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Compact Dual-Band Zig Zag Shaped Implantable Antenna for Biomedical Devices

Rajiv Kumar Nehra[a*] & N S Raghava[b]

[a]Department of Electronics and Communication Engineering, Bharati Vidyapeeth's College of Engineering, New Delhi 110 063, India
[b]Department of Electronics and Communication Engineering, Delhi Technological University, New Delhi 110 042, India

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This paper presents a highly compact volume 12 mm^3 Zig Zag-shaped implantable antenna for biomedical applications. The antenna performance is closely analyzed in terms of penetration depth, different human tissues, substrate materials, reflection coefficient, Impedance Bandwidth, directive gain, and SAR values. The three different models are analyzed for different resonating frequencies. It is found that the proposed antenna shows dual ISM bands (900 MHz to 970 MHz 2.36GHz to 2.49 GHz) with impedance bandwidth of 7.77 % and 5.5% respectively. The proposed implantable antenna is successfully fabricated and tested in skin mimicking gel (vitro model). The performance of the proposed antenna is enhanced by using a sorting pin and slots that provides dual ISM bands, an acceptable SAR of 856.3 W/KG, and a directive gain of -28.68 dBi. Parametric analysis of the proposed implantable antenna has been studied in detail. Simulated and fabricated results are compared and found almost similar

Keywords: ISM (Industrial Scientific and medical); SAR (Specific absorption rate); BMD (Biomedical devices); IMD (implantable medical devices); MDAN (medical body area network)

1 Introduction

In today's world, health is the most important concern for everyone. If any patient goes to a hospital, he or she mustwait for a long time in a long queue for medical check-ups, especially in countries having high population. Many serious diseases are diagnosed by doctors at a later stage. This may lead to getting serious damage to patients. So now a day's implantable medical devices are emerging as a new hope for a healthy lifestyle. Such devices are implanted inside the human body, and all biological information of the human body like sugar, blood pressure, glucose level, heartbeat, the oxygen level in the blood, *etc* will be retrieved. This technology is extremely beneficial to human beings for maintaining their health and anticipating their internal organs update in ad- vance[1]. In biomedical devices, an implantable antenna is a key component to establish wireless communication between BMDs and external receiver station. For diagnosis purpose, BMD is implanted inside the human body, so the size of BMD is always a great concern. Further, it is known that the major size of BMD is covered by an implantable antenna itself, which attracts worldwide researchers to work on antennasize minimization[2]. So, miniaturization of an implantable antenna for BMD is highly demanded. Various techniques have been studied by researchers so far. Miniaturization is achieved by lengthening the current path on the patch sur- face. Due to this reason, researchers generally use meandered antenna[3] to get a small size. This approach is further modified by using a sorting pin that makes the patch and ground surface sorted to each other, which results in a large current path on the patch and ground surface. Eventually, such antennas (PIFA) shift their resonating frequency to lowerside[4]. Since the antenna is inside the human body so the internal environment of the human body is of absorbing nature and hence degrades antenna performance. To get best performance from implantable antennas, is quite challenging task for researchers in lossy environment of human body[5]. So, to evaluate performance of implantable antenna, SAR is also an important aspect. The amount of heat absorbed by the body per kg of mass is defined as SAR. A very high absorption of antenna radiation may cause a serious problem (temperature rise) in the human body because the higher temperature may change the relative permittivity of human tissue[5,6].

*Corresponding authors:
(Email: rajiv.nehra@bharatividyapeeth.edu; nsraghava@dtu.ac.in)

One more important challenge is to provide a wireless charging facility for the existing battery in BMDs. All electronic devices work on DC biasing energy. The proper functioning of BMDs can only be ensured with charged DC battery. It is quite inconvenient for patients to charge or replace the battery of BMDs by making surgery every time. So, compatible methods for wireless charging of the battery are very much required. To achieve wireless charging, the implantable antenna must be designed with dual bands (ISM bands). Here, the two bands are utilized in the manner like one band is used for data transmission during telemetry sessions and the other band utilizes radiation and convert them into DC voltage using rectifier, filter (integral component of BMDs) for wireless charging without disturbing the position of IMDs in the human body. In this paper, a highly compact Zig Zag- shaped implantable antenna has been designed, simulated, and analyzed for different parameters. An acceptable range of SAR is achieved, which is quite low as compared to IEEE standard safety guidelines[7,8] along with dual bands (ISM frequency bands), and the highly miniatured volume of the implantable antenna. The designing consideration steps, parametric study, performance analysis, and experiment results of a highly compact Zig Zag-shaped implantable antenna have been provided in detail. The measurement of a fabricated proposed implantable antenna with detailed discussion hasbeen carried out.

2 Design and Fabrication of The Proposed antenna

A very compact implantable antenna is proposed that has an extremely small size as compared to recent reference papers[8-15]. All designed dimensions of antenna are presented in Table 1. An implantable antenna is designed in X mm x Y mm size. The proposed antenna is having the shape of two symmetric serpentine paths with one centre strip which is resembled with Zig Zag shape hence named a highly compact Zig-Zag shaped implantable antenna as shown in Fig. 1.

Table 1 — Design Parameters of Proposed Antenna.

Parameters	Value (mm)	Parameters	Value (mm)
A	0.5	E	0.4
B	1.5	F	0.45
C	1	r	0.75
D	0.25	s	2.75
X	6	p	2.25
Y	4	q	1
H	0.25		

2.1 Designing sequence of the proposed antenna

1. Initially, a size of X mm x Y mm is considered for patch design. Then the concept of meandered planer antenna is adapted to provide a longer current path. The symmetrical serpentine shape is designed on both sides of the centre strip with A mm width shown in Fig. 1(a). After the optimization process, a good impedance matching is achieved at position (r, s) of coax feed. This 1st designed antenna shows the resonating frequency of 1.48 GHz with a reflection coefficient of -23.65 dB. The impedance bandwidth of 12.94% from 1.39 GHz to 1.57 GHz has been achieved in Fig. 1(f).

2. To achieve the resonating frequency in the ISM band from 1st designed antenna, a sorting pin with radius 0.2 mm is introduced between the patch and ground surface via the substrate. Inclusion of sorting pin in 1st designed antenna is termed as 2nd designed antenna shown in Fig. 1(b). Complete optimization of sorting pin position on the patch surface is studied in detail. At last, sorting pin position (p, q) is finalized. At this specific position, 2nd designed antenna turned into a dual-band antenna shown in Fig. 1(f). This antenna exhibits resonating frequencies of 0.94 GHz, and 2.34 GHz with impedance bandwidth of 3.2% and 5.26% respectively. The reflection coefficient at both resonating frequencies is -10.2 and -21.44 dB respectively.

3. To take both frequency bands in the standard frequency range (ISM Bands), 3 slots are embedded on the left side of patch surface in 2nd designed antenna shown in Fig. 1(c). With help of 3 slots, ISM Bands are achieved with sufficient impedance bandwidth. Now the proposed implantable antenna exhibits resonating frequencies of 0.93 GHz and 2.43 GHz with impedance bandwidth from 0.90 GHz to 0.97 GHz (7.77%) and 2.36 GHz to 2.49 GHz (5.5%) along with -14.14 dB and -35.70 dB reflection coefficient respectively shown in Fig. 1(f). The width of each strip except D in given Fig. 1(c) is A mm. This antenna is designed on substrate Rogers 6010 RT/Duroid that has a relative permittivity of 10.2 and dielectric loss tangent 0.0023. The same material (Rogers 6010 RT/Duroid) is also placed over a patch surface which is called a superstrate. A high dielectric superstrate makes the antenna more efficient towards stabilizing the

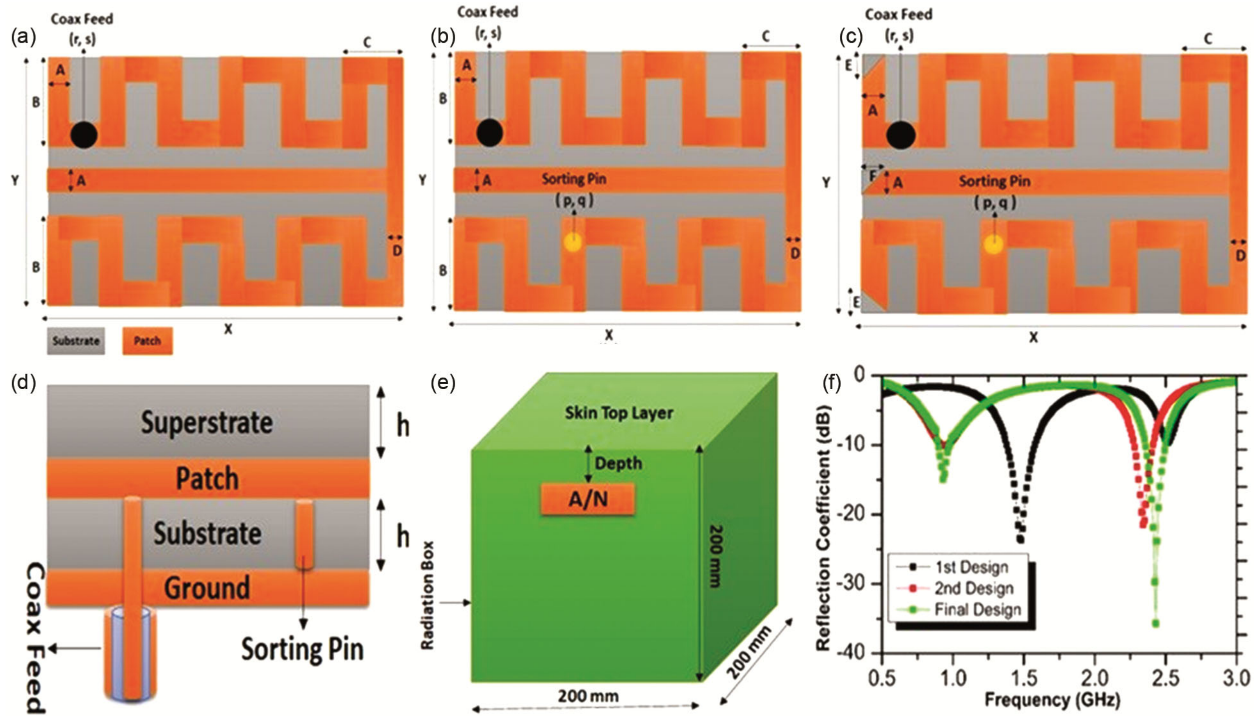

Fig. 1 — The designing sequence of Proposed antennas. (a) 1st designed antenna with feeding position (r, s). (b) 2nd designed antenna with sorting pin. (c) Design of Final proposed implantable antenna with slots. (d) Side view of the final proposed antenna with coaxial feed and sorting pin. (e) Placing of the final proposed antenna inside the skin box with a depth of 3.5 mm from the top surface. (f) Reflection coefficient of design sequence of antennas

fluctuation in relative permittivity and avoids antenna absorption from surrounding. Substrate and superstrate are selected in such a way to reduce reflection, better biocompatibility, and good impedance matching. Substrate and superstrate have a thickness of h mm each. So total volume of the proposed antenna is X mm x Y mm x 2*h mm (12 mm^3). The coaxial feed is used to excite the proposed antenna which has 50-ohm resistance. The position of the coaxial feed connector is at r, s position. At this point, the antenna exhibits good impedance matching. The final proposed antenna is placed at penetration depth of 3.5 mm inside human skin box in Fig. 1(e).

Ansys high-frequency structure simulator has been used for the analysis and designing of proposed research work. A skin box is created in the HFSS simulation tool by assigning a specific value of relative permittivity, bulk conductivity, and dimensions. The skin has unique properties like permittivity, bulk conductivity, and mass density based on the operating frequency. The proposed implantable antenna is designed in an ISM band (2.4 to 2.48 GHz), so the skin box is assigned with relative permittivity of 42.9 and bulk conductivity of 1.56 siemens per meter[17]. The volume of the skin box is 200 mm x 200 mm x 200 mm shown in Fig. 1(e).

3 Parametric Study of Proposed Antenna

The proposed implantable Antenna performance is exorbi- tantly investigated by varying the penetration depth in several tissues of the human body. Therefore, different tissues and depth of penetration of the proposed implantable antenna are deliberated in detail. Parametric study of various dielectric materials is also analyzed for the final antenna design.

3.1 Effect of penetration depth in skin model

Figure 2(a) represents the variation of reflection coefficient of the proposed implantable antenna at a different penetration depth from the top surface of the skin tissue model. During the investigation of penetration depth effect on proposed im- plantable antenna, antenna is placed at 6 different depths from the top surface of the skin tissue model. It is elucidated that the proposed antenna performs well in 2 ISM bands with a slight variation of resonating frequency. The penetration depth shows negligible effect on the performance of proposed antenna. At 3 mm penetration depth, the performance of

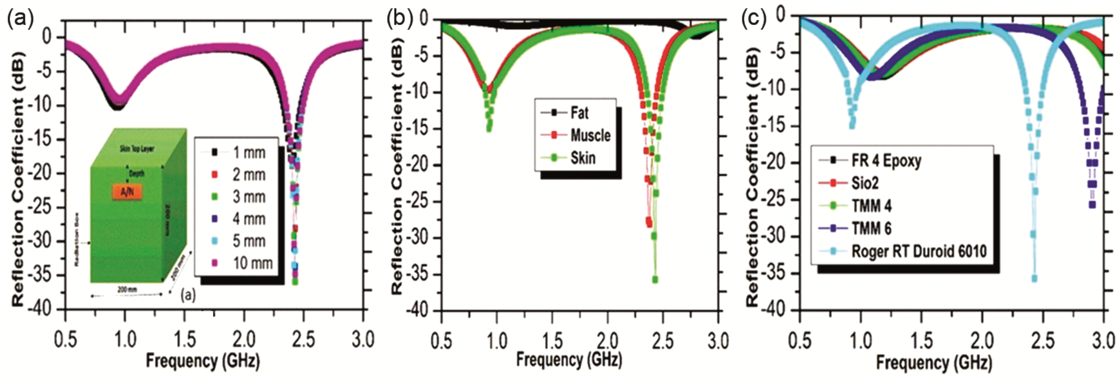

Fig. 2 — Reflection coefficient of proposed antenna at different penetration depths in skin tissue model. (b) Reflection coefficient of proposed antennain different human body tissues. (c) Reflection coefficient of the proposed antenna of different substrate materials.

proposed antenna upgrades in the lower ISM band (902 MHz to 928 MHz). It means the proposed antenna almost holds its performance (ISM Bands) with penetration depth.

3.2 Effect on antenna performance in various human body tissues

To validate the performance of the proposed antenna, it is placed in the vicinity of different human body tissues like Skin, Fat, Muscle, *etc*. The performance of the proposed antenna is evaluated in terms of reflection coefficient and is shown in Fig. 2(b). The reflection coefficient curves indicate that the proposed antenna performs excellent results in the ISM band when kept in the skin model, while in the fat and muscle layer, the antenna has lost a lower ISM band (S11-10 dB).In the skin layer, it radiates energy in dual bands with good impedance matching. It implies that from given human tissues, the proposed antenna is extremely suitable for skin tissues at 3.5 mm deep inside from the top surface.

3.3 Effect of substrate materials on antenna performance

Substrate material provides mechanical strength and robustness to any microwave antenna. Depending upon different dielectric properties, five substrates have been investigated for performance evaluation of the proposed antenna. The reflection coefficient performance is shown in Fig. 2(c). It is observed that the substrate material Rogers 6010 RT/Duroid exhibits outstanding performance in dual ISM bands. Furthermore, other substrates do not show good response in desired frequency bands. So, the selection of Rogers 6010 RT/Duroid substrate material is an excellent choice for the proposed implantable antenna.

3 Measurement and Results Discussion

The implantable antennas are generally tested in two different methodologies. One is vivo model in which human body phantom is carried out and implantable antenna is placed at specific position inside it. Other method (vitro model) is to develop skin mimicking gel solution which has same properties of human skin at specific operating frequency. In this section, to test the proposed antenna's performance, vitro model is adopted. Skin mimicking gel is depicted in Fig. 3(a). This liquid gel has properties equivalent to human skin of dielectric constant er=42.9, Bulk Conductivity of 1.56 Siemen/meter in the ISM band[16]. Specific quantity of sucrose 53%, deionised water 47%, and carbomer 0.5 gram in 40 mL solution, is mixed well and put that solution at 80 °C for one hour[17]. Then solution is left to cool down for some time shown in Fig. 3(a). The proposed antenna Measurement set up is shown in Fig. 3(c). The proposed implantable antenna is immersed with a depth of 3.5 mm in skin mimicking gel as shown in Fig. 3(c). KEYSIGHT Field Fox RF Analyser N9914A 6.5 GHz network analyzer and 50-ohm SMA connector are used to measure antenna parameters. The proposed antenna is fabricated on printed circuit board shown in Fig. 3(b). To install sorting pin, cautious efforts are taken place. A drilling machine with radius 0.2 mm is used to make sharp hole in PCB. Copper wire is inserted as sorting pin between patch and ground surface of proposed antenna. To develop the slots on patch surface, etching technique is used to remove specific conducting area using copper chloride solution. Then fabricated antenna is tested successfully in the microwave lab. Measured results have good agreement with simulated results shown in Fig. 3(e).

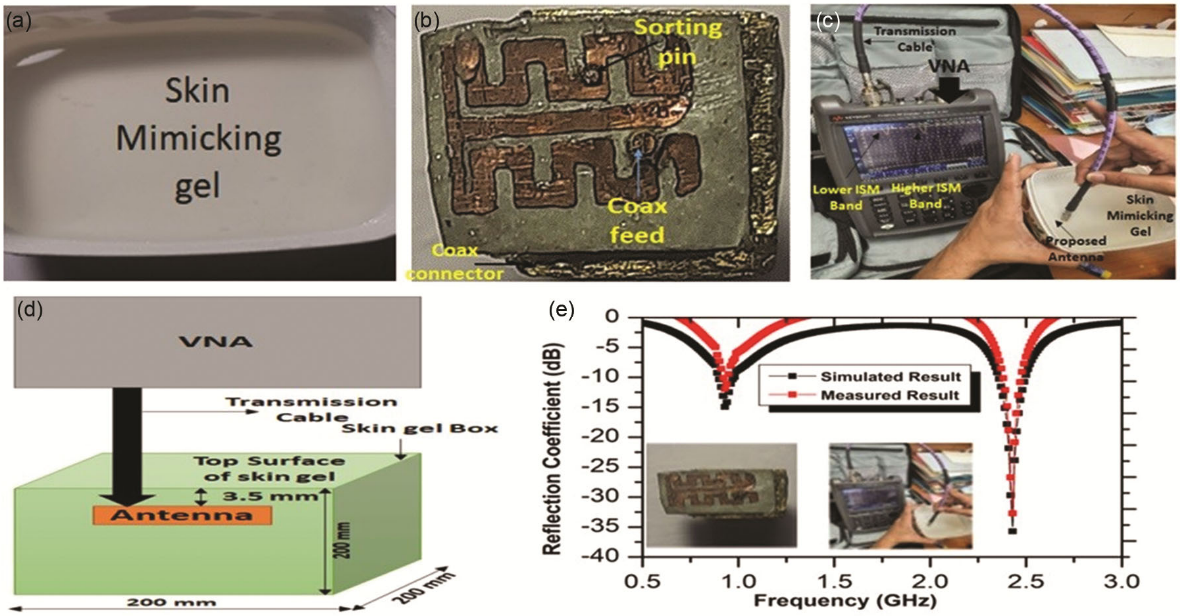

Fig. 3 — (a) Skin mimicking gel (vitro model) at 2.43 GHz. (b) fabrication of proposed implantable antenna. (c) Measurement sight of the fabricated antennain the microwave lab. (d) Prototype model of antenna result measurement. (e) Reflection coefficient of simulated and fabricated antenna. (e) .

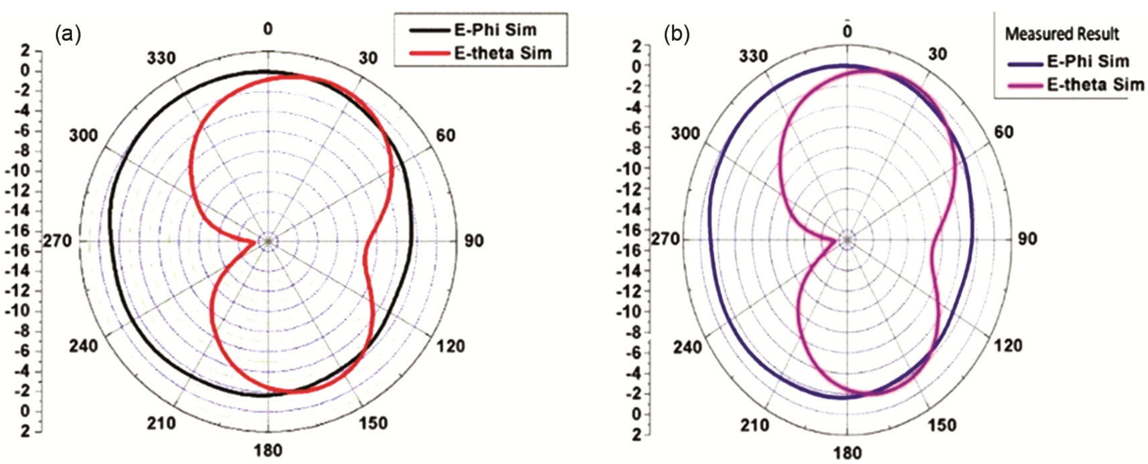

Fig. 4 — (a) Simulation of the Radiation pattern of the proposed antenna at 2.43 GHz. (b) Measurement of the radiation pattern of fabricated antenna at 2.43 GHz

The fabricated antenna is tested and measured reflection coefficient (dB) in skin gel with dual-band performance shown in Fig. 3(c). The fabricated antenna shows dual bands with slight variation in reflection coefficient. It has impedance bandwidth from 0.92 to 0.94 GHz and 2.38 to 2.47 GHz in lower and higher ISM bands respectively. However, the slight variation of the simulated and fabricated antenna in impedance bandwidth occurs due to limitation of fabrication technique, soldering technique, presence of air gap, imperfection of sorting pin, and glue between patch surface and superstrate. Prototype of measurement set up of implantable antenna is also presented in Fig. 3(d).

From Fig. 4, it is well observed that the simulated and fabricated antenna exhibits almost similar radiation pattern for gain performance. Moreover, with introduction of sorting and slots, proposed antenna design has improved gain value from - 30.30 dB (1st design antenna) to -28.68 dB. The negative value of gain shows that human body tissues absorb radiation from antenna section in BMDs. This absorption of antenna radiation leads to get negative value of gain. But this gain value is sufficient to

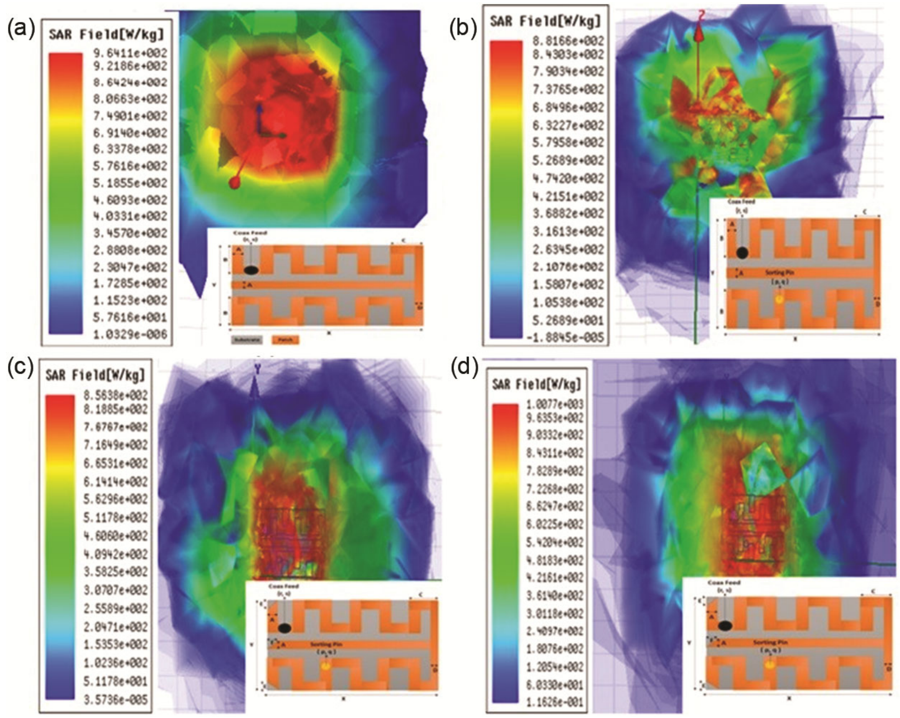

Fig. 5 — SAR Analysis (a) SAR analysis of 1st designed antenna at 1.48 GHz (b) SAR analysis of 2nd designed antenna at 2.34 GHz (c) SAR analysis of final proposed antenna with slots and shorting pin at 2.43 GHz. (d) SAR analysis of final proposed antenna with slots and shorting pin at 0.93 GHz.

establish wireless communication between BMDs and external receiver station.

4 Evaluation of SAR Distribution

As per IEEE standard safety guidelines, the human body should not absorb 1.6 w/kg or above for 1 gram of human body tissue and 2 w/kg or above for 10 grams of human body tissue[8]. So, designing an implantable antenna with this limited SAR value is our prime concern. The absorbed power by the human body and electric field is given as.

$$\text{SAR}=\int_{sample} \frac{\sigma(r)\,|\vec{E}(r)|^2}{\rho(r)}\, dr \quad ...(1)$$

$$\vec{E}(\text{r}) = \frac{1}{jw\epsilon\mu}[\kappa^2\vec{A} + \nabla(\nabla\cdot\overrightarrow{A})] \quad ...(2)$$

Where $\sigma(r)$ a current density of antenna

$\vec{A}$ is the magnetic vector potential.

$\vec{E}$(r) is the electric field with the function of distance r from an antenna.

$\kappa^2\vec{A}$ is an electric field in the far-field region.

$\nabla(\nabla\cdot\overrightarrow{A})$ is an electric field in the near field region.

From equation (2) magnetic vector potential follows the spatial variation of current distribution (J).

Table 2 — SAR and Input Power of all designed antennas.

Antennas	Max SAR for 1gram	Max input power (mW) C95.1-1999(1g-avg)
1st designed antenna	964.1	1.65
2nd designed antenna	881.6	1.81
Final proposed antenna at Upper ISM Band (2.43 GHz)	856.3	1.87
Final proposed antenna at Lower ISM Band (0.95 GHz)	1007.7	1.58

Slope discontinuity of magnetic vector potential is caused by double derivative

(2) which increases the value of an electric field and hence SAR increases. SAR will be increased if an electric field is high, but this value can be reduced by having uniform current distribution along the antenna surfaces and the electric field in the near region from the antenna dominates and absorbs power. This parameter is the most important concern for patient safety. All designed antennas are having an acceptable range of SAR as demonstrated in Fig. 5.

For 1 mW input power of transmitting antenna, the maximum value of SAR would be 1600 instead of 1.6. The SAR of designed antennas with their input transmitting power is listed in Table 2. The 1st

Table 3 — Comparison Table of Proposed Antennas with Recent Research Published Work.

Ref	fr (GHz)	Volume (mm3)	Gain (dBi)	Bandwidth%	SAR (1gram)	Ground slot	Via
[9]	0.402, 0.915, 2.45	52.5	-40, -32, -22	15, 9.9, 4.2	665, 837, 759	Yes	Yes
[10]	0.92	486.4	-	11	-	No	Yes
[11]	2.46	127	-20.4	10.2	213	No	No
[12]	0.402, 2.4	642.62	-36, -27	7.4, 6.6	832, 690	No	Yes
[13]	0.402, 2.45	179.02	-30, -22	23, 21.3	-	Yes	Yes
[14]	0.915, 2.45	24	-28, -22	9.8, 8.5	971, 807	No	No
[15]	2.45	80.01	-23.1	12.8	-	Yes	Yes
[16]	2.45	91.9	-20.3	18.3	649	Yes	Yes
Final proposed antenna	0.93, 2.43	12	-21.65, -28.28	7.7, 5.5	1007.7, 856.3	No	Yes

designed antenna depicts an acceptable range of 964.1 W/KG SAR as represented in Fig. 5(a). However, due to this, transmitting power of 1st designed antenna reduces to 1.65 mW. The 2nd designed antenna has shown SAR value of 881.6 W/KG as observed from Fig. 5(b) which is lesser than the previous one. Later, for final proposed antenna, the SAR has been enhanced up to a great extent as shown in Fig. 5(c), and this proposed antenna is increased to 1.87 mW at 2.43 GHz and 1.58 mW at 0.95 GHz. The above results reaffirm the higher transmitting power, which ensures the reliability of the communication link of an implantable antenna.

At this point, it is required to compare different performance parameters of the proposed antenna design with recent works as tabulated in Table 3. It is observed that the proposed work provides the least volume of antenna which is quite significant for biomedical implantable devices, and the proposed antenna has dual ISM bands. One band can be used to transmit data during telemetry sessions and the other band can recharge the device’s battery inside the human body wirelessly. The proposed antenna is also having a reduced value of SAR which ensures patient safety and reliable communication link.

5 Conclusion

A highly compact Zig-Zag-shaped implantable antenna is simulated and analyzed for biomedical application. The design shows great compactness in the size of the antenna (12 mm^3) and exhibits dual ISM bands for biomedical devices. Also, in the odd environment of the human body where absorption always degrades antenna performance, the proposed antenna has a low value of SAR (856.3) and good directive gain (-28.68 dBi) at a 2.43 GHz resonating frequency. The proposed antenna performance like reflection coefficient, gain, impedance bandwidth, SAR value, dual ISM bands have been enhanced using sorting Pin and slots technologies on the patch surface. To validate proposed antenna results, skin mimicking gel is also prepared at 2.43 GHz frequency. Proposed antenna is fabricated in microwave lab and successfully tested in skin mimicking gel solution (vitro model). With best of our knowledge, the proposed fabricated antenna has least volume among latest related research work. Good agreement between simulated and measured results has been achieved.

6 Future scope

For the future aspect, proposed antenna can be transformed to circular polarised antenna along with improved directive gain. The rectenna system can also be designed for wireless charging of embedded battery in BMDs.

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