 33.88 mm^3. When thickness is kept at 0.381 mm, then CP characteristics has been lost completely. However, 510 MHz bandwidth has been attained from 2.05 GHz to 2.56 GHz. With this thickness, volume of proposed antenna is of 36.88 mm^3. Similarly, 0.787 mm thickness is simulated for proposed antenna which has been achieved 700 MHz impedance bandwidth. It is distinctly perceived that volume of antenna is correlated with bandwidth. If size increases, then bandwidth of antenna also increases. The detailed analysis of thickness of substrate and superstrate is demonstrated in Fig 5.8 (b). The 3 dB bandwidth outcome is reflected in Fig 5.8 (a) which shows that the only thickness of 0.127 mm is resulted in CP characteristics.

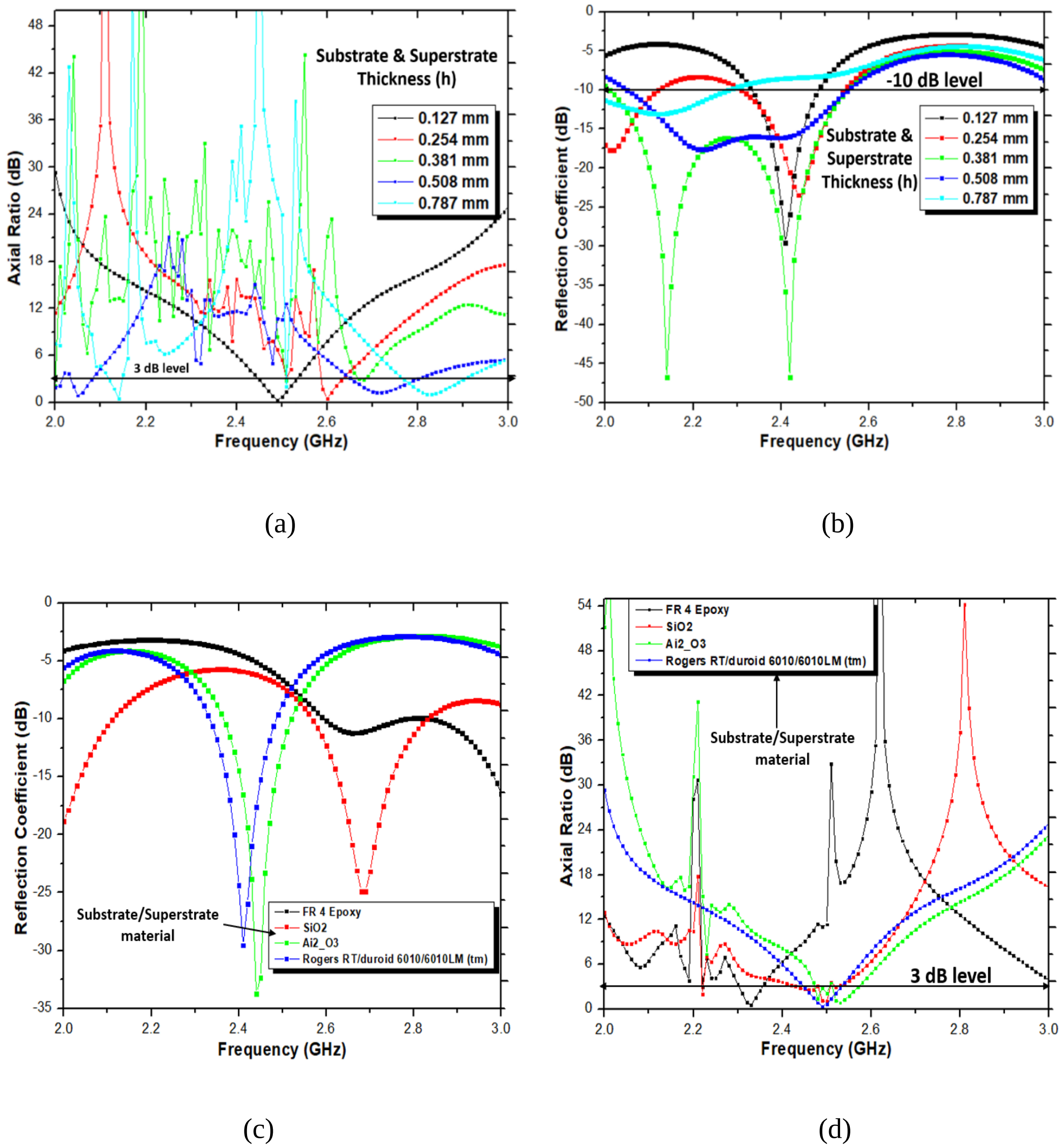


Fig. 5.8 (a) The axial ratio curve of final antenna at various material height. (b) The S_{11} of final design medical antenna at various substrate thickness. (c) The S_{11} of final design antenna for varius substrates. (d) The axial ratio curve of proposed antenna for different substrate materials.

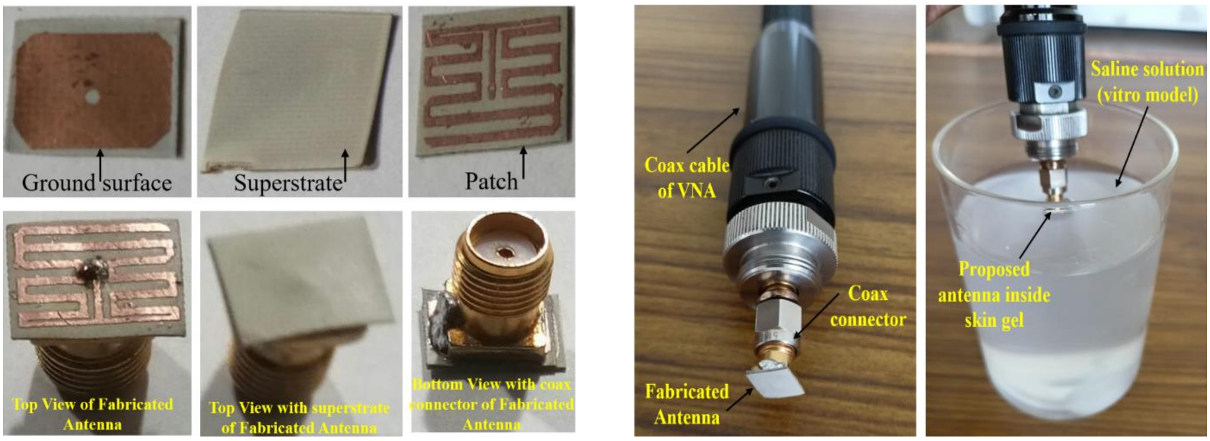
b). Effect on performance of proposed antenna based on substrate/superstrate materials.

The execution outcomes of final design antenna is restrained with various substrate and superstrate materials like FR 4 epoxy, SiO_2, Ai_2O_3, and Rogers rt duroid 6010. With FR 4 epoxy, the proposed antenna has shown best impedance matching with frequency range 2.6

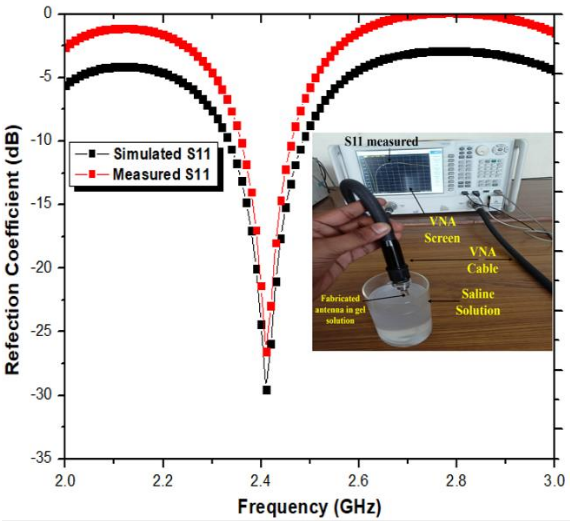
GHz - 2.78 GHz presented in Fig 5.8 (c). It has lost radiation in standard ISM band. Moreover, CP characteristics are observed in little bandwidth from 2.31 GHz to 2.35 GHz. Then SiO_2 material is considered for proposed antenna. The dual band has been received but not in standard ISM bands. No CP characteristics is attained. So, this material is also not suitable for proposed antenna. Similarly, Ai_2O_3 is substituted as substrate and superstrate. This material has shown best result in terms of reflection coefficient with frequency range 2.37 GHz - 2.51 GHz. However, axial ratio less than 3 dB is observed from 2.48 GHz to 2.57 GHz which is almost out of ISM band. At last, Rogers rt duroid 6010 material is used and has given excellent results. With this substrate and superstrate, proposed antenna has presented in this paper. The S_{11} and axial ratio outcome have been shown in Fig 5.8 (c) and (d).

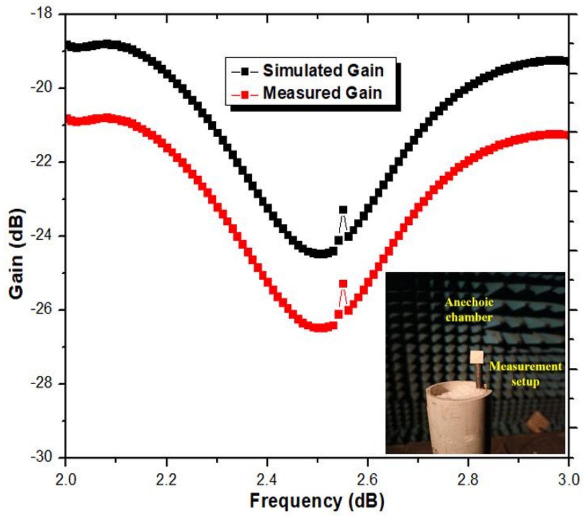
5.4 Measurement and Discussion.

To validate the simulation outcomes of final antenna design, the skin mimicking gel is prepared under some precautions. The sucrose, ionised water, and carbomer are mixed under certain proportion and mixer is heated at 80^0 C for one hour. This gel is considered for vitro testing method for implantable antenna. The proposed antenna is fabricated using photolithography technique. The proposed antenna including patch, ground, superstrate, coax feed is depicted in Fig 5.9 (a).



(a) (b)





(c) (d)

Fig. 5.9. (a) The fabricated propsoed antenna. (b) The measurement site of propsoed antenna with saline solution. (c) The measured and simulated S_{11} of propsoed antenna. (d) Gain set up and measurement of proposed antenna ion anechoic chamber.

The saline solution or skin mimicking gel is presented in Fig 5.9 (b). The fabricated final design antenna is validated in saline solution and has shown slight variation of reflection coefficient from simulated antenna as shown in Fig 5.9 (c) due to glue on bottom surface of superstrate, soldering, some imperfections etc. The gain is measured in anechoic chamber for final design fabricated medical antenna shown in Fig 5.9 (d) and received similar results.

5.5 Comparison of Final Suggested Antenna with Recent Work.

In this part, the comparison of recommended work has been discussed with recent published papers shown in Table 5.4.

Table 5.4 The comparison table of suggested research work with neoteric released work.

Ref Paper	Size (mm^3)	Resonating Frequency (GHz)	-10 dB bandwidth (MHz or %)	3 dB band width (MHz or %)	Gain (dB)	SAR for 1 gram of tissue standard (w/kg)	CP	**Improvement of proposed work over previously published work**
[47]	121.9	2.4	21.5 %	------	-33	486	No	**Size reduction: 89.9%, CP performance achieved.**
[39]	479.04	0.402	52 MHz	------	-34.9	……	No	**Size reduction: 97.4%, CP performance achieved, BW improved by 88 MHz.**
[36]	127	2.45	16.15 %	6.09 %	-22.33	254.74	Yes	**Size reduction: 90.32%.**
[76]	30.01	0.915	9.4 %	------	-21	------	No	**Size reduction: 59.04%, CP performance achieved.**
[78]	127	2.4	6.2%	8.13 %	-27.2	------	Yes	**Size reduction: 90.32 %, Gain improved: 3.75 dB, SAR acceptable.**
Proposed work	**12.29**	**2.41**	**5.98 %**	**80 MHz**	**-23.45**	**901**	**Yes**	

From the Table 5.4, it is justified that the recommended antenna has least volume with good impedance bandwidth. This antenna is behaved as CP antenna with 80 MHz axial ratio bandwidth and received gain value of -23.45 dB. The SAR merit of final design antenna is in acceptable limits.

5.6 Conclusion

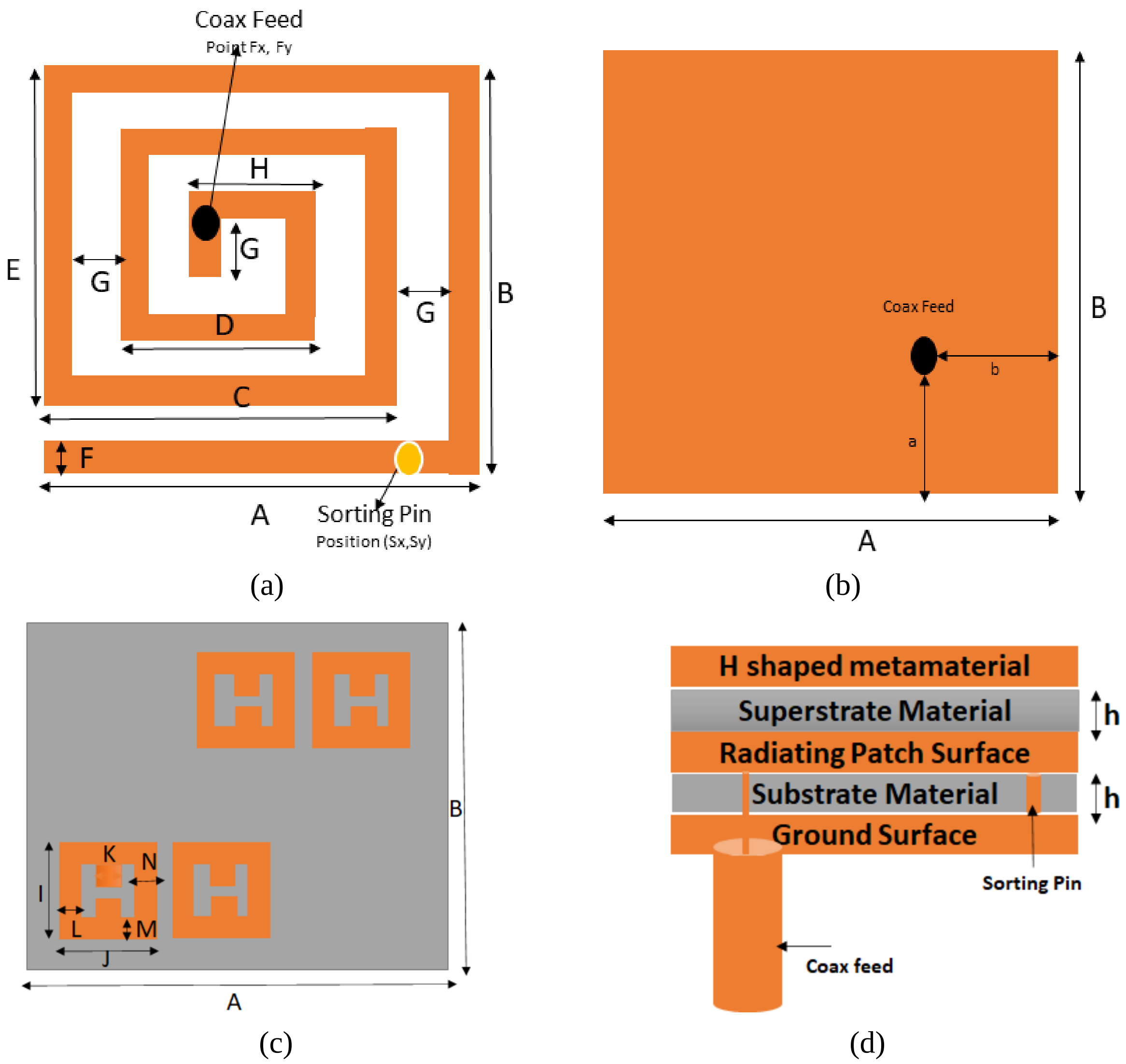
In this paper, the designing approach, parametric study, and simulation results are discussed in detail. For validation purpose, the recommended antenna is fabricated and got testing in skin gel having electrical properties at 2.41 GHz. The recommended antenna has impedance bandwidth 140 MHz which is enhanced by 20 MHz using triangular slots on radiator and ground plane. The final suggested medical antenna is circularly polarised with 3 dB bandwidth with frequency range 2.45 GHz - 2.53 GHz. The SAR value is improved from 916 to 901. The gain is also enhanced from -25.67 dB to 24.37 dB. Overall, the proposed antenna has been received excellent results with least volume. The recommended antenna is suitable choice for medical applications.

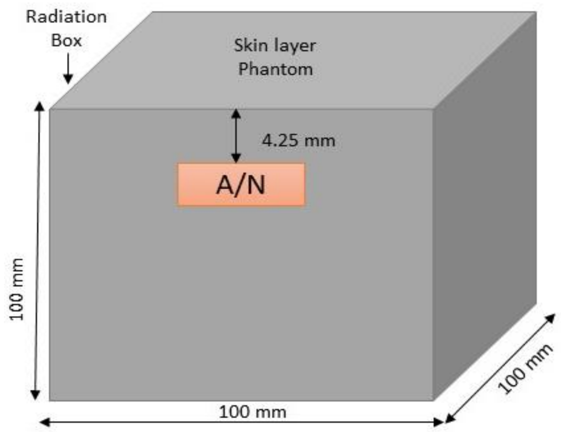
In this paper, almost results are achieved with better performance. But there are some limitations in this research work. The proposed antenna does not have wide band for circular polarisation. Only 80 MHz axial ratio bandwidth (ARBW) has been received which is not in complete ISM band. There is still scope of size reduction in this work. So, to overcome such drawbacks, one more proposed antenna is discussed at length.

5.7 Designing of Proposed Antenna with Sequential Steps.

5.7.1 Design of Final Proposed Antenna:

Generally, a high dielectric constant substrate is preferred to avail compactness, and good antenna execution like return loss or S_{11}, and radiation pattern. The same dielectric material is also used as a superstrate to avoid antenna patches from direct contact with human body tissues. In this paper, the spiral-shaped implantable antenna is proposed with dimension 7 mm x 6 mm x 0.254 mm (10.67 mm^3). The Roger's family substrate with e_r 10.2 of 0.127 mm thickness is considered for antenna designing. To lengthen the current path, Spiral-shaped radiating surface is used. The superstrate is place over patch surface to detract extra radiation in an unwished side, and exclude human tissue contact with the conducting part of antenna [6]. The antenna dimension is depicted in Fig. 5.10 below.





(e)

Fig. 5.10 (a) Top view dimensions of the final implantable antenna. (b) ground plane of final implantable antenna. (c) Design of Metamaterial structure on superstrate surface. (d) Side view of the Proposed implantable antenna. (e) simulation set up of skin tissue for proposed antenna.

The spiral shaped antenna is fed with coax feed at position (2.25, 3.5, 0). The size of coax cylinders is chosen to match 50-ohm impedance. Generally, researchers use unequal slots on patches or ground which cause disturbance in orthogonal modes and hence attain CP characteristics. But ground slots are resulted into back radiation which degrades radiation efficiency for major lobes. So, in this research work, based on parametric study, a sorting pin is applied in between the radiator and ground plane at a specific position (6,0.25,0). The sorting pin or via with diameter of 0.4 mm is placed in the middle of radiator and ground plane of the proposed antenna. At last, a metamaterial with H-shape structure on the superstrate is applied which is reflected in Fig. 5.10 (c). The different variables of antenna size are conferred in Table 5.5.

Table. 5.5 The dimensions detail of proposed implantable antenna.

Parameters	**Values (mm)**	**Parameters**	**Values (mm)**
A	7	J	1.275
B	6	K	0.4
C	6	L	0.3
D	4	M	0.1
E	5	N	0.175
F	0.5	A	1.785
G	0.5	B	2.035

H	3	H	0.127
I	1.025	(Fx, Fy) position	2.25, 3.5
(Sx, Sy) position	6, 0.25		

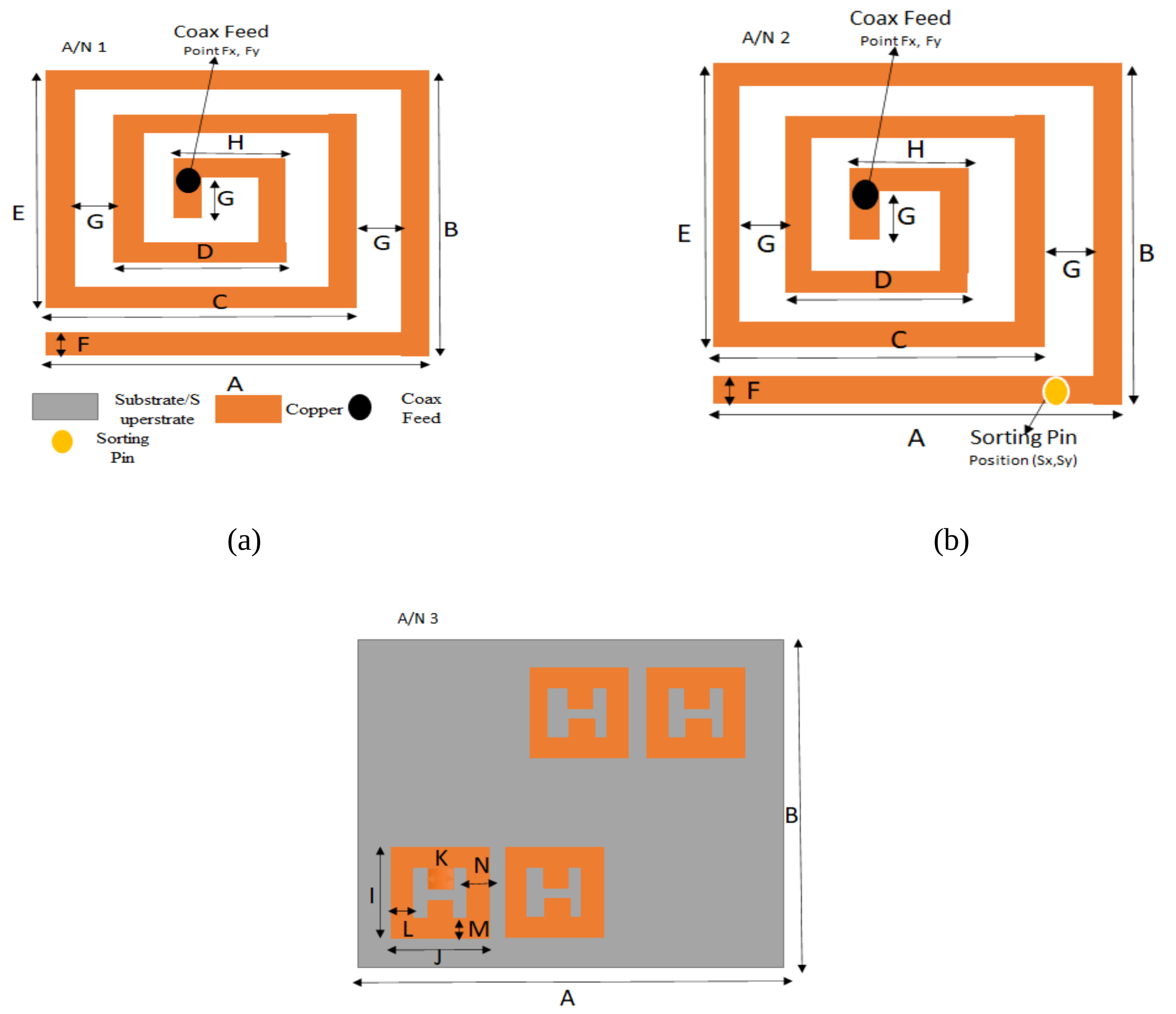
The material specifications are reflected in table 5.6. The simulation set up of final medical antenna is presented in Fig 5.10 (e). The skin box is considered with dimension 100 mm x 100 mm x 100 mm. The final designed antenna is placed at 4.25 mm below the top surface of skin box. The skin box has electrical properties like dielectric constant 38.1, bulk conductivity 1.44 siemens per meter at frequency of 2.45 GHz. The complete simulation work is carried out on HFSS simulation tool.

Table 5.6 Material specification of proposed work.

Material/substrate used	**Relative permittivity (e_r)**	**Relative permeability (u_r)**	**Dielectric Loss tangent**	**Bulk conductivity**
Rogers RT duroid 6010	10.2	1	0.0023	0

5.7.2 Design of Final Proposed Antenna with Step Wise Sequence:

The concluding design of the proposed antenna is completed in three steps. In every step, optimization is done to get desired results. The all designing steps of the final proposed antenna is presented in Fig 5.11.



(a) (b)

(c)

Fig. 5.11 (a) Design of reference antenna (A/N 1). (b) Design of modified antenna with sorting pin (A/N 2). (c) Design of H shaped metamaterial on superstrate surface (A/N 3).

a) Step 1: First, the reference antenna is designed using spiral shape. The coax feed is optimized. This antenna is resonated at 2.53 GHz with very poor impedance matching. The S_{11} of reference antenna is depicted in Fig. 5.12 (a). The antenna does not show CP characteristics shown in Fig. 5.12 (b).

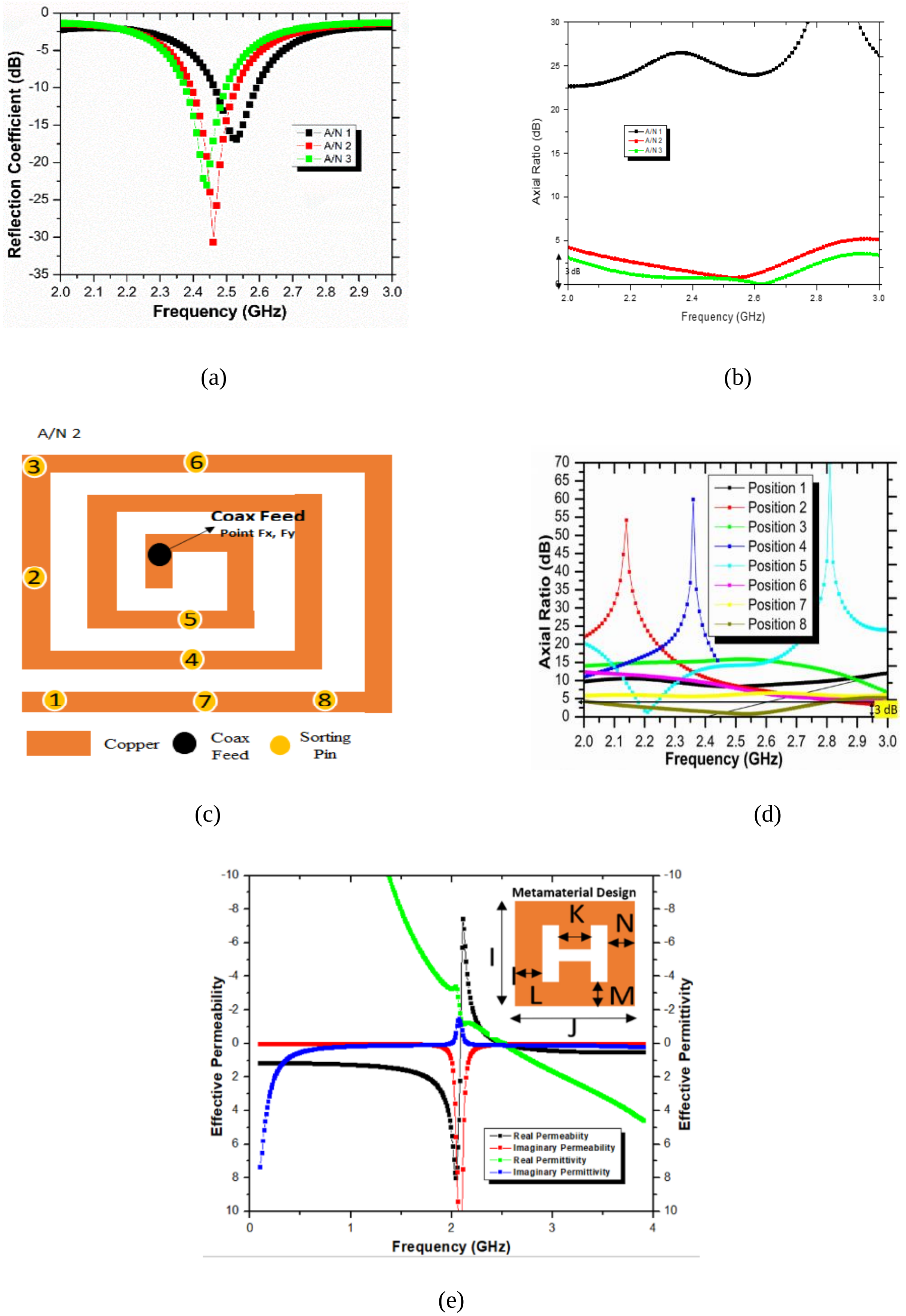


Fig. 5.12 (a) The reflection coefficient of all designed antennas. (b) The axial ratio curve of all

designed antennas. (c) The position of sorting pin on patch surface of A/N 2. (d) the axial ratio curve analysis for every sorting pin positions. (e) Characteristics curve of metamaterial design with effective permittivity and permeability.

b). Step 2 (A/N 2): In this step, radius 0.2 mm sorting pin is implemented in the middle of radiating and ground plane. The sorting pin is place at different positions on patch surface shown in Fig. 5.12 (c). The eight different positions are analyzed to match impedance. Every position of pin is investigated in Fig. 5.12 (c). At position number 8, the antenna has given better results. The reflection coefficient -30.64 dB is received at resonating frequency 2.46 GHz shown in Fig. 5.12 (a). The 120 MHz impedance bandwidth is attained from 2.4 GHz to 2.52 GHz. The antenna (A/N 2) has been received best axial ratio curve with bandwidth of 530 MHz with frequency range 2.15 GHz - 2.73 GHz shown in Fig. 5.12 (b). From pin number 1 to 7, the antenna has not shown CP characteristics.

The parametric study based on sorting pin positions has been discussed. All position coordinates of sorting pin are presented in Table 5.7.

Table.5.7 Different sorting pin positions on A/N 2 patch surface.

Sorting Pin Position Number	**Coordinate points (mm)**
1	0.5, 0.25, 0
2	0.25, 3, 0
3	0.25, 5.75, 0
4	3, 1.25, 0
5	3, 2.25, 0
6	3, 5.75, 0
7	3.25, 0.25, 0
8	**6, 0.25, 0**

c). Step 3 (A/N 3): The metamaterial structure is implemented on superstrate surface to attain more axial ratio bandwidth. With this H shaped structure, the 3 dB bandwidth has been enhanced to 830 MHz. The axial ratio bandwidth is lying in frequency range 2.01 GHz - 2.84 GHz shown in Fig. 5.12 (b). The reflection coefficient of -22.99 dB of this final design antenna is presented in Fig. 5.12 (a) at resonating frequency 2.44 GHz. The -10 dB bandwidth of 110

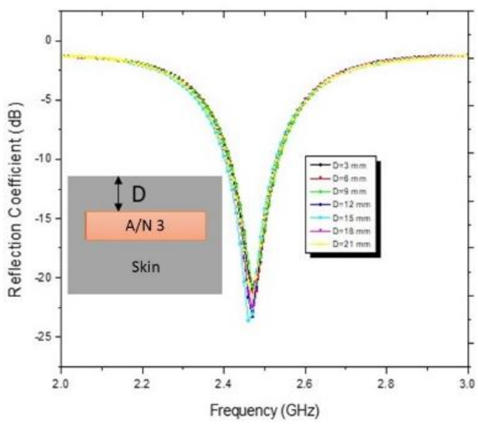
MHz has been received with frequency range 2.38 GHz - 2.49 GHz. The characteristics of metamaterial regarding permittivity and permeability has been shown in Fig. 5.12 (e).

5.8 Parametric Study of the Final Designed Implantable Antenna.

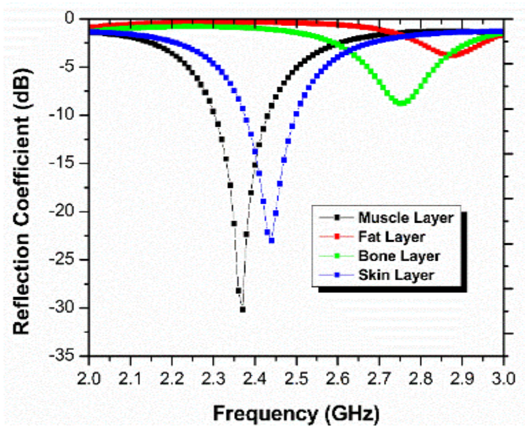
Antenna execution is deeply calibrated by the altering penetration depth in different tissues body tissues. Hence upon, final medical antenna is simulated with different tissues and depth of penetration. The detailed study of different materials is also examined for the proposed antenna design.

5.8.1 Effect of Penetration Depth in Skin Box:

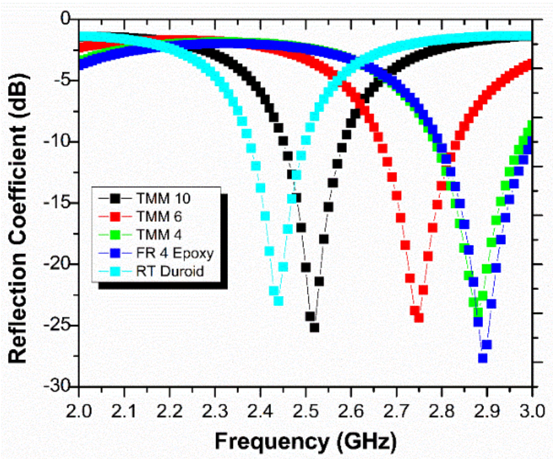
A skin box that resembles human skin is taken with size 100 mm x 100 mm x 100 mm presented in Fig. 5.10 (e). The proposed antenna is implanted with different depths of penetration D. The penetration depth D varies from 3 mm to 21 mm by increasing 3 mm each time. The reflection coefficient of such a parametric study is depicted below in Fig. 5.13 (a). The Fig. 5.13 (a) demonstrates that the suggested antenna does not show a major change in resonating frequency.



(a)



(b)



(c)

Fig. 5.13 (a) S_{11} of the suggested antenna (A/N 3) at different depths of penetration. (b) S_{11} of suggested antenna in various body substance models. (c) S_{11} of suggested antenna in the various substrate material.

5.8.2 Effect of Different Body Tissues on Proposed Antenna Execution:

To validate the achievement of the final antenna design, different body tissues like skin, muscle, fat, and bone are taken into consideration. The parametric examination of the reflection coefficient in different tissues is displayed in Fig 5.13 (b). The suggested implantable antenna is kept at 4.25 mm penetration depth in different human body tissues. It is examined that antenna in skin tissue gets good performance of return loss at frequency 2.44 GHz. When muscle tissue is considered as a radiation box, the suggested antenna shifted resonating frequency from 2.44 GHz to 2.37 GHz with an impedance bandwidth of 120 MHz with frequency range 2.31 GHz - 2.43 GHz. Almost ISM band is missing for the proposed antenna if muscle tissue is used for implantation purpose. In the fat tissue box, the final design antenna is completely degraded and does not work as radiator. Finally, the recommended antenna is situated in bone tissue at same (4.25 mm) depth of penetration. Now antenna exhibits a S_{11} of -8.76 dB at 2.75 GHz which is not acceptable to setup wireless communication between a medical device and an external station. It is well concluded that the proposed antenna worked well only in skin tissues with excellent performance in the ISM band.

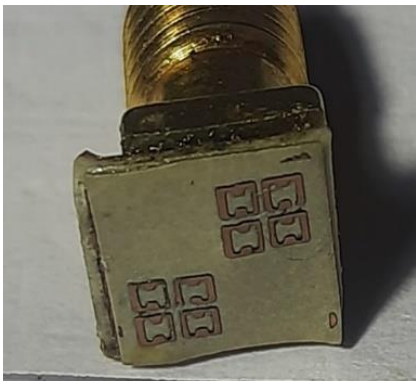
5.8.3 Effect of Dielectric Material of the Proposed Antenna:

The substrate of an antenna is a key part to provide physical strength and mechanical support. For the PIFA antenna, we use dielectric material as a substrate. Various substrates are investigated deep. Before concluding the material for the final antenna design, we explored various substrates with different e_r such as Rogers 6010, TMM4, TMM6, and TMM10 with a height of 0.127 mm and relative permittivity of 10.2, 4.5, 6.02, 9.8 respectively. All substrate materials are family members of Rogers material. All materials have the same tangent loss with different dielectric constant. Fig 5.13 (c) depicts the study of reflection coefficient for different substrate materials. It is precisely noted that the final antenna design exhibits the best impedance matching in the ISM band with Rogers RT/duroid 6010 material. All other substrate materials have shifted resonating frequency to a higher value which is outside the ISM band. From the mentioned materials, FR4 epoxy is the cheapest one but this material shows good transmission at 2.89 GHz with a S_{11} of -27.65 dB. The analysis of different materials suggests adopting Rogers RT/duroid as best suited material for this research work.

5.9 Proposed Antenna Fabrication, Simulation and Testing Outcomes

The recommended medical implantable antenna (A/N 3) is fabricated using printed circuit board technology. The model implantable antenna with dimension 7 mm x 6 mm x 0.254 mm is manufactured with substrate Roger 6010/6010LM having ε_r 10.2 and tan(δ) 0.0023. A cautious effort is taken place to install a coax feed in such a miniaturized size of the proposed antenna. To install sorting pin through the substrate, drill machine of radius 0.2 mm prepared hole. Later, we inserted copper wire of the same radius through the substrate which simply sorted the ground and patch surface together. Fig. 5.14 demonstrates the proposed configuration of fabricated antenna prototype of radiating patch surface and metamaterial loaded design on superstrate.

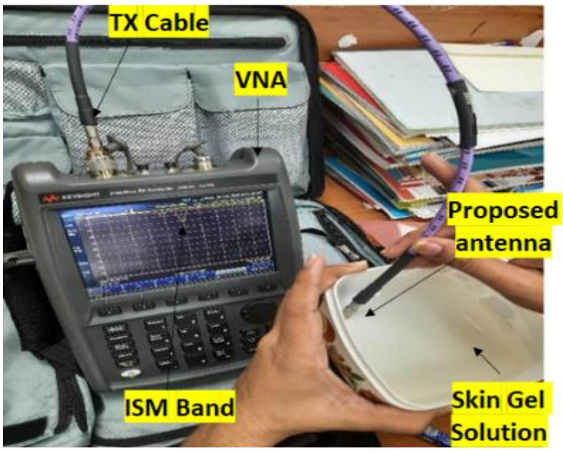
(a)

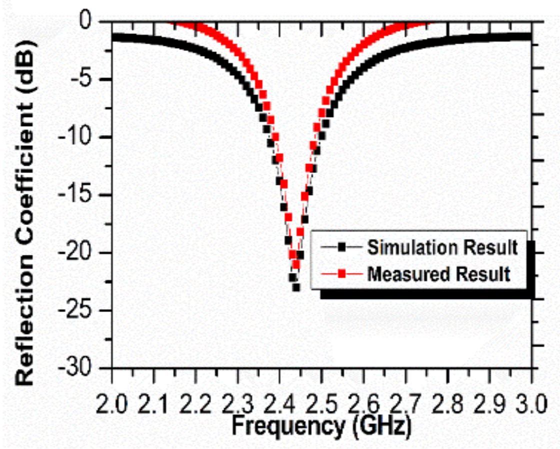


(b)

Fig. 5.14 (a) Radiating patch surface of the fabricated medical device antenna. (b) H-Shaped metamaterial design on the superstrate surface.

Simulation work is successfully endowed with finite element method in Ansoft HFSS. The recommended implantable antenna is dipped in saline solution at 4.25 mm. Skin mimicking gel was replicated by a 3D box in Fig 5.10 (e) with skin properties at 2.45 GHz in Ansoft HFSS. For ISM bands, competence of skin like dielectric constant and bulk conductivity are received from [11]. To validate the execution of the final design implantable antenna, the results of the fabricated structure of the final design antenna are measured with help of the KEYSIGHT Field Fox RF Analyser N9914A 6.5 GHz network analyzer in Fig 5.15 (a). Since an implantable antenna goes inside a human body, so to emulate the body tissue model and for the testing purpose of the antenna prototype, skin mimicking gel is prepared under specific consideration [11]. For making saline solution (skin mimicking gel) the amount of sucrose (53%), deionized water (47%), and carbomer (0.5 gram for 40 mL solution) are mixed well. This mixture is kept on heating at 80^0 C for 1 hour. Then it is cooled down to room temperature. The measurement setup along with saine solution gel is depicted in Fig 5.15 (a). There upon similitude of simulation and testing outcomes of S_{11} of the final implantable antenna is eyesight in Fig 5.15 (b).





(a) (b)

Fig.5.15 (a) Measurement setup of the final designed implantable antenna with saline solution. (b) Comparison of the reflection coefficient of simulated and fabricated proposed implantable antenna.

The fabricated proposed antenna shows a reflection coefficient of -21.67 dB at resonating frequency 2.44 GHz with impedance bandwidth of 90 MHz with frequency range 2.39 GHz - 2.48 GHz. Slight variation in impedance bandwidth between fabricated and simulated antennas has been observed. This variation is due to not having exact electrical properties of skin mimicking gel as compared to simulation skin model. Superstrate with metamaterial design is situated on patch surface with help of glue. The presence of an air gap in glue may cause some losses too. Overall fabricated and simulated antennas exhibit good agreement in their performance.

a) Assessment of SAR:

SAR is the most vital parameter for implantable antennas to ensure human safety during telemetry sessions. As per IEEE, two standards are given for one gram and ten grams of human tissues. For 1 gram of tissues, SAR must not exceed 1.6 W/KG otherwise SAR will result in a temperature rise of neighboring tissues. This may cause serious health issues for the patients.

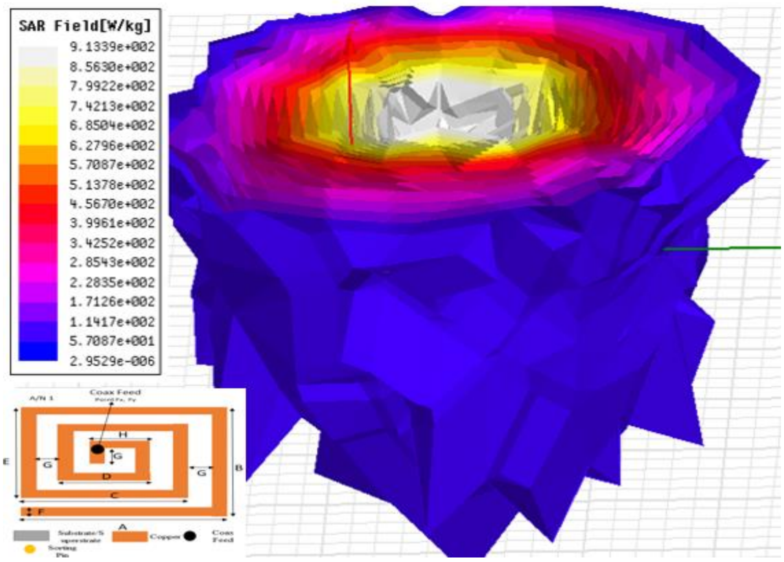
For setting input power as 1 watt, the maximum SAR of A/N 1 is 913.3 for 1 gram of tissue. To provide complete safety for the patient, the input power of A/N 1 should be less than 1.75

m watts. For all stepwise designed antennas, SAR values are mentioned in Table 5.8.

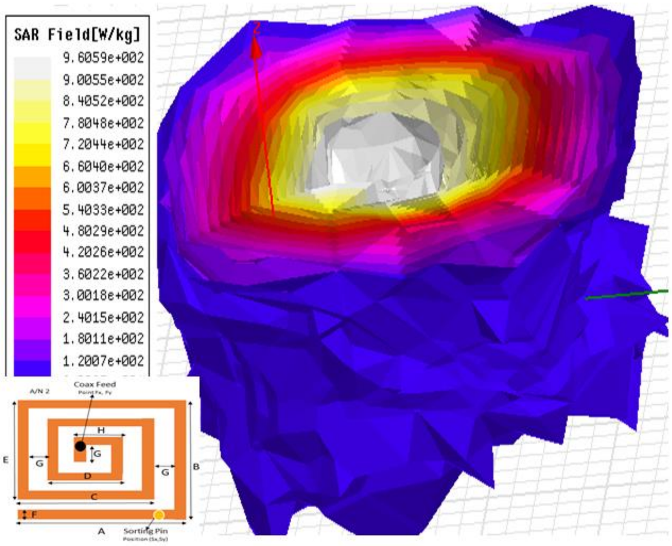
Table 5.8. Summary sheet of SAR for different antenna designs with input power for 1 gram of tissue.

S. No	**Antenna**	**Resonating Frequency (GHz)**	**SAR (W/KG)**	**Input power (mW)**
1	A/N 1	2.53	913.3	1.75
2	A/N 2	2.46	960.5	1.66
3	A/N 3	2.44	952.7	1.67

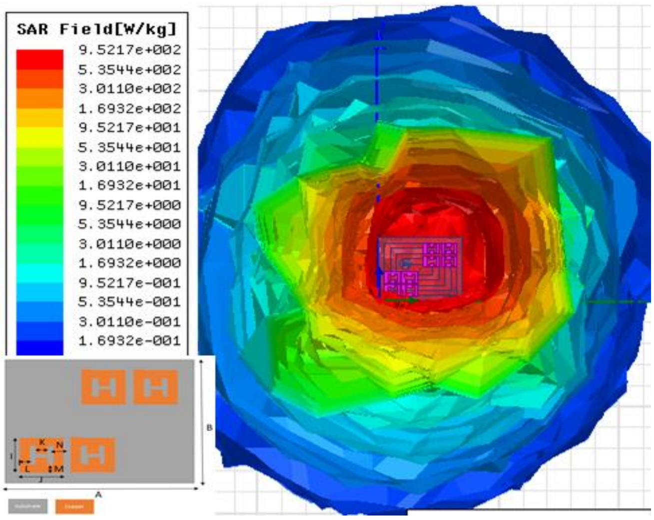
From Table 5.8, it is clearly shown that the final design antenna needs an input power of 1.67 mW. This much power is sufficient for biomedical applications. SAR of different designs of implantable antennas is depicted in Fig 5.16.



(a)



(b)



(c)

Fig. 5.16 (a) SAR of A/N 1 for one gram of body tissue. (b) SAR of A/N 2 for one gram of body tissue. (c) SAR of the proposed antenna (A/N 3) for one gram of tissue.

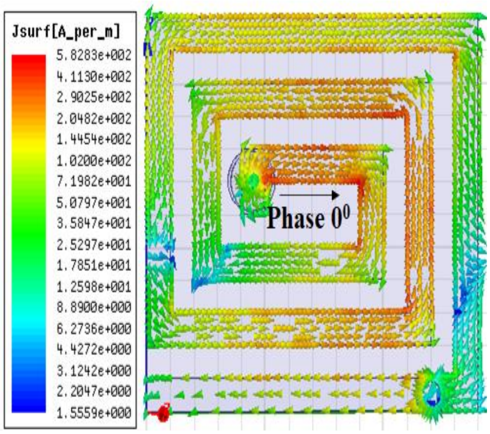
Overall, the achievement of the recommended medical antenna is highly recommended after comparison with recently published work. The proposed antenna exhibits small volume, good CP properties along with merit standard of SAR value. The comparison table of recently released work with our suggested implantable antenna is presented in Table 5.9.

Table. 5.9 Comparison of recent published work with proposed implantable antenna.

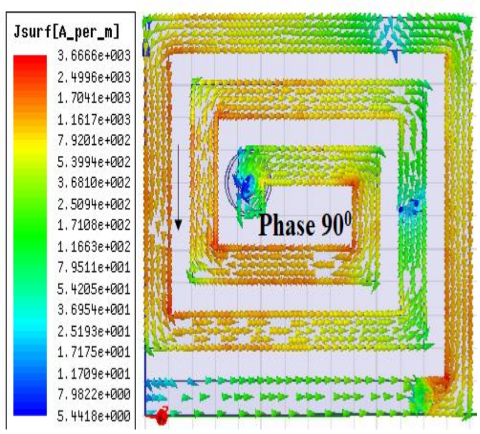
Reference	Resonating Frequency (GHz)	Dimension (mm^3)	Impedance Bandwidth %	Axial Ratio Bandwidth (MHz)	SAR for 1 gram	CP	Improvement of proposed work over previously published work
[67]	2.45	468.12	4.4 %	-----	314	No	Size reduction: 97.72%, Impedance BW improved by 0.22%, CP
[62]	2.4	73.41	3.34 %	-----	336.84	No	Size reduction: 85.46 %, Impedance BW improved by 1.28%, CP
[47]	2.4	121.97	21.5 %	-----	486	No	Size reduction: 91.25 %, CP
[8]	2.4	38.46	14.9 %	-----	568.2	No	Size reduction: 72.26%, CP
[38]	2.4	24.92	8.3 %	2.49 %	------	Yes	Size reduction: 57.18 %, ARBW improved by almost 39%.
This work	**2.44**	**10.67**	**4.62 %**	**830 MHz or 41.29 %**	**952.1**	**Yes**	

b) CP Performance and Gain of Proposed Implantable Antenna:

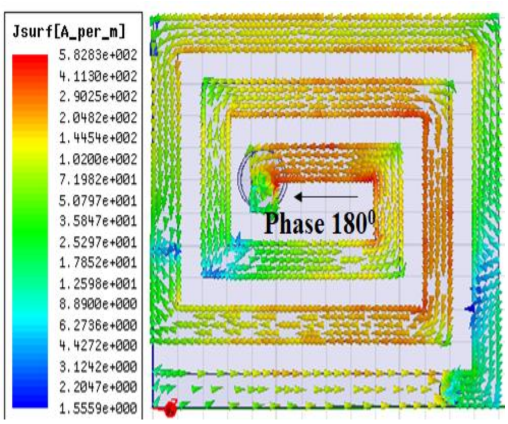
For any microwave antenna to be an implantable antenna, Circular polarization behavior is extremely recommended. During telemetry sessions, the CP behavior of the implantable antenna leads to enhancing the patient's mobility and freedom. The proposed antenna performs CP characteristics having excellent axial ratio bandwidth of 830 MHz in the ISM Band. Concerning axial ratio, CP behavior is well expressed in Fig 5.12 (b). The internal mechanism of CP proposed implantable antenna (A/N 3) can be demonstrated by observing surface current distribution. Fig. 5.17 delineates the surface current division on the patch surface of the metamaterial-loaded suggested implantable antenna at f_r of 2.44 GHz. It is clearly shown with four different phases (0^0, 90^0, 180^0, and 270^0). From Fig. 5.17 (a), at 0^0 phase surface current distribution is dominant in the + X direction (rightward). At 90^0 phase Current distribution is dominant in the -Y direction (downward). The surface current density for 0^0 and 90^0 are examined in equal magnitude and just opposite phase with 180^0, and 270^0 respectively. From Fig.5.16, the dominating current is turning in a clockwise direction which explains the left-hand circular polarization behavior for the metamaterial-loaded proposed implantable antenna (A/N 3). The surface current division yields the suggested antenna (A/N 3) a perfect circular polarized antenna as shown in Fig. 5.17.



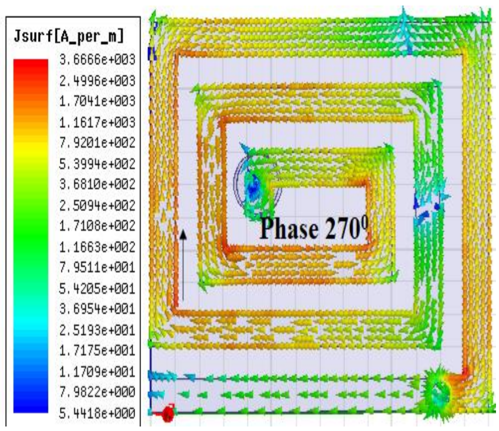
(a)



(b)

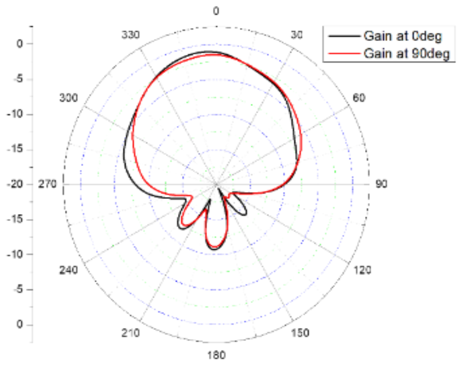


(c)

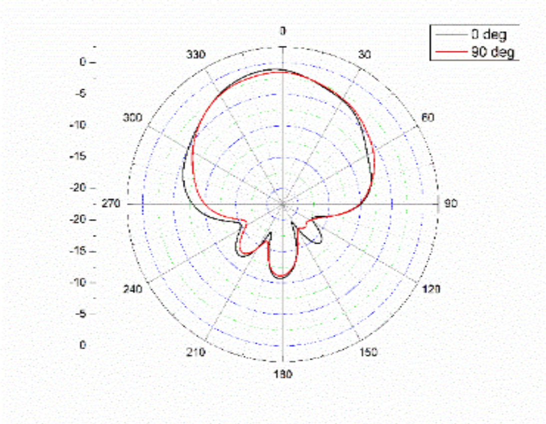


(d)

Fig. 5.17 (a) Surface current division of radiating path (patch) final implantable antenna with 0^0 phase angle at 2.44 GHz. (b) at 90^0 (c) at 180^0 (d) at 270^0.



(a)



(b)

Fig. 5.18 (a) Normalized simulated gain of the recommended antenna at 2.44 GHz. (b) Normalized measured gain of the proposed antenna at 2.44 GHz.

From Fig 5.18, it is well demonstrated that the final medical antenna (A/N 3) shows the simulated gain of -29.6 dB at 2.44 GHz resonating frequency. The complete setup of the fabricated antenna is tested for the gain parameter. The measured value of gain is obtained -30 dB at 2.44 GHz. Both simulated and measured gain parameters have good agreement. Slight variation may happen due to environmental effects in saline solution.

c) Link Margin Analysis:

In this paper, our assumption is to utilize the recommended medical antenna in the hospital environment for biodata transmission. The telemetry scenario is taken place in a hospital with wireless communication. To substantiate the wireless communication between the medical device antenna and external station, the link margin must be at least greater than zero dB. As per the European Research Council Standard [18], we are bounded to use 25 µW transmitted power to this proposed implantable antenna. All the specifications of transmitting antenna, receiver, and signal quality are presented in Table 5.10.

Table. 5.10 Details of Wireless communication parameters.

Transmitting End	
Resonating Frequency	2.44 GHz
Transmission Power	25 µW
Transmission Power (dBm)	-16
Transmission Antenna Gain	-29.6 dB
EIRP	-46.6 dB
Feeding Loss	1 dB
Radiation Propagation	
Distance	Variation
Free Space Loss (L_f)	Distance dependant
Receiver Station	
Receiving Antenna Gain	2.15 dB
Ambient Temp (K)	293
Boltzmann Constant	$1.38 \times 10^{(-23)}$
Noise Power Density (N_O)	-199.95 dB
Noise Figure	3.5
Signal Quality	
Bit Rate B_r	Variation
Bit Error Rate	$1 \times 10^{(-5)}$
E_b/ N_O (Ideal PSK)	9.6 dB
Fixing Deterioration	2.5 dB

To calculate the link margin, it is essential to find free space loss from the equation given below.

L_f (dB)= 10 $\log_{10} (4\pi d/\lambda)^2$ (5.1)

Where,

d = The closeness between the transmitter antenna and receiver antenna.

λ = The operating wavelength of the transmitting antenna.

For the different values of d, free space loss is presented in Fig 5.18 (a). Link margin calculation is taken for distance d=4 meter with help of the standard equation given below.

$$Link\ margin = Link\ \ C/N_o - Required\ \ C/N_o$$

$$Link\ \ C/N_o = P_t - L_{feed} - G_t - L_f - L_a + G_r - L_{feed} - N_o \quad (2)$$

$$Required\ \ C/N_o = E_b/N_o + 10 \log B_r - G_c + G_d \quad (3)$$

For distance **d=4-meter, B_r= 70 Kb/s**.

Link C/N_o = -46.03 -1-29.6 – 52.2276 – 0.5 + 2.15 – 1 + 199.95 (4)

Link C/N_o = 71.74 dB (5)

Required C/N_o = 9.6 + 48.45 + 2.5 (6)

Required C/N_o = 60.55 dB

(7)

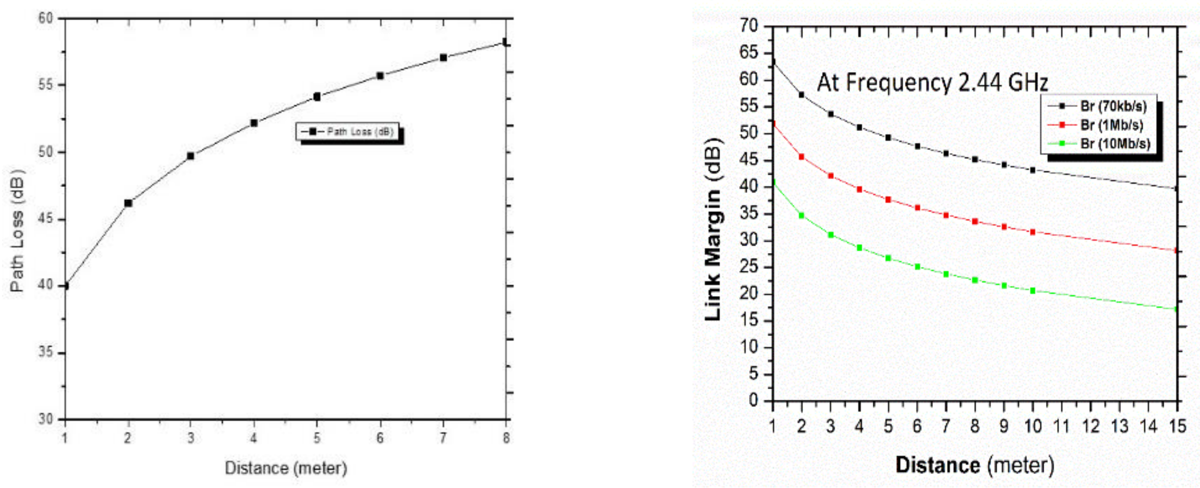
Link Margin is calculated below.

Link Margin = 71.74- 60.55

(8)

Link Margin = 11.19 dB

The variation of path loss and link margin w.r.t the distance is explained in Fig 5.19 (a).



(a) (b)

Fig. 5.19 (a) Path loss of Transmitting antenna at a different distance. (b) Link margin of the final implantable antenna at 2.44 GHz frequency for different bit rates at different distances.

From Fig 5.19 (b), it is well demonstrated that a wireless communication link is nicely established between transmitting and receiving antenna with different bit rates at distances from 1 meter to 8 meters. At 4 meters, the link margin of the proposed research work is obtained 11.19 dB for a bit rate of 70Kb/s. From link margin analysis of the suggested final design antenna, it can be noted that it is a better preference for telemetry sessions in biomedical devices for health care monitoring.

5.10 Conclusion

The highly miniaturized implantable antenna is designed and validated experimentally in saline solution (skin mimicking gel) for biomedical applications. Best performance is achieved via sorting pin and metamaterial design. -10 dB bandwidth and 3 dB bandwidth of the recommended antenna have perfectly covered the ISM band. The proposed antenna (CP) exhibits almost maximum axial ratio bandwidth (830 MHz) as compared to recently published papers. With this miniaturized size (10.27 mm^3) of the proposed antenna, an acceptable value of SAR 952.1. Simulated and the tested results of the suggested final design antenna are reasonably comparable. The analytic study of proposed implantable antenna has been successfully carried out. Detailed analysis of link margin has ensured good wireless communication establishment between transmitting and receiving antenna. The fabricated prototype work is promising for biomedical applications.

Chapter 6

Conclusion and Future Scope

Conclusion and Future Scope

This chapter of dissertation is mainly detached in two parts: (1) Conclusion of complete research work. (2) Future scope of given research work. The present thesis is concentrated on miniaturised size, the circular polarisation, specific absorption rate, impedance bandwidth, axial ratio bandwidth.

Conclusion of presented research work:

Now a days, human health is the biggest concern due to enormous reasons like bad eating habits, no exercise, drinking alcohol, smoking, and environmental pollution. Many times, hazardous diseases are detected at the later stage of patients that consequently result in loss of human life. High population with low economic growth nations have poor medical facility. Patients must wait for long hour during medical check-ups. With the rapid growth of wireless technology, the biomedical devices (BMDs) are introduced in medical science. These devices are implanted inside human body by means of surgery to get bio-information of internal human body environment. To setup the wireless communication link between medical devices and external base station, medical device antenna must be an integral part of BMDs. The implantable antenna ensures the performance of BMDs with its characteristics like impedance bandwidth, circular polarisation, low SAR, high gain, miniaturised size etc. This impedance bandwidth plays important role in biomedical implantable antennas. With high value of impedance bandwidth, large no of channels can be framed for data transmission. The reconstruction of original signals can be easily recovered at external receiver stations. The high value of impedance bandwidth is suitable for high data rates and better link margin. In BMDs, circular polarization (CP) implantable antennas are of very high demand. During the telemetry sessions, the implantable antenna suffers from multiple losses. For linear polarized antenna, patients must sit in rigid posture to avoid losses. With CP characteristics of implantable antenna, the patients can enjoy full mobility during data transmission. For BMDs, researchers focus on receiving better CP characteristics of implantable antenna and eventually provide big relief for patients during telemetry sessions. To ensure the patients safety, SAR parameter of implantable antenna is most important concern. Due to absorbing nature of human body tissues during data transmission, the temperature of neighbouring tissues may rise. If rise in temperature of 1^0 to 2^0, this may change the dielectric constant of body tissues and consequently may cause severe diseases. By considering all aspects of SAR, IEEE has given two standards. For one gram of tissue, the maximum limit of SAR is 1.6 W/KG and for ten gram of substance is 2 W/KG. So as per given standard, the medical device antenna must be designed with SAR below 1.6 W/KG or 2 W/KG for 1 gram and 10-gram body tissues respectively. Human body itself is of absorbing nature so getting good value of gain is tough task. Moreover, the implantable antenna works with very low signal strength. Consequently, such antenna shows negative gain value in desired frequency band. So, antenna with better gain is highly preferred for BMDs.

The medical device antenna is the most sizable part of BMDs. As the frequency of Industrial Scientific and Medical (ISM) band is small as compared to most of the available wireless devices, the biggest challenge at this frequency is the voluminous physical dimension of the antenna.

So, to slacken the dimension of BMD, the size reduction of medical device antenna becomes very crucial. Highly compact size of implantable antenna with low resonating frequency is preferred. Plenty of techniques have been explored to minimize the size of implantable antenna over the time. The meandered, spiral shape with sorting pin has been investigated in detail for miniaturization.

Various techniques like sorting pin, slots, metamaterial, magnetodielectric substrates, meandered and spiral shaped patch have been implemented to ameliorate return losses, impedance bandwidth or -10 dB bandwidth, axial ratio bandwidth or 3 dB of circular polarisation, gain, and SAR value. The thesis has been formulated as follows:

In the first chapter, a detail knowledge of BMDs and implantable antennas are explored. Next, the implantable antenna with essential parameters, requirements, and available bands for biomedical application has been explained. In the end different type of realistic human body environment at ISM band frequencies are explored. This detailed study lays the foundation that is needed to understand research in this thesis.

In the second chapter, literature survey of implantable antennas has been discussed at length. The size reduction techniques have been demonstrated from early research days to recent research trends. Great reduction of size in implantable antenna has been studied by involving various efficient techniques like meandered, spiral, sorting pins, and slots etc. The circular polarised antenna and its significance have presented with gradual development of research in this prospect. Low SAR value of implantable antenna with useful techniques are discussed w.r.t international standards. The implantable antenna suffers from lossy human body environment and hence it shows low value of gain. In the end, gain enhancement techniques are focussed for implantable antenna.

In the third chapter, dual band implantable antenna has been designed in ISM band. The dual band antenna is designed with 12 mm^3 volume which is least among recent published work. The final suggested antenna resonates at two bands i.e., 0.93 GHz, 2.43 GHz. In both ISM band, proposed antenna shows 7.7 % and 5.5 % impedance bandwidth. SAR value in both bands are below IEEE standard values (1.6 W/KG) for 1 gram of substance. Two ISM bands have been achieved without ground slots of proposed antenna that avoids back radiations.

Overall, this is observed that final design antenna shows surpassing execution with dual band characteristics.

In forth chapter, the medical device antenna is designed in ISM band. 1st designed antenna show 190 MHz impedance bandwidth. To enhance -10 dB bandwidth of 1st designed antenna, magnetodielectric substrate (MDS) materials have been implemented as substrate material with some non-zero positive value of e_r and u_r. The impedance bandwidth has been improved from 190 MHz to 410 MHz. Then MDS 2 and MDS 3 materials have been used to improve bandwidth from 190 MHz to 350 MHz respectively. The f_r is also reduced from 2.44 GHz to 1.78 GHz, 2.01 GHz, and 2.13 GHz for all three MDS materials respectively. It means that MDS material worked well to improve impedance bandwidth up to large extent. One more triple ring slotted circularly polarised implantable antenna is explored. In this design, three rings with coaxial feed at circular patch are designed. This design is optimized in ISM band with sufficient impedance bandwidth. But to attain CP, ground slots are proposed. The proposed antenna exhibits axial ratio bandwidth from 2.38 GHz to 2.67 GHz with acceptable SAR value of 944.2. This proposed antenna is reported with least volume of 9.77 mm^3 w.r.t recent research work.

In the fifth chapter, the complex fabrication of PIFA, patch stack, and metamaterial antennas is considered. To get advantage over mentioned implantable antennas, simple meandered structure implantable antenna is designed with patch and ground triangular slots. The 1st designed antenna with meander structure is optimised at 2.44 GHz with RC of -24.54 dB. The -10 dB bandwidth of 120 MHz is achieved with frequency range 2.37 GHz - 2.49 GHz. To get circular polarisation, four triangular slots are implemented on patch surface. With these slots, antenna has improved impedance bandwidth from 120 MHz to 140 MHz. At last, the circular polarisation is achieved by using similar four triangular slots on ground surface. The proposed antenna now is shown circular polarisation with 3 dB bandwidth of 80 MHz with frequency range 2.45 GHz - 2.53 GHz. The proposed antenna is reported with volume of 12.29 mm^3 and acceptable SAR value of 901 which is quite better among recent research work. A wideband circularly polarised antenna is also considered. A simple spiral structure implantable antenna is designed with sorting pin and superstrate metamaterial of H shaped. The 1st designed antenna with spiral structure is optimised at 2.53 GHz with RC -16.89 dB. The -10 dB bandwidth of 120 MHz with frequency range 2.47 GHz - 2.59 GHz is achieved. To get circular polarisation, sorting pin is implemented between patch and ground surface. With this sorting pin, antenna has shown circularly polarised with axial ratio bandwidth of 530 MHz from 2.15 GHz to 2.73 GHz. To further improve the axial ratio bandwidth, H shaped metamaterial is used on superstrate surface. With this implementation of metamaterial, axial ratio bandwidth is improved from 530 MHz to 830 MHz. The proposed antenna is reported with volume of 10.67 mm^3 and acceptable SAR value of 952.7 which is quite better among recent research work.

In the end, the sixth chapter consists of the overall epitome and ensuing realm of the dissertation. In this thesis, we designed circular microstrip patch antenna with circular rings, meandered, spiral, MDS and PIFA antenna to achieve high impedance bandwidth, high gain, circular polarisation in ISM band with compact size. These antennas can be used as implantable antenna for biomedical application.

In this way, this thesis has been discussed size reduction, bandwidth, circular polarisation, low SAR, and gain enhancement using slots, PIFA, MDS, spiral, and meandered shapes.

The future scope of presented research work:

In this thesis, the implantable antennas are designed using meandered and spiral shaped approach. These techniques have worked excellent for size miniaturisation, but upcoming researchers should focus on different shape for novelty purpose. The designing of the implantable antennas is taken place on rogers rt duroid substrate. Generally, this substrate is quite expensive as compared to others like FR4 epoxy. So, working on inexpensive substrate/superstrate is strong need for reducing the cost of medical devices.

In this thesis, the performance enhancement techniques like sorting pin, metamaterials, and slots are used. But sorting pin technique is subjected to have complex fabrication process of proposed antennas. So, researchers must work on simple and efficient techniques to improve antenna's parameters. The slots of rectangular and triangular shape have been used for research work. Some different shape slots can be experimented for performance enhancement.

In this thesis, the designing of implantable antennas is discussed at length. But designing of medical devices are not covered. So, researchers must start working on designing of all integral parts of medical devices. The efficient techniques to reduce the power level of integral component of BMDs must be explored.

The almost research work is based on implantable antennas. To transfer the power by means of wireless medium, the rectenna design and testing methods must be explored. For all dual band implantable antennas, the battery for BMDs must be charged wirelessly. This work can only be possible by designing proper antenna and rectifier. In this way, the battery life of BMDs can be improved for several years which encourage every patient to install such devices rather than creating fear or anxiety.

The almost work is dealt with antenna execution in terms of -10 dB bandwidth, 3 dB bandwidth, circular polarisation, specific absorption rate. But the link margin of designed antennas must be calculated and measured just to ensure the distance of short-range communication between BMDs and external receivers. For link margin, researchers must work on high gain, large bandwidth, bit rates.

The low value of gain for all implantable antennas are the biggest disadvantages due to lossy medium and low power strength. The researchers must keep on working hard to increase the directive gain of implantable antennas. Having high directive gain can improve the radiation properties and link margin.

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LIST OF PUBLICATIONS

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