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Design of Enhanced Skin-Implantable Patch Antenna for Wireless Biomedical Applications

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Abstract: - In this paper presents a miniaturized patch antenna designed for skin implantation in the industrial, scientific, and medical (ISM) band (2.40-2.50 GHz). The finite element method using HFSS simulation software was used for simulation purposes. In a homogeneous skin phantom, the proposed antenna achieved a reflection coefficient (S11) of -70.021 dB and a corresponding peak gain of -19.16 dBi at the resonating frequency of 2.418 GHz. The antenna demonstrated a frequency band of 501 MHz (2.252-2.753 GHz) and a percentage bandwidth of 20.1%. Additionally, the calculated maximum specific absorption rate (SAR) met the safety standards outlined by IEEE C95.1-1999 and C95.1-2005. Compared to other designed antennas, the proposed antenna exhibited lower SAR values, higher gain, and improved scattering parameters (S11). To ensure the safety of human tissue, the allowable input power was also calculated. These results indicate that the proposed antenna is suitable for implantable applications.

Keywords: Implantable antenna, ISM band, Defected ground structure (DGS), and specific absorption rate (SAR).

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1. Introduction

With the world's population continuously expanding, biotelemetry has emerged as a crucial tool for monitoring human health. To achieve precise monitoring and effective treatment, biomedical devices known as implantable medical devices (IMDs) are now being inserted into the human body[1]. These devices are capable of collecting real-time data and wirelessly communicating with external devices. Implantable patch antennas are frequently used with IMDs to facilitate wireless communication and transmit real-time data to receiving antennas outside the body. Link budget analysis can determine the distance between the implantable antenna and the external receiving antenna. Far-field radio frequency (RF)[2] wave telemetry, which offers high data rates and long-distance communication, is an especially advantageous method of communication from implantable antennas[3]. The design of implantable antennas presents unique challenges that set it apart from the design of free-space antennas[4]. This is due to the presence of lossy human tissue surrounding the implantable antenna, which can greatly affect the antenna's parameters. As a result, designing implantable patch antennas requires careful consideration and specialized expertise to overcome these challenges [5].

- High efficiency
- Stable radiation pattern
- Low Specific absorption rate(SAR)

Implantable patch antennas play a crucial role in collecting patient data by communicating with external antennas of a base station. During surgical procedures, it can be challenging to position the implantable patch antenna at the perfect angle with respect to the receiving antenna, making it important to have a stable radiation pattern. A stable radiation pattern ensures consistent and reliable communication between the implantable antenna and the external device, regardless of the orientation of the transmitting and receiving antennas. This is crucial to ensure that accurate patient data is collected without interference or loss of data due to variations in the angle or position of the implantable antenna.

The Specific Absorption Rate (SAR)[6] is a measure of the energy absorbed by human tissue from electromagnetic waves, and high SAR levels can pose a risk to the body. As a result, it is crucial to maintain low SAR levels during the design of implantable antennas. However, achieving effective communication between the implantable antenna and the external device is equally important, especially in medical applications, where high gain is essential. Therefore, when designing implantable antennas, it is necessary to balance the trade-off between minimizing SAR and maximizing gain to ensure optimal performance while minimizing any potential harm to the human body.
Implantable Medical Devices (IMDs) operate on different frequency bands depending on the standards they comply with. The two most commonly used bands are the Medical Implant Communication Services (MICS) band ranging from 402-405 MHz and the Industrial, Scientific, and Medical (ISM) band ranging from 2.40-2.50 GHz. Several studies, such as [4]-[8], offer detailed guidance on overcoming design challenges and testing implantable antennas.

Since IMDs require batteries for operation, they need to be replaced periodically, and there is a risk of infection during surgery. To address these issues, researchers are now designing implantable systems that use two frequency bands simultaneously. One band is used for wakeup purposes, while the other is used during sleep mode to conserve battery power.

In this paper an inset line feed implantable patch antenna is proposed with improved specific absorption rate , S11 parameter, frequency band and defected ground structure (DGS) [9]-[10]

2. Methodology

Keeping different implantation scenarios in mind a small, efficient patch antenna has been designed for skin implantation in the ISM band (2.418 GHz) which is capable of transmitting and receiving signals with high performance

A. Proposed Antenna Design

The proposed antenna design is illustrated in Figure 1 and is intended for use in an environment surrounded by human tissue. To accommodate this, both the substrate and superstrate layers of the antenna are made of Rogers6010 material with a height (h) of 0.635mm, which has a relative dielectric constant (Sr) of 10.2 and a tangent loss of 0.0023 [6].The radiating patch of the antenna is a rectangular-shaped coil that has been shifted to a lower frequency band to achieve resonance at 2.723 GHz [11]. To increase the surface current path, four rectangular strips have been added at specific positions on the coil. A fork-like shape with five prongs has been added to the underside of the coil to further increase surface current distribution, which results in resonance at the ISM band (2.418GHz). The addition of a pair of rectangular elements on either side of the fork handle stabilizes the radiation pattern.To further improve the antenna's performance, a rectangular strip has been introduced above the fork. This has increased the S11 to (-31dB). Connecting the coil to an outer ring with a 0.07mm strip has increased the S11 to (-70.021 dB). The Defected Ground Structure (DGS) has been incorporated into the design, which has increased the bandwidth and reduced the Specific Absorption Rate (SAR) value to half that of the existing antenna.The proposed antenna has a total volume of 101.6mm3, with dimensions of 10×8×1.270mm3. Overall, the modifications made to the patch shape, dimensions, and geometry have resulted in a more efficient antenna design with improved performance characteristics.

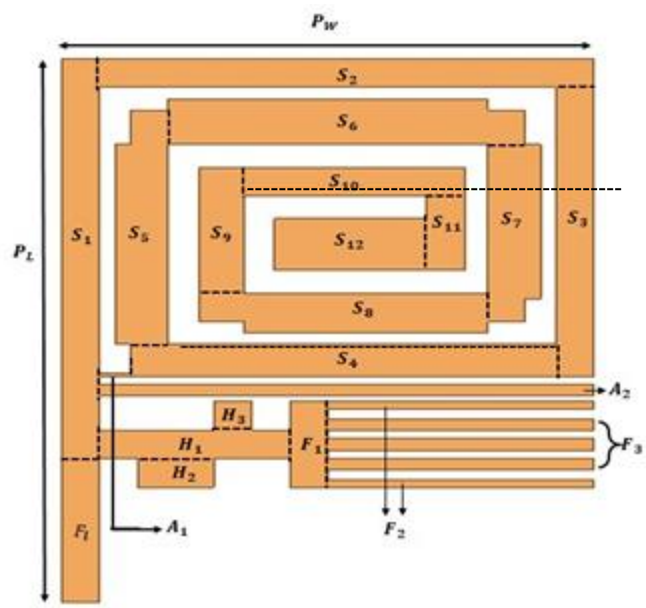

Figure 1(a) Geometry of proposed antenna: Top

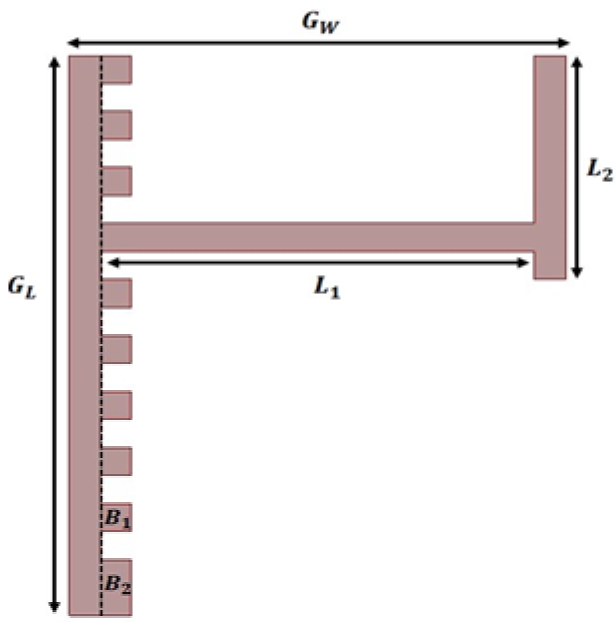

Figure 1(b) Geometry of proposed antenna: bottom

Figure 1(c) Geometry of proposed antenna: Side

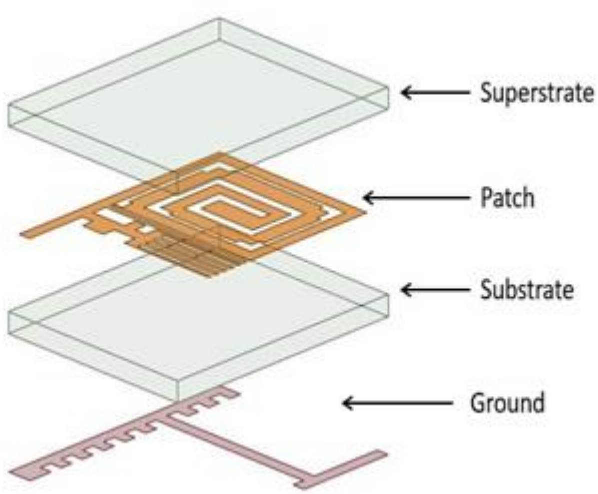

Figure 1(d) Geometry of proposed antenna: layered View

TABLE 1. OPTIMISED DIMENSION OF PROPOSED ANTENN

Parameter	Length (mm)	Width (mm)	Parameter	Length (mm)	Width (mm)
S_1	9.5	0.5	H_3	0.5	0.5
S_2	7.0	0.5	A_1	6.5	0.07
S_3	5.5	0.5	A_2	6.5	0.5
S_4	6.1	0.5	F_1	1.5	0.5
S_5	4.6	0.6	F_2	3.5	0.125
S_6	5.2	0.5	F_3	3.5	0.2
S_7	3.7	0.5	P	P_L=10	P_W=8
S_8	4.3	0.6	F_l	2.5	0.5
S_9	2.7	0.5	G	G_L=10	G_W=8
S_{10}	3.4	0.5	L_1	7.0	0.5
S_{11}	1.8	0.5	L_2	4.0	0.5
S_{12}	2.4	0.5	B_1	0.5	0.5
H_1	2.5	0.5	B_2	1.0	0.5
H_2	1.0	0.5			

Simulation Setup

Proposed antenna was designed, simulated and analyzed using finite element method in an soft high frequency structure simulator (HFSS) software [7]. A three layer heterogeneous human tissue box model which contains skin, fat and muscle is realized of dimension 40×40×49mm3 in HFSS. The frequency depended electrical properties of skin (Sr= 38, σ =1.44S/m),fat (Sr= 5.28, σ =0.11S/m) and muscle (Sr=52.73,σ=1.74S/m) respectively in ISM band (2.4GHz) is taken from [12] and antenna is simulated at 7.73mm depth value in tissue box model which surrounded by radiation box.

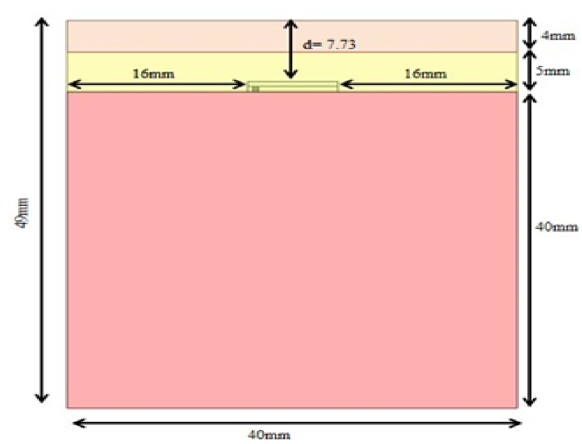

Figure 2 (a) Three layered cubic skin model

Methods are used to determine a feature's importance. Several machine learning classifiers are utilised for classification, and an ensemble of different techniques is employed to improve the model's performance.

3. Simulated Results and Discussion

This section contains simulation results of proposed antenna place 7.73mm deep in heterogeneous human tissue box model. Fig.3 represents reflection coefficient (S11) and frequency graph of proposed antenna. From fig.3 it is observed that proposed antenna works in frequency range from 2.252-2.753GHz and reflection coefficient S11 equals to -70.023dB at 2.418GHz frequency which covers the ISM band.

The fig.4(a) represents far field gain radiation pattern and surface current density at 2.418 GHz frequency respectively, Implantable patch antennas are small and unobtrusive, making them ideal for implantation in or on the human body. However, due to their small size and the surrounding lossy human skin tissue, they typically exhibit low gain. The gain of an antenna is a measure of its ability to radiate electromagnetic energy in a particular direction. Larger antennas have higher gain than smaller antennas. Implantable patch antennas have small radiating elements, which limits their ability to generate a strong electromagnetic field.

However, by changing width of the three center prongs of the fork in the radiating patch, the proposed antenna achieves a stable far-field gain radiation pattern in both the E-plane and H-plane. By introducing a pair of rectangular element in either sides of the fork handle the stable radiation pattern observed. This design results in a peak gain of -19.16 dBi at a frequency of 2.418 GHz. Despite the low gain, the surface current density (shown in Fig. 4 (b)) is quite high at the resonant frequency of 2.418 GHz.

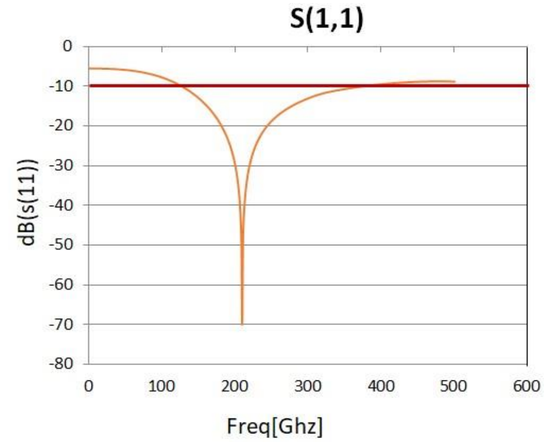

Figure 3 The reflection coefficient (S_{11}) of proposed antenna

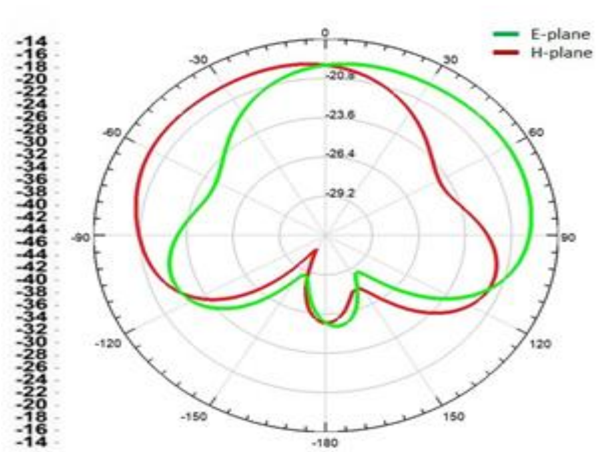

Figure 4(a)

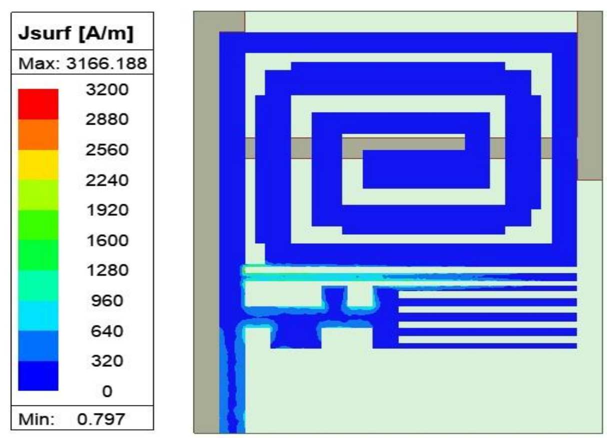

Figure 4(b)

The fig.5 represents the average SAR distribution for 1 gram tissue at 2.418 GHz frequency. To ensure the safety of human skin when using a proposed antenna, it is necessary to conduct a SAR study and determine the maximum allowable input power. This study will evaluate the amount of electromagnetic energy absorbed by the human body, specifically the skin, and ensure that it does not exceed the safe limits.By conducting this study, we can ensure that the proposed antenna operates within safe parameters and does not pose a risk to human health.

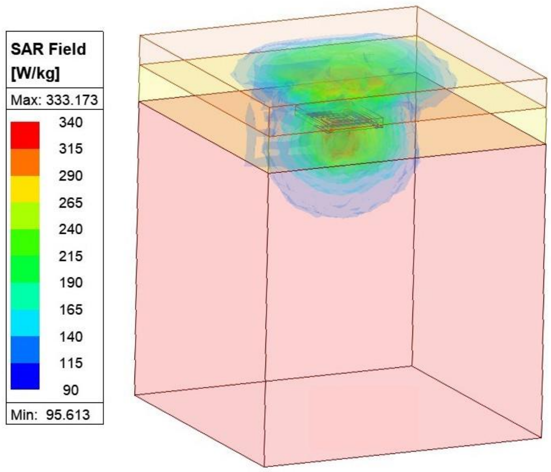

Figure 5. The average SAR distribution for 1gram tissue at 2.418GHz frequency

The IEEE has established specific limits for the specific absorption rate (SAR) for implantable patch antennas. These limits are set at 1.6 and 2 W/kg for tissues weighing 1 gram and 10 grams, respectively. In our proposed antenna, with a transmitter power of 1 watt, the average SAR values calculated are 333.17and 61.19 W/kg for 1 gram and 10 gram tissues, respectively. To ensure safety, we have calculated the maximum transmitter power (input power) allowed for tissues weighing 1 gram and 10 grams at 2.418 GHz, as shown in Table 2. These calculated transmitter powers are significantly greater than the required transmitter power of 20µW. Thus, the SAR value is not a concern for our proposed antenna.

Table 2.Maximum SAR Values And Maximum Allowable Input Power

Frequency (GHz)	**IEEE Standard**	**Maximum SAR(W/kg)**	**Maximum input power[Mw]**
2.45	C95.1-1999 [13]	1g-avg 333.17	1.95
2.45	C95.1-2005 [14]	10g-avg 61.19	32.154

Table 3 Comparison of Proposed Antenna with Other Existing Antenna

Ref.	Frequency (GHz)	Volume (mm)3	Gain (dBi)	S_{11} (dB)	Band width (%)	SAR (W/kg) For 1g and 10g tissue
[1]	2.455	127	-16.2	-34.85	23.21	621.97 63.0
[2]	2.450	24	-22.8	-30.25	8.57	807.34 102.04
[3]	2.46	127	-22.0	-25.24	7.7	213.0 26.6
[4]	2.450	31.5	-21.2	-18.23	8.6	491.9 59.0
This work	2.418	101.6	-19.16	-70.02	20.1	333.17 61.19

4. Conclusion

This paper introduces a new skin-implantable patch antenna that operates at a frequency of 2.418 GHz within the ISM band. The proposed antenna has an impressive impedance bandwidth of 20.1% and exhibits excellent reflection coefficient (S11) of -70.023 dB at a frequency of 2.418 GHz. Moreover, the antenna shows stable radiation patterns and high far-field peak gain of -19.16 dBi at 2.418 GHz. In addition, SAR values have been calculated using various IEEE standards to ensure safety. It is worth noting that the proposed antenna has low SAR with improved gain and frequency band, making it suitable for biomedical applications. Furthermore, the maximum allowable input power of the proposed implantable antenna was calculated, and it was found to be much greater than the required transmitter power of 20µW.To further enhance the performance of the proposed antenna, future work could include conducting link budget calculations.

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