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A 9.73 GHz wide-band off-body patch antenna for biomedical applications

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ABSTRACT

The primary goal of this study is to design a simple antenna that has a wide bandwidth and low return loss for biomedical applications. The paper shows the recommended antenna's three-stage modeling, with the goal of assessing every important parameter while a Teflon or polytetrafluoroethylene (PTFE) polymer substrate is used. In order to better comprehend, a comparison with prior studies employing teflon and similar substrate materials is conducted for the proposed patch antenna. The analysis includes the phantom model, evaluating performance criteria such as specific absorption rate (SAR), return loss, bandwidth, and gain values relevant to biomedical applications. The antenna works at two different frequencies: 9.73 and 9.39 GHz, one in free space and another in a skin-cotton layer. The bandwidth of the antenna is 4.067 GHz in free space at the resonance frequency of 9.73 GHz, where the return loss is -62.18 dB. The performance of the proposed antenna in the field of biomedical applications, its underlying reasons, and its impacts are discussed in detail in this study.

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1. INTRODUCTION

The need for patch antennas for biomedical applications has grown recently, with a particular emphasis on exploring the potential of teflon as a substrate material. Wide band patch antennas are required in biomedical applications because wide band antennas can transmit more information than traditional narrowband antennas, which is important for new biomedical devices that require high data rates. High frequency wide band technology is favored for its simplicity, small size, affordability, light weight, ease of use, and fast data transfer. These qualities have made it a widely chosen option [1], [2].

Parameswari and Chitra [3] describe a wide band patch antenna with a hexagonal shape for biomedical applications, which is the detailed overview of the different substrate at different shapes of the patch antenna and its impact on the biomedical devices. A flexible patch antenna, designed for biomedical applications, operates at a frequency of 2.46 GHz when placed in open space. It has a relatively narrow bandwidth of 0.03 GHz, as reported in [4]. Smida *et al.* [5] developed a wearable patch antenna with low loss tangent, which is tested in simulation on the leg, arm, and chest. The antenna demonstrated a maximum gain of 2.5 dB in free space, while the maximum gain observed on the human body is 2.2 dB on the chest. Additionally, the antenna exhibited a high bandwidth of approximately 1.38 GHz and a low reflection coefficient of -30 dB. A circular-shaped patch antenna is developed in [6] with a partial ground, which has a wide range of bandwidth at 11.2 GHz but a comparatively lower gain and efficiency of 1.2 dB and 37.5%, respectively. It is important to maximize the efficiency of the antenna since the human body acts as a medium that absorbs electromagnetic (EM) waves, converting them into heat and energy [7]. Wu *et al.* [8] presented a patch antenna based on teflon for biomedical applications, demonstrating a SAR value of approximately 0.693 W/kg within a body phantom. The antenna exhibited a return loss of -33 dB at an operating frequency of 6.5 GHz. Kumar *et al.* [9] documented a patch antenna utilizing a teflon substrate, delivering a narrow bandwidth characterized by a return loss of -37 dB. While existing studies contribute valuable insights, there remains a gap in comprehensive research focusing on teflon-based patch antennas for biomedical applications. The challenge lies in achieving high bandwidth, low return loss, and minimal SAR. Designing the antenna requires special attention to minimize backward radiation, which can result in harmful effects on human tissues known as specific absorption rate or (SAR) [10]–[13]. Simultaneously, careful consideration must be given to keep the antenna's overall size as compact as possible [14]. This study contributes by presenting a simple three-stage modeling approach that is easy to fabricate to assess key parameters, offering a comparative analysis with previous teflon-based studies, and evaluating the antenna's performance within a phantom model. As the antenna is for biomedical applications, the main objective is to minimize the return loss as much as possible with a high bandwidth and gain while also minimizing the SAR value by using a teflon substrate. The initial step involves designing a wideband patch antenna using a substrate made of teflon or PTFE (polytetrafluoroethylene) polymer. Teflon is an optimal material for the patch antenna's substrate due to its low-loss tangent, which makes it an effective insulator that performs efficiently at high frequencies. Additionally, the ease of processing and capability to shape teflon into intricate forms further enhance its significance in antenna design.

The main significance of this study is to highlight the crucial requirements of patch antennas in advancements in biomedical engineering like medical devices, remote patient monitoring, healthcare systems, and telemedicine. In this article, the process of developing and analyzing the rectangular patch antenna takes place within the CST software environment, where the antenna design is described in step by step and analyzed along with the important parameters. Following that, a model resembling skin-cotton is generated within the CST environment, and the antenna is positioned at a distance from the phantom to assess its performance. The paper is structured as follows: In section 2, the modeling of a patch antenna in cotton-skin phantom is described, while in section 3, the comprehensive result analysis section compares this proposed antenna with previous works. Finally, in section 4, the concluding discussions with future possibilities are given based on the overall study.

2. METHOD

The wideband antenna is created using a teflon substrate, which has a dielectric constant (ε_r) of 2.1. The substrate has a height of 1.5 mm, and when combined with other annealed copper layers, the overall antenna thickness measures 1.57 mm (0.035 mm+1.5 mm+0.035 mm layers). Figure 1 presents the methodology for the design, optimization, and evaluation of the proposed teflon-based wideband patch antenna.

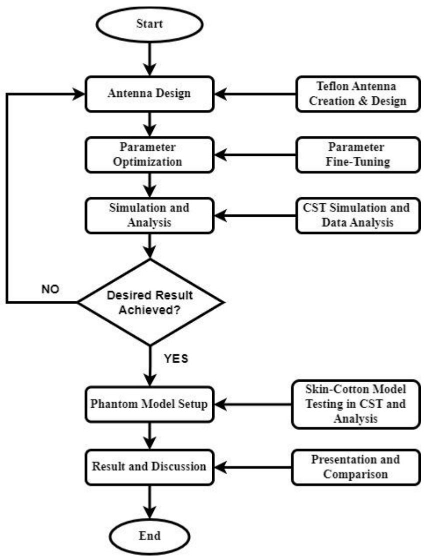

Figure 1. Flowchart of the overall procedure

Figure 2 illustrates the antenna's three stage design for the finalized, suitable configuration. In the initial phase in Figure 2(a) (antenna 1), a standard rectangular patch with partial ground is chosen as the fundamental wideband dimension. In the second phase in Figure 2(b) (antenna 2), the patch is modified by cutting both edges next to the microstrip feeding line. Finally, in the last stage of Figure 2(c) (antenna 3), the middle section of the partial ground is removed to optimize the output performance of this patch antenna. Figure 2(c) depicts the overall view (front and bottom) of the patch antenna. The antenna is fed through a 50 Ω microstrip feed line. This type of feeding mechanism ensures efficient power transfer and impedance matching between the antenna and the transmission line.

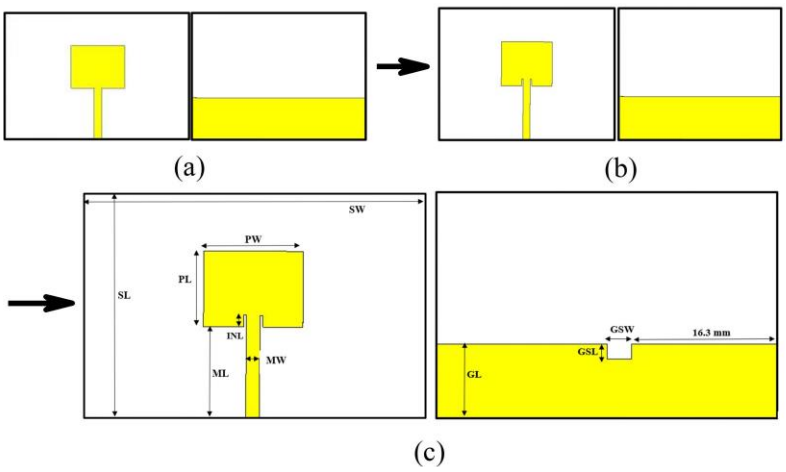

Figure 2. Design at different stages; (a) primary dimension (antenna 1), (b) with cutting patch (antenna 2), and (c) proposed antenna (antenna 3)

Table 1 represents all the antenna parameter values for the best optimized outcome. Table 2 represents the value for the skin-cotton phantom [4]. Figure 3 shows the antenna in the phantom model. The skin cotton model is 20 mm away from the high frequency wideband patch antenna because the antenna port is relatively large so that the signal can penetrate deeper into the phantom.

Table 1. Proposed optimized antenna parameter

Parameters	Length (mm)	Parameters	Length (mm)
SW	38	PW	10.95
SL	25	PL	8.363
MW	1.5	ML	10.2
GL	8.16	GSL	1.6525
InL	1.4	GSW	2.7

Table 2. Phantom model values

Layer	Dimension W×L×H (mm^3)	Permittivity (ε_r)	Conductivity, σ (S/m)
Cotton	38×25×1	1.6	0.04
Skin	38×25×1.5	45	0.27253

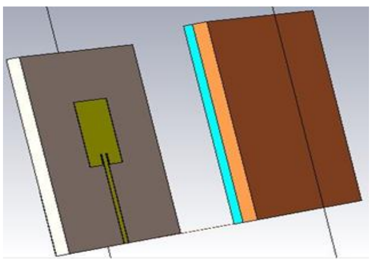

Figure 3. Antenna with the skin-cotton phantom model

3. RESULTS AND DISCUSSION

Figure 4 presents the simulated return loss (S_{11}) for the three previously mentioned antenna stages. Antenna 1 exhibits a return loss of approximately -19.33 dB at the 10.81 GHz resonant frequency, satisfying the required -10 dB criteria. Antenna 2 demonstrates a lower return loss of around -24.124 dB at a slightly lower resonant frequency of 9.99 GHz. Notably, the proposed antenna 3 shows a significant reduction in S_{11}, reaching approximately -62.18 dB at the 9.73 GHz resonant frequency. Additionally, it offers an approximate bandwidth of 4.067 GHz.

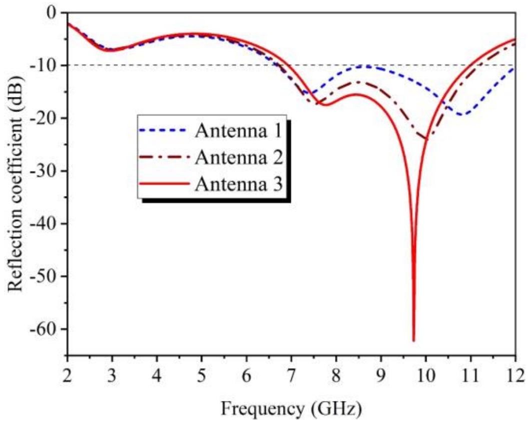

Figure 4. Comparison of S_{11} among three antennas

Figure 5 illustrates the analysis of the simulated voltage standing wave ratio (VSWR) for the three antennas. All three antennas exhibit VSWR values that fall within the acceptable range for biomedical applications. Specifically, antennas 1, 2, and 3 display VSWR values of 1.242, 1.1326, and 1.0015, respectively, at their respective resonance frequencies.

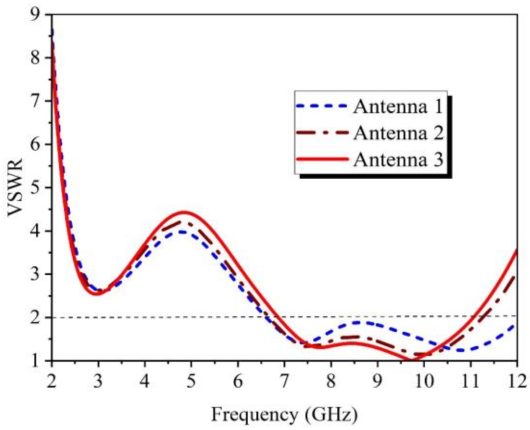

Figure 5. Comparison of VSWR among three antennas

Figure 6 shows the angular distribution of the electromagnetic radiation emitted by the antenna in both 3D view Figures 6(a), 6(c), and 2D view Figure 6(b), 6(d). The antenna operates at its resonance frequency of 9.73 GHz with a directivity of 3.471 dB in free space, where directivity with a skin-cotton phantom is 5.389 dB at 9.39 GHz. The antenna also has a gain value at its resonance of 2.965 dB in free space, while in skin cotton, the gain is 4.528 dB, indicating its ability to strengthen the signal it receives or transmits. Overall, the antenna efficiency is quite good, converting 85.42% (free space) and 84.02% (skin-cotton) of the input power into radiated power at its resonance frequency.

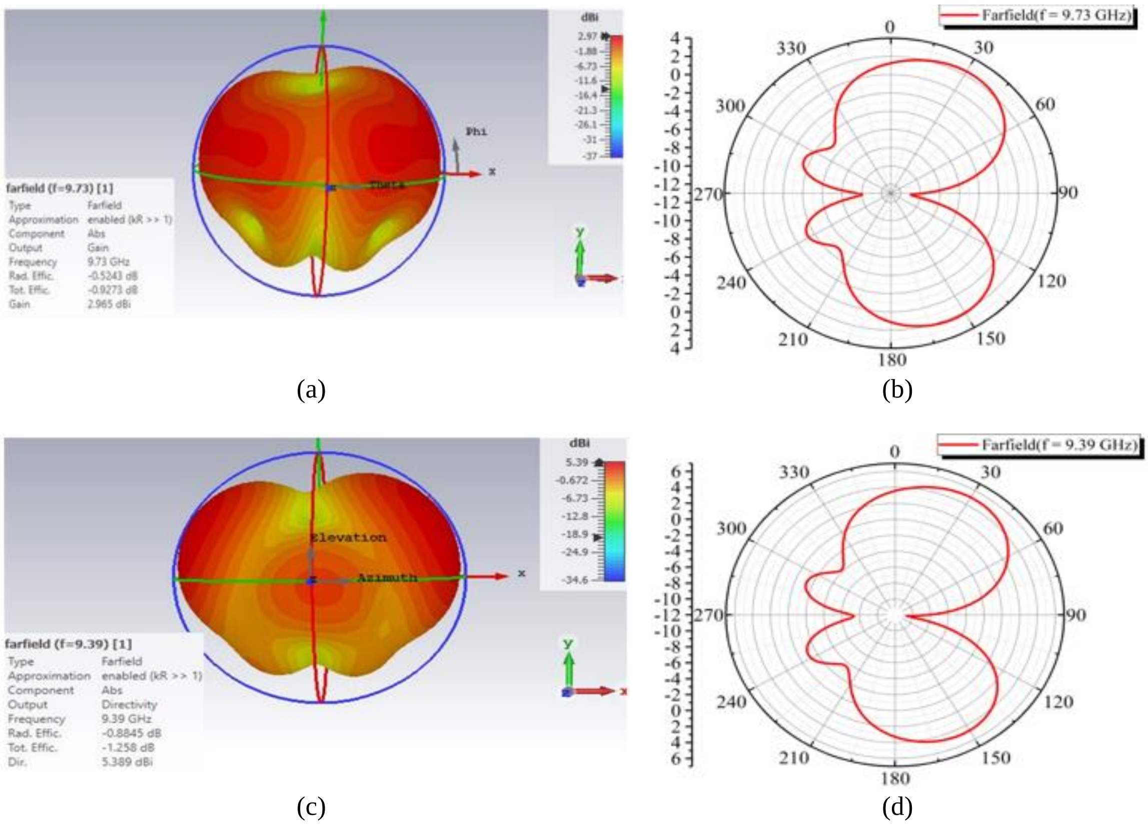

Figure 6. Radiation pattern; (a) 3D in free space, (b) 2D in free space, (c) 3D in phantom, and (d) 2D in phantom

The antenna design is tested using a skin-cotton-based phantom, simulating real-life conditions. The results of the tests indicate that the antenna has the potential for biomedical applications. This is evident from the notable difference in the S_{11} parameter, as shown in Figure 7. The antenna's performance on the phantom suggests its potential usefulness in various biomedical scenarios.

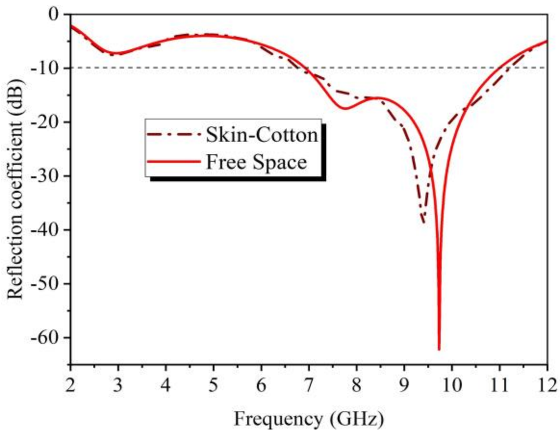

Figure 7. Comparison of S_{11}

The VSWR values obtained for open space and the skin-cotton phantom model are shown in Figure 8. The VSWR value for open space is 1.0015, whereas the value for a skin-cotton phantom is 1.023. Table 3 shows the performance of the antennas in different circumstances. When the antenna is put in a phantom model, the frequency shifts, and the other properties change considerably.

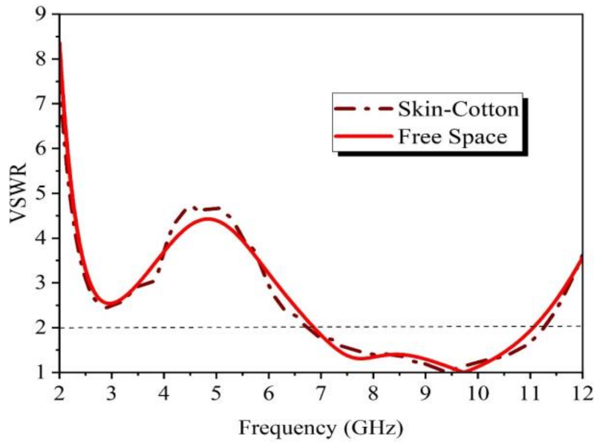

Figure 8. Comparison of VSWR

Table 3. Performance of antenna

Layers	S_{11} (dB)	Operating frequency (GHz)	VSWR	BW (GHz)
Free space	-62.18	9.73	1.0015	4.067
Skin-cotton	-38.88	9.39	1.023	4.4427

Table 4 contrasts the proposed teflon-based patch antenna with others designed for biomedical use, specifically those employing teflon or similar substrates. In this comparison, the antenna stands out with notably lower return loss at the operating frequency. The proposed antenna excels in offering a remarkably low SAR alongside a high bandwidth, setting it apart from other teflon-based antennas in the same context. The gain value of this patch antenna surpasses that of previous antennas presented in other studies, where the values are comparatively lower. Figure 9 depicts the SAR value of the antenna when tested under the skin-cotton phantom model. The federal communications commission (FCC) has set a limit of 1.6 W/kg for the SAR value, which corresponds to 1 gram of human tissue [15]–[18]. During the simulation, the power absorbed is measured to be 0.314469 mW. As a result, the SAR value determined based on the simulation is 0.184233 W/kg for 1 gram of tissue, which is also relatively lower in Table 4. These findings provide valuable information about the antenna's potential impact on human tissue and help ensure compliance with safety regulations. The antenna is built to meet IEEE safety standards for medical applications involving human bodies [19], [20], ensuring it operates safely in close proximity to individuals.

Table 4. Comparison of the antennas

Application on	Substrate material	SAR (1 g) (W/kg)	Free space, S_{11} (dB)	Operating frequency (GHz)	BW (GHz)	Gain at resonance (dB)	Ref.
Skin-cotton (Biomedical)	Kapton polyimide	1	- 20.58	2.46	0.03	NR	Naik *et al.* [4]
Arm-chest-leg (Biomedical)	Rogers 5880	6.02	-30	2.4	1.38	2.50	Smida *et al.* [5]
Skin-fat-muscle (Biomedical)	Teflon	0.693	-33	6.5	2.28	NR	Wu *et al.* [8]
Muscle (Biomedical)	Teflon	NR	-37	2.45	0.08	NR	Kumar *et al.* [9]
Arm-thigh-leg-back (Biomedical)	Rogers 5880	1.58	-20	2.45	0.19	2.06	Arif *et al.* [21]
Biomedical	FR4	NR	-29	8.8	0.70	NR	Parasuraman *et al.* [22]
Biomedical	Teflon	NR	-20	1.89	0.12	1.22	Santhanam and Palavesam [23]
IoT (Biocompatible)	Teflon	NR	-31	7.443	~ 0.4	NR	Khan *et al.* [24]
Skin-fat-muscle (Biomedical)	Rogers 5880	122.7	−24.56	3.3	1.5	-18.5	Jawad *et al.* [25]
Skin-cotton (Biomedical)	Teflon	0.184	-62.18	9.73	4.067	2.965	This work

* NR = Not reported

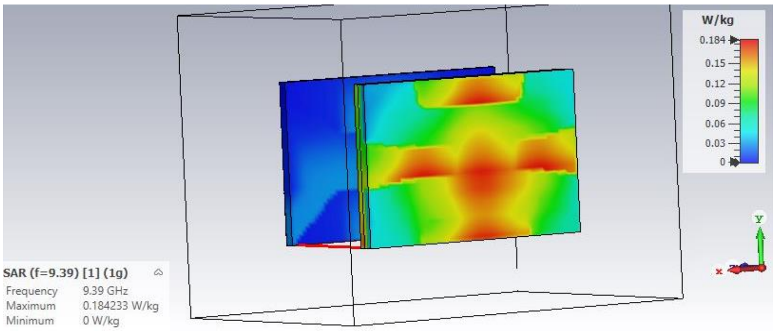

Figure 9. SAR analysis with skin-cotton phantom

4. CONCLUSION

In this study, the enhanced performance of the Teflon-based rectangular patch antenna, highlighted by notably low return loss, moderate gain, a better bandwidth, and a low SAR value, underscores its considerable potential to improve biomedical applications significantly. This improvement promises better signal strength and ensures safety in close proximity to individuals. The proposed antenna proves its efficacy in medical applications through a comparative study with previous antennas, showcasing improvements in all the performance criteria. The results showed that when the antenna is placed in a skin-cotton phantom, there is a difference of approximately -23.3 dB (37.47%) in return loss compared to free space. The shift in frequency by 0.34 GHz (3.49%) indicates the antenna's capability to safely detect suspicious tissues in a human phantom model, supported by its low SAR value. Additionally, the gain, directivity, and antenna efficiency showed some variations. Based on this analysis, it can be inferred that the proposed antenna is well-suited for off-body biomedical applications. In the future, further research can explore the antenna's potential in various biomedical applications, including tumor detection, stone detection, infected lung detection, or its integration with other imaging techniques. Additionally, clinical trials and validations can be conducted to assess the performance and effectiveness of the patch antenna in real-world biomedical applications.

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