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Compact Power-Symbol Shaped Microstrip Antenna for Healthcare Monitoring Systems

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Abstract: In this study, a microstrip patch antenna is presented to be used in biomedical systems and applications, that has an operating frequency covering the Industrial Scientific and Medical (ISM) band (2.4-2.5 GHz). The size of the proposed implantable medical antenna is 28 mm×28 mm×0.69 mm, where Rogers RO3210 material with a thickness of 0.62 mm has been used as a substrate. The antenna is analyzed under planar and bent conditions inside a three-layer of human tissue (skin, fat and muscle); where the simulations are carried out with the help of CST MWS software program. Finally, the Specific Absorption Rate (SAR) values are assessed to check the amount of harmful electromagnetic fields absorbed by the human body. In the light of all these mentioned data and results, it has been concluded that the proposed antenna design is suitable for use in healthcare applications.

Keywords: implementable antenna, industrial scientific and medical (ISM) band, microstrip antenna, specific absorption rate (SAR)

Sağlık Hizmetleri İzleme Sistemleri için Kompakt Güç Sembolü Şekilli Mikroşerit Anten

Öz: Bu çalışmada, Sınai, Bilimsel ve Tıbbi cihaz (SBT) bandını (2.4-2.5 GHz) kapsayan bir çalışma frekansına sahip, biyomedikal sistem ve uygulamalarda kullanılmak üzere geliştirilmiş bir mikroşerit yama anten sunulmuştur. Önerilen implant edilebilir tıbbi antenin boyutu 28 mm×28 mm×0.69 mm olup, alt katman olarak 0,62 mm kalınlığında Rogers RO3210 malzemesi kullanılmıştır. Anten, üç katmanlı bir insan dokusu (deri, yağ ve kas) içinde düzlemsel ve bükülmüş koşullar altında analiz edilir ve ilgili simülasyonlar CST MWS yazılım programı yardımıyla gerçekleştirilir. Son olarak, insan vücudu tarafından emilen zararlı elektromanyetik alanların miktarını kontrol etmek için Özgül Soğurma Oranı (ÖSO) değerleri değerlendirilir. Tüm bu bahsi geçen veriler ve sonuçlar ışığında, önerilen anten tasarımının sağlık hizmeti uygulamalarında kullanılmak için elverişli olduğu sonucuna ulaşılmıştır.

Anahtar Kelimeler: implant edilebilir anten, mikroşerit anten, özgül soğurma oranı, sınai bilimsel ve tıbbi cihaz bandı

1. Introduction

Different Radio Frequency (RF) systems and designs are developed for biomedical applications in recent years [1]. Bio-implantable antenna studies are the core of these RF systems and they have an increasing popularity in the last decade. This is because it provides great convenience and benefit in deciding on diagnosis and treatment methods. These implanted antennas, which transmit the data

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measured by various sensors, are placed inside the human body and extend the life of many patients. Moreover, implantable antennas can also be used for applications such as diagnostics, monitoring applications, temperature, and blood pressure measurements [2].

In an ordinary case, a patient's condition is examined by many repeated tests depending on his/her disease. Similarly, the patient might need to see a doctor at frequent intervals. Such situations bring additional physical and psychological difficulties to the patient. The usage of implanted antennas with in-body sensors help to prevent that. This can be done by connecting medical implants to telephone system or internet by using compatible antennas to communicate and transmit data to responsible people. There are a few frequency bands used in antenna designs to ensure those aforementioned wireless communications. These frequency bands are determined by the European Telecommunications Standards Institute (ETSI) [3], the most commonly used bands for medical purposes are Medical Implant Communication System (MICS) (402-405 MHz) and Industrial Scientific and Medical (ISM) bands (2400-2500 MHz). 0.4331-0.4348 GHz, 0.868-0.8686 GHz and 0.9028-0.928 GHz frequency bands are also defined for the ISM band by ETSI [4].

The hard task in the antenna design process is to design a broadband antenna [5,6]. Previously reported biocompatible antennas were implanted inside human body to be used for medical applications, and they were characterized by using different numerical methodologies [7-10]. The literature review shows that it is impractical to use antennas operating at 402-405 MHz MICS band without miniaturization; since these antennas are approximately seven times larger in size than the ones operating at ISM band [11]. In [12], a MICS band implanted antenna was presented that has a bandwidth of 36 MHz and a size of 25 mm×18 mm. A maximum bandwidth of 225 MHz was achieved in [13], where the total dimension of the reported antenna was 17 mm×17 mm×18 mm. A tri-band antenna that operates in both MICS and ISM bands was reported in [14]. The presented antenna had a narrow bandwidth of 113 MHz and 70 MHz in MICS and ISM band, respectively. Unlike in-body antennas, a wearable antenna for body area network purpose was designed in [15] with high gain and small size by placing a highly truncated metasurface underneath the planar monopole. In [16], a spiral planar inverted-F antenna (PIFA) was designed by using a superstrate material to protect the implanted antenna from short-circuiting. This antenna had also a narrow bandwidth and a total size of 32 mm×24 mm×8 mm. It is important to emphasize that by designing an antenna that operates at ISM band, in other words, by selecting a higher resonance frequency, the antenna size can easily be reduced and the operating bandwidth can be improved. Moreover, it is also possible to provide higher bit rate with large bandwidth, which provides a significant benefit for antenna performance [17].

Satisfactory results were obtained in the above-mentioned studies; however, in these studies either the operating bandwidth was narrow, the antenna size was large, the reflection coefficient (S_{11}) value at the resonance frequency was high, or the gain value was low. Our aim in this study is to design a wide band, small size implantable antenna for biomedical observations. For that reason, a microstrip patch antenna is designed and analyzed when it is implanted inside a three-layered human tissue (skin, fat, and muscle) at 2.45 GHz frequency (ISM band). The substrate thickness of the antenna is selected as 0.62 mm and Rogers RO3210 dielectric material is preferred. This is a biocompatible material and suitable for many millimeter wave applications. Furthermore, the total dimension of the designed antenna is 28 mm×28 mm×0.69 mm. The study is organized as follows: the detailed interpretation of the antenna design is made in Section 2, where the effect of some design parameters of antenna are also performed. The characteristic performance of the presented antenna is analyzed with respect to the simulation results in Section 3. Finally, in Section 4, the pros and cons of the study are summarized.

2. Antenna Design

The proposed antenna resembles the power-on symbol. As seen in Figure 1, the blue parts indicate copper, which has a thickness of 0.035 mm, whereas the grey parts represent the substrate material. Nested circular shaped patch elements are used for radiation. The feeding line, that has an impedance of 50 Ohms, is directly connected to the inner ring on the top part of the antenna. Moreover, the circular gaps between each nested copper rings have a thickness of 1 mm. The thickness of circular gaps is selected as 1 mm; because only with this value, the antenna has a resonance frequency at the desired 2.5 GHz and moreover, a good impedance matching is achieved, which results to have a reflection coefficient value of -41.53 dB at 2.5 GHz. The antenna is designed with Rogers RO3210 (σ = 0.0027 (S/m), ε_r = 10.8), a substrate material with a thickness of 0.62 mm. An increase in relative permittivity decreases the effective wavelength of the antenna and causes a reduction in resonance frequency. Last but not least, the distance between the upper edge of the ground plane and center of the inner ring patch is taken as 2 mm.

The radius value of each nested circle and the optimum dimensions of the microstrip antenna are shared in Table 1, where L indicates the length of the substrate and W indicates the width of the substrate. The proposed antenna is also compact in size with total dimension of 28 mm×28 mm×0.69 mm (231.5λ×231.5λ×5.12λ, where λ is the wavelength at the lowest operating frequency).

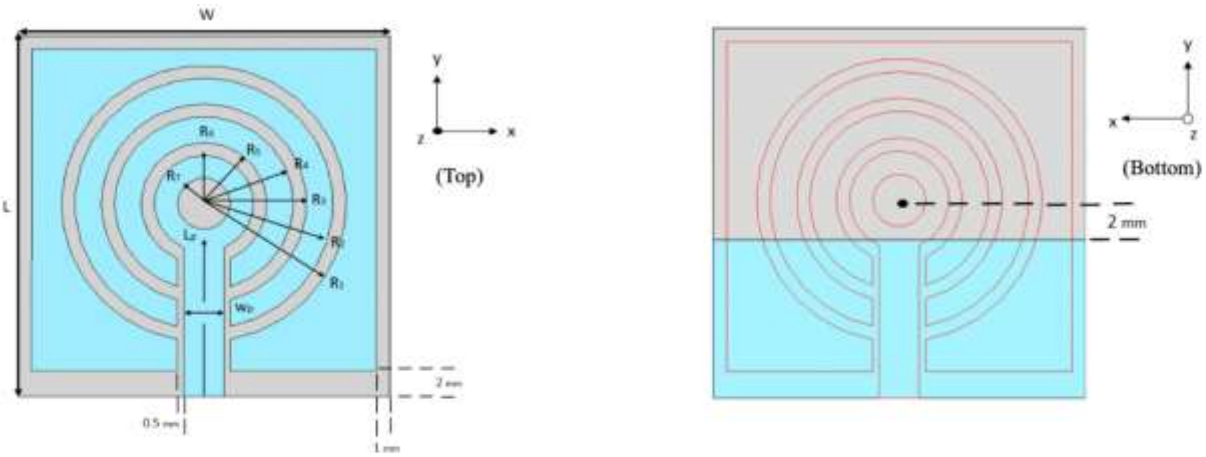

Figure 1. The top and bottom side view of the antenna element.

Table 1. Antenna geometry parameters.

Parameter	W	L	W_p	L_p	R_1	R_2
Size (*mm*)	28	28	3	14	10.7	9.7
Parameter	R_3	R_4	R_5	R_6	R_7	
Size (*mm*)	7.7	6.7	4.7	3.7	2	

The effect of variation in some antenna dimensions are analyzed in the following paragraphs, where the simulations of the reported antenna are performed by using CST Microwave Studio. First, a comparison is made to observe the effect of substrate thickness on reflection coefficient (S_{11}). Rogers RO3210 material is available in the market with 0.62 mm and 1.24 mm thicknesses; and Figure 2 shows the effect of these thicknesses on S_{11} plot. It is also important to emphasize that the feeding line width is specifically determined to obtain the best impedance matching for both 0.62 mm and 1.24 mm substrate thicknesses. Moreover, the width of feeding line is determined as 1.1 mm to achieve the impedance matching for 1.24 mm substrate thickness. The proposed miniature antenna has been shown to be consistent and has a desired resonance at 2.5 GHz, when it is designed with a thickness of 0.62 mm.

Another parametric study is executed for the length of the ground plane. To make this analysis, the distance between the upper edge of the ground plane and center of the inner ring radiator is revised. The measurements are made once the aforementioned distance is varied as 1, 2 and 3 mm. Figure 3 depicts the reflection coefficient curves for each value. As seen from the graph, the best impedance matching is obtained with the 2 mm value, which is plotted with the green color. This examination proves that ground plane has a major impact in impedance matching, and adjusts the input impedance and operating bandwidth [18].

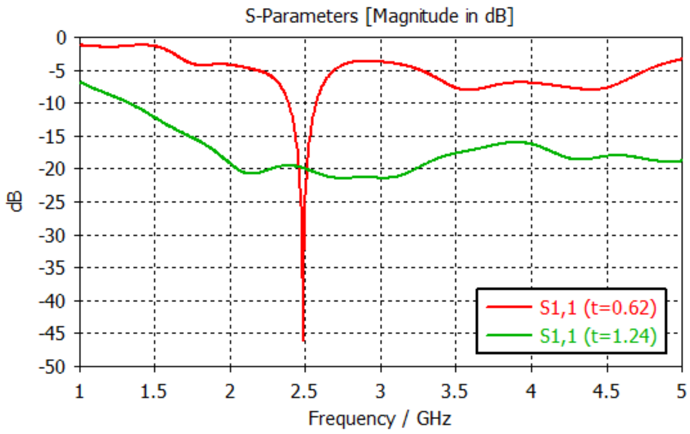

Figure 2. Simulated reflection coefficient for different substrate thickness.

The operating bandwidth of the antenna has been shown to be largely dependent on the substrate thickness due to the impedance matching [19]. It is observed that with the assigned values in Table 1 for substrate thickness and length of the ground plane, the proposed antenna successfully covers the whole ISM band.

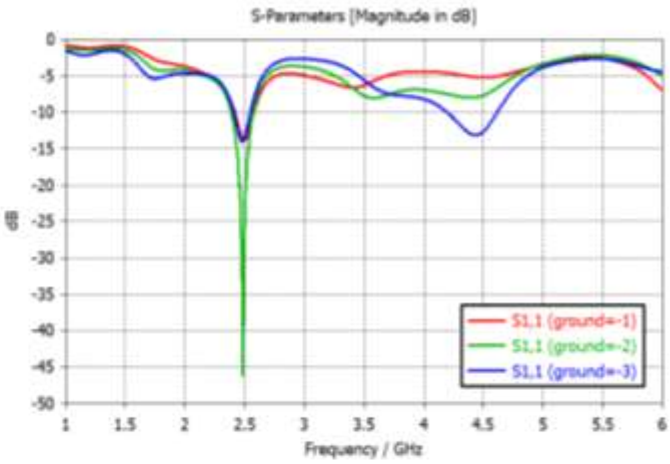

Figure 3. Reflection coefficient simulated with different values for the ground parameter.

3. Numerical Results

Some antenna parameters are analyzed for the proposed antenna under this title of the manuscript. In medical applications to model practical use in real life, antenna simulations are performed when placed in three-layer human tissue. The thickness of skin, fat and muscle used for that purpose are 4 mm, 4 mm, 8 mm, respectively. The details of tissue properties at 2.45 GHz are detailed in Table 2 [20]. Figure 4 presents the image of the antenna inside human body within the simulation environment. As seen from the figure, the implanted antenna is located at the bottom part of the fat tissue. This is done similarly in real life applications, as it is more practical to position the antenna in fat tissue due to its physical form. Moreover, placing the antenna inside the fat layer also protects the antenna from external factors as there is a certain distance between the body surface and antenna. The planar condition results of the antenna are depicted in Figure 5. In the following paragraphs, the antenna in bent conditions will be examined and a comparison will be made between these two conditions. Results in Figure 5 show that the impedance bandwidth of the proposed antenna is 0.19 GHz, which is from 2.38 GHz to 2.57 GHz. This is determined by calculating the part of the curve that remains below -10 dB of S_{11} value ($S_{11} \leq -10\ dB$). Moreover, the antenna has a resonance frequency of 2.49 GHz, which is just at the desired value. -41.53 dB reflection coefficient value at the resonance frequency shows that convincing impedance matching is provided.

Table 2. Dielectric parameters of human tissues at 2.45 GHz [20].

	Muscle	Fat	Skin
Conductivity (*S/m*)	1.73	0.10	1.46
Permittivity	52.7	5.28	38
Density (kg/m^3)	1060	1100	1100
Thickness *(mm)*	8	4	4

Although return loss (RL) and reflection coefficient are different parameters, they are directly related to each other with $RL = -S_{11}(dB)$ formula, where $S_{11}(dB) = 20\log_{10}|S_{11}|$ indicates reflection coefficient in decibel form. Hence, the S_{11} graph also gives us information about the return loss as well. A high return loss value indicates less reflected power and it also means that a proper impedance matching is provided with high efficiency [21], which is a desired property for many multi-purpose antennas.

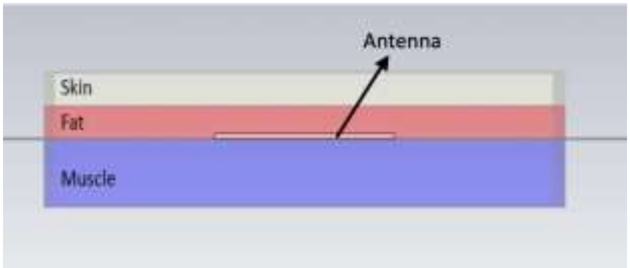

Figure 4. Antenna under planar conditions positioned inside the human tissue model.

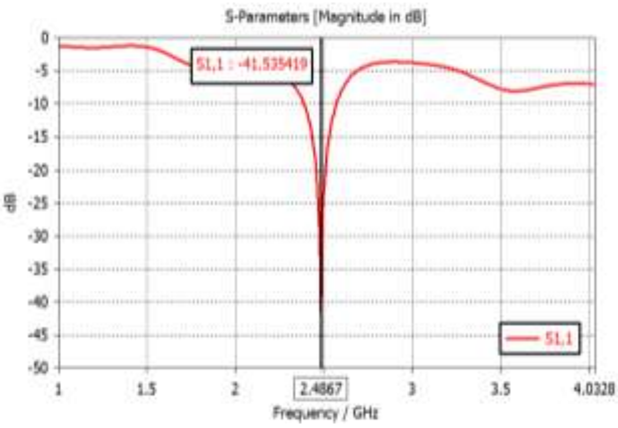

Figure 5. Reflection coefficient of the antenna positioned inside human tissue.

Radiation pattern is the variation of the power radiated by an antenna [22,23]. Figure 6 shows the far field radiation pattern of the presented antenna in polar form. The lobe with the greatest field strength is the main lobe and maximum radiation occurs in the direction of that main lobe. The side and back lobes are smaller than the main lobe in terms of field strength. Figure 6 indicates the *E* and *H*-plane radiation patterns of the proposed antenna. The blue and black curves represent the co and cross-polarization characteristics, respectively. It is observed that the size of the main lobe is 5.97 dBi. Furthermore, the *E*-plane pattern of the antenna exhibits an omnidirectional radiation characteristic at the resonance frequency of 2.48 GHz.

Figure 7 shows the surface current distribution on the antenna. The current distribution for resonance elements is carried out using lossless transmission line analysis, thereby enabling an adequate assessment of the properties of the element close to resonance. The current accumulates intensely in the feedline and from there it is transmitted to the center and outer ring radiating patches. It is observed that the density in these regions has increased.

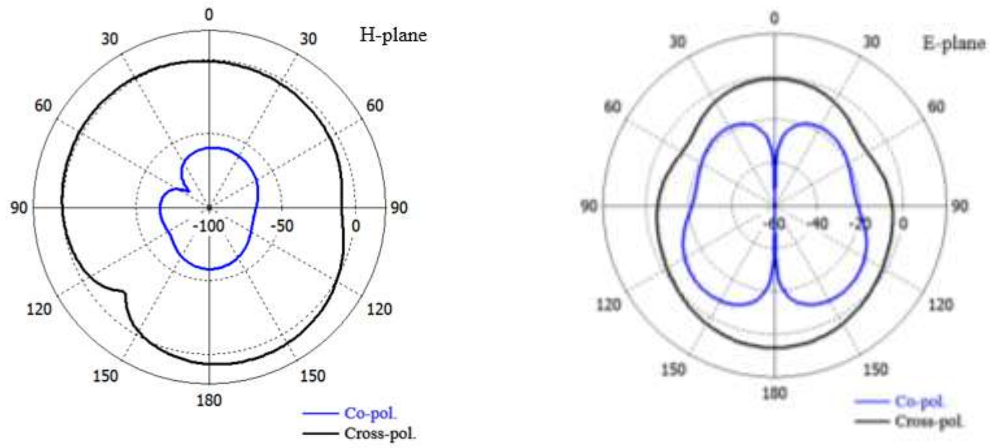

Figure 6. Far-field radiation pattern of the antenna at the resonance frequency for *H*-plane and *E*-plane, respectively.

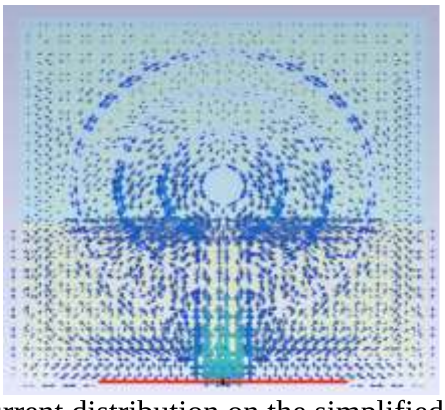

Figure 7. Surface current distribution on the simplified human body model.

SAR indicates the amount of power absorbed by human body from the operating antenna element. In other words, it shows the amount of power absorbed by the tissue mass. The power can be absorbed up to a certain value in terms of patient's health [24]. This value is limited with 1.6 W/kg for 1 g of tissue with 2 mW input power. Figure 8 shows the SAR simulation result of the proposed antenna. It is seen that the value in the center is the highest, since it is the radiating part of the antenna. At the end of this analysis it is observed that the SAR value is within the acceptable range, which means that it would not harm the human body and the tissue.

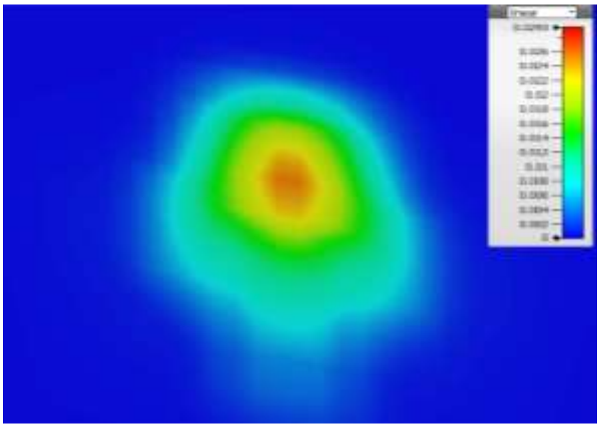

Figure 8. SAR analysis of the proposed antenna.

Human body is not always planar, sometimes it is in curvature shape. Therefore, the performance of the proposed antenna needs to be analyzed in bent conditions as well [25]. As shown in Figure 9, both the antenna and three-layered human body are bent to a certain value. The S-parameter results in bent and planar conditions are obtained separately. Both results are compared in a single graph as also shown in Figure 9. One can say that in both conditions the antennas cover the ISM band. The reflection coefficient of the antenna at the resonance frequency in planar condition is -46.39 dB, whereas the reflection coefficient under bent condition is -31.22 dB. The importance of bending the antenna is to approach the realistic conditions in real life usage as the antenna placed in curved areas of the body should also give acceptable results.

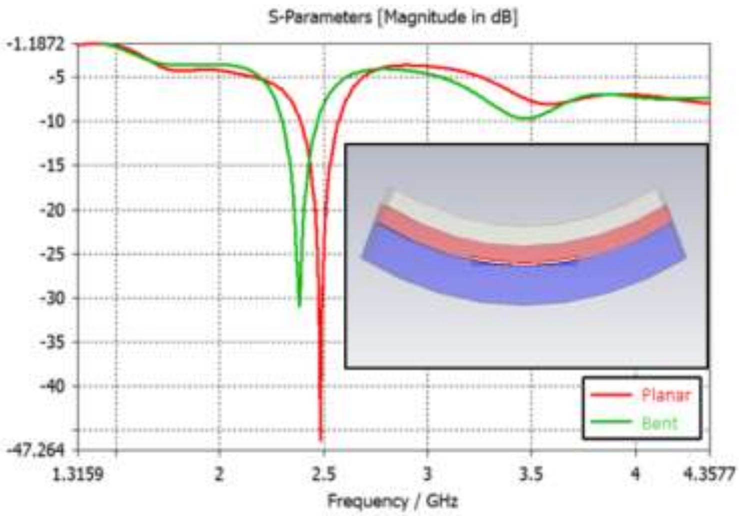

Figure 9. S_{11} curves of both planar antenna and antenna under bent conditions inside three-layer tissue model.

Table 3. Comparison with other in-body antennas in literature.

	Band	**Bandwidth**	S_{11}	**Size**
[3]	ISM	102 MHz	-14 dB	10×10 mm2
[10]	MICS	~130 MHz	-25 dB	22.5×22.5 mm2
[12]	MICS	36 MHz	-11.2 dB	25×18 mm2
[14]	ISM	70 MHz	-28 dB	10×10 mm2
[24]	MICS	100 MHz	-25 dB	14×14 mm2
	ISM	300 MHz	-30 dB	
This work	ISM	190 MHz	-41.53 dB	28×28 mm2

A comparison table is provided in Table 3 to better analyze and compare the radiation characteristic and performance of the proposed antenna. As seen from the table, the presented antenna has the best bandwidth performance except the ISM band of [24]. It also has the lowest S_{11} value at the resonance frequency, which indicates that the best impedance matching is achieved with the proposed antenna design. Even though the reported antenna has a compact size of 28 mm×28 mm, it is the largest in size when compared with the studies in [3,10,12,14,24].

4. Conclusion and Discussion

In this article, implantable microstrip patch antenna in human tissue model is designed and the characteristic of the antenna is presented. The gain value of the proposed implanted antenna is calculated as -19.4 dBi at 2.5 GHz frequency value. Furthermore, the impedance matching is very low at 1 to 2 GHz and 3 to 5 GHz frequency intervals. As a result, low reflection coefficient values are obtained. This is a desired feature, since our purpose in this study is to design an antenna that only operates at ISM band, where $S_{11} \leq -10\ dB$, through the simulated frequency interval. The designed antenna proves to be convenient to be used for biomedical applications with its small size, satisfactory reflection coefficient values in planar and bent conditions. In addition, low SAR value shows that the antenna does not harm tissues, while maintaining the safety of the patients. For future work, it is planned to fabricate the proposed antenna design and perform the in-vivo or in-vitro experimental analyzes to verify the simulation results.

Authors’ Contributions

GEK and TO wrote up the article. The authors read and approved the final manuscript.

Competing Interests

The authors declare that they have no competing interests.

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