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Design and Optimization of a Smart Wearable Antenna for Biomedical Telemetry Applications

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Abstract

The development of a compact, efficient, and multifunctional wearable antenna is specifically designed to support biotelemetry applications such as continuous physiological monitoring, remote diagnostics, and data transmission for medical purposes. The proposed antenna incorporates novel materials and design strategies, including high flexibility, a lightweight structure, and biocompatibility, ensuring comfort and wearability for long-term use. Optimization techniques, such as parameter variation, simulation-driven design, and fabrication considerations, are employed to achieve desirable radiation characteristics, minimal interference with body tissues, and optimal integration with wearable sensors. The antenna's gain, bandwidth, and operating frequency are all designed to minimize power consumption and satisfy the demanding needs of biotelemetry systems. The antenna is crafted from Polyimide Lossy material and has overall dimensions of 40 mm × 30 mm × 0.1 mm. The completed antenna has a 10 dB bandwidth that is centered at 2.4 GHz and functions at that frequency. According to simulation data, it has minimal effects on efficiency, bandwidth, gain, and reflection coefficient.

Keywords: Resonant Frequency, Operational Bandwidth, Compact Size, Computer Simulation Technology, Voltage Standing Wave Ratio, Directivity.

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1. Introduction

The advancement of wireless communication technologies has significantly influenced various sectors, particularly in the field of biomedical telemetry. One of the key components driving this progress is the development of wearable antennas designed to facilitate seamless and continuous monitoring of physiological parameters in healthcare settings. Wideband wearable antennas, specifically tailored for biomedical telemetry applications, have gained support for frequencies, ensuring reliable communication for data transmission from wearable health monitoring devices [1]. The challenge lies in designing antennas that are not only small enough to be incorporated into compact wearable devices but also capable of operating effectively within the frequency bands allocated for medical telemetry. This will explore various methods to achieve miniaturization while maintaining high performance [2]. It focuses on key aspects such as antenna miniaturization, multi-band operation, SAR reduction techniques, and the integration of the antenna into wearable devices. By addressing these challenges, the proposed antenna design aims to enhance user comfort, ensure safety, and support high-performance wireless communication, wearable sensors in healthcare, fitness tracking, and other personal applications [3]. Among the various components that make these devices possible is the facilitation of wireless transmission of health-related data, body temperature, and electrocardiograms (ECGs), from the wearable sensors to remote monitoring systems [4]. In the realm of wireless communications, antennas are crucial. All types of antennas have advantages and uses. One may argue that antennas are the foundation of wireless communication and practically everything else: without them, the modern world would not have been possible [5].

2. Related Works

Wearable antennas are a critical component in these devices, enabling wireless communication between the device and healthcare for telemetry applications. These applications can range from monitoring heart rate and electrocardiogram (ECG) signals to tracking blood glucose levels and respiratory data. To ensure reliable and efficient communication, wearable antennas must meet strict requirements such as compact size, low power consumption, high efficiency, and minimal electromagnetic interference with the human body. The antenna model functions as a resonator and ground plane has been added to the antenna design, implemented by making rectangular slots in the rectangular patch. Both in the body-worn casing and in the open area, the antenna offers exceptional efficiency and gain. The antenna should be effective as itabsorbs electromagnetic waves and converts them into energy and heat. The main consideration inthat designing an antenna is to have minimum backward radiation; by maintaining this we can reduce the damage to human tissue [1]. A rectangular patch antenna that is small enough for biomedical applications has a narrow bandwidth. The frequency range of the intended design is 5.725GHz to 5.825GHz. In this study, a wearable substrate with the necessary small and straightforward structural dimensions is used to build a miniature microstrip patch antenna with a ground. In cases of biological applications such as stroke imaging and breast cancer tumor identification to distinguish between MRI and PET scanners, etc., a tiny microstrip patch antenna is generally preferred. We use CST Studio to design the antenna. The outcomes demonstrate that the antenna design has potential for use in biomedical settings. Flexible materials such as denim, polyesterand neoprene rubber will be used to create the mimicked antenna [2]. For 2.45/3.45 GHz, a wearable antenna with directional performance and precise parameters was introduced. The antenna consists of two substrates printed with the desired dimensions. Wearers can rest easily against the substrate used in this antenna, suchas smart patches or biosensors communicating with hospital equipment [3]. Wearable antenna design in relation to health monitoring systems enables worldwide communications and monitoring. Properties including flexibility, affordability, and data transmission rate need to be considered in order to suit wearable antenna needs [13]. The proposed antenna was found to use PDMS as the substrate material. The rapid evolution of wearable technology has significantly impacted the healthcare sector, enabling real-time health monitoring and providing essential data for early diagnosis and continuous patient care [4]. Antennas are better suited for most biological applications, including breast cancer tumor detection to differentiate between benign, malignant, and normal breast tissues, and stroke imaging. This work focuses on creating a 13 × 12 × 1.6 mm antenna on an FR4 substrate. Its structure is straightforward and small. Therapeutic applications of this antenna that rely on local heating include angioplasty, ablation of the heart and other tissues, and prostate hyperplasia. The partial ground design allows for miniaturization while maintaining key performance metrics such as high gain, low SAR (Specific Absorption Rate), and efficient bandwidth. Such an antenna is crucial for enhancing the overall performance of wearable health monitoring systems, where space and power constraints are significant factors. Additionally, the compact antenna design ensures that the device remains comfortable, unobtrusive, and effective for continuous use [5].

3. Proposed Antenna Design

Initially, basic antenna simulation in CST involves setting up a simple antenna structure (like a dipole or patch antenna), defining materials, boundary conditions, and running the simulation to observe key performance metrics. A rectangular patch antenna is constructed with a dielectric height, having ground and patch material as copper and substrate as polyimide lossy material. The edges of the antenna are made with a half-circleto avoid back radiation. The feed used here is the microstrip feed technique [7]. Designing research that requires a balance between performance, safety, and the specific needs of the application, such as wireless communication, sensing, or imaging. Radiation patterns are used to construct a high-gain,small antenna for biotelemetry applications. Gain characteristics are noted for the simulated output. The patch's overall measurements are 27mm x 20mm x 0.1 mm, while the substrate's measurements are 40mm x 30mm x 0.5mm. The measurement of the ground is 20mm x 30mm x 0.1mm mm. The body absorbs a lot of electromagnetic waves as energy and heat. The minimum backward radiation (Specific Absorption Rate) needs special attention. The size of the antenna should be as small as possible. Biomedical antennas are used as implantable devices, wearable sensors, medical imaging, and patient monitoring systems. In the case of implantable devices, low-frequency bands (e.g., 402 MHz – 405 MHz for medical implants) are common to ensure safety and efficient power transfer. Antennas for biomedical applications need to be small and lightweight to fit within wearable or implantable devices without causing discomfort. Flexible designs are also important for wearable biomedical devices to conform to the body. Figures 1 and 2 show the proposed antenna's front view and the side view of the proposed antenna.

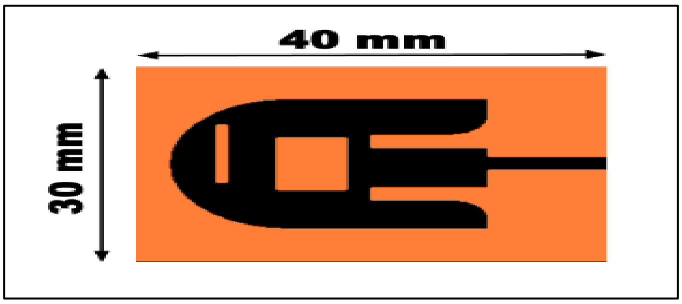

Figure 1. Bio Antenna's Front View

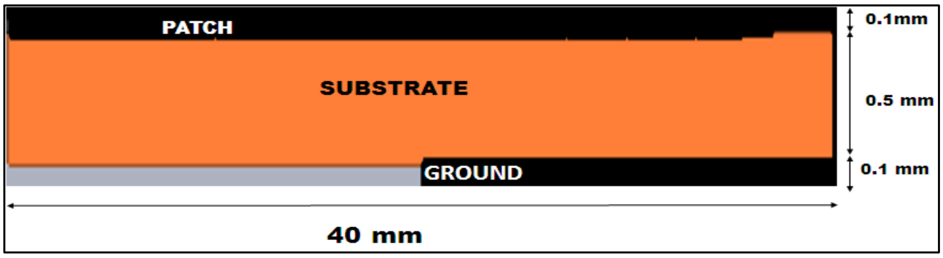

Figure 2. Bio Antenna’s Side View

Power consumption is a key design constraint, especially for implantable devices powered by batteries or energy harvesting methods. Efficient transmission and reception of signals are critical for minimizing energy use. Biomedical antenna designs require a careful balance between compactness, efficiency, biocompatibility, and safety.

Table 1. Dimensions of Antenna

Component	**Length**	**Width**
	Dimensions in mm	
Patch (Copper Annealed)	27	20
Substrate (Polyimide Lossy)	40	30
Ground (Copper Annealed)	20	30

Table 2. Comparison of Flexible Substrate Material

Substrate	**Relative Permittivity (εr)**	**Tangent Loss (δ)**
Polyimide	3.5	0.002
Felt	1.2	0.016
Polyamide	3.5	0.025

From implantable medical devices to wearable health monitoring systems, the suggested designs, such as patch antennas, slot antennas, microstrip antennas, and wearable textile antennas, are appropriate for a range of biomedical applications. Each design must be optimized for its specific application, ensuring efficient operation, minimal power consumption, and compliance with safety regulations like SAR limits. Table 1 provides the overall dimensions of the antenna designed. Table 2 addresses the comparison of flexible substrate materials.

4. Result

After simulating the proposed antenna design in CST, the primary results include parameters that determine its performance in terms of input time signals, output time signals, scattering parameters, total efficiency, radiation efficiency, Far-Field region, and gain accordingly. A powerful tool for electromagnetic simulation, the concept of input and output time signals is closely tied to how time-domain simulations and analyses are performed. CST is often used to simulate the behavior of various types of electromagnetic systems, including antennas, circuits, and other RF components. These systems can be excited by input signals, and the resulting outputs can be analysed over time. The input time signal in CST software represents the excitation or driving signal applied to a system, such as a circuit, antenna, or electromagnetic structure. Following the application of the input time signal, CST can compute how the system responds at different points in the simulation space. The output time signal in any system or simulation, including in software like CST Studio Suite, refers to the response of the system after it has been excited by an input signal. The characteristics of output time signals are important for analyzing how a system behaves and how it responds to various inputs over time. In an RF system, the amplitude can represent the signal strength or power.

4.1 Reflection Coefficient

To describe and assess the functionality of linear electrical networks, including transmission lines, antennas, and microwave components, S-parameter reveal information on the coupling, transmission, and reflection of radio frequency signals. Figure 3 shows that the obtained S parameter value is -23.791 and the reflection coefficient obtained is 2.41GHz. The obtained result lies between 2.24 GHz to 2.63 GHz.

4.2 Gain of the Antenna

Antenna gain is a crucial performance indicator that assesses how successfully an antenna sends or receives energy in a particular direction. A common metric to assess an antenna's directivity is gain, which quantifies the amount of power radiated in the desired direction relative to an idealized antenna that emits power uniformly in all directions, known as an isotropic. Figure 4 shows the gain characteristic, and the obtained gain is 2.140dBi.

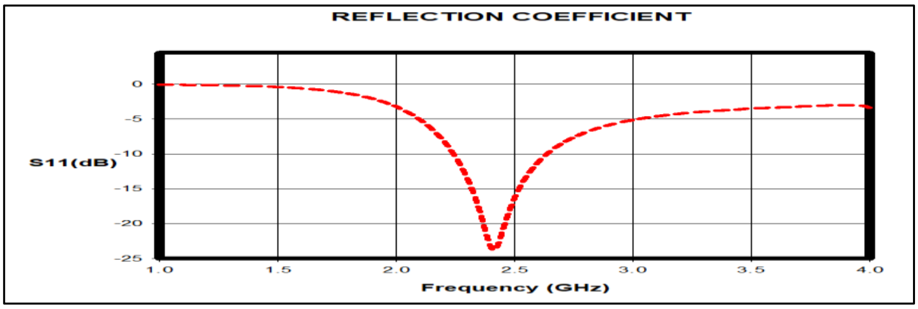

Figure 3. Reflection Coefficient

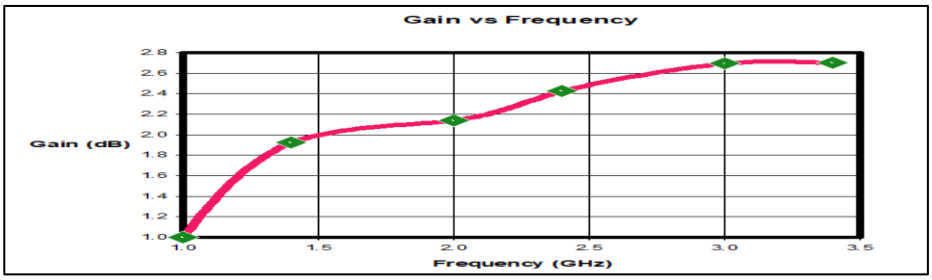

Figure 4. Gain Characteristics

4.3 Far-Field Radiation Pattern

The area at a considerable distance from the antenna or radiating structure where electromagnetic waves are fully generated and propagate predictably. When examining the properties, including efficiency, gain, directivity, and radiation pattern, the far-field region is crucial.

(a) **(b)**

Figure 5. Far-Field Radiation Pattern of Bio Antenna: (a) Radiation Pattern E Plane (b) Radiation Pattern H Plane.

By automatically calculating and visualizing far-field findings, it enables you to examine the antenna's radiation patterns in various directions and tailor the design to your particular use case. You can ensure your antenna works well in practical situations by defining the region and evaluating the outcomes. Figure 5 represents the Far-Field Radiation Pattern of the antenna's E-plane and H plane. This pattern, which is sometimes shown as a polar distribution, describes how the radiated power is spread in various directions as a 3D radiation pattern. A 3D plot shows the radiation pattern is shown in a spherical coordinate system, providing a view of directional characteristics in all directions [9]. The far-field radiation pattern allows you to visualize how an antenna radiates energy in the far-field region. It provides a comprehensive understanding of antenna performance by showing key metrics like gain, beam width, and radiation efficiency. These tools help optimize antenna designs for specific applications, ensuring that they meet the desired radiation characteristics.

4.4 Efficiency

Radiation efficiency is an important performance metric of an antenna that measures how effectively the antenna radiates. This is especially crucial for antennas operating in high-power environments, where losses can significantly impact performance [8]. Radiation efficiency (in %) is displayed as a result. This illustrates the proportion of input power that is released as electromagnetic waves, with values closer to 100% indicating a highly efficient antenna design. A high radiation efficiency is desirable because it indicates that the antenna is effectively radiating the input power into free space, which is important for communications, radar, and broadcasting. In order to generate the same radiated power, a low-efficiency antenna will need greater input power, which might result in lower performance and higher operational expenses. If the antenna is very efficient, the majority of the energy is radiated as electromagnetic waves. Figure 6 represents the efficiency plot of the proposed antenna.

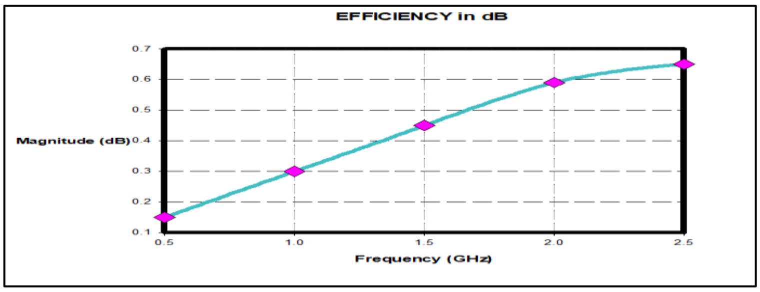

Figure 6. Efficiency

5. Conclusion and Future Work

The patch antenna is designed to support biotelemetry applications. This antenna has been designed with a polyimide substrate, which is more efficient and economically reasonable for fabrication, and its dimensions are 40 mm X 30 mm x 0.5 mm. The patch and ground are made of copper due to its flexibility and wearability. The successful design of such antennas requires the integration of several parameters, including miniaturization, flexibility, biocompatibility, and low power consumption, while maintaining an efficient radiation pattern for accurate data transmission. The antenna model functions as a resonator with a ground plane, which is implemented by making rectangular slots in the rectangular patch. Both in the body-worn casing and in the open area, the antenna offers exceptional efficiency and gain. Ensuring that the antenna is small enough for wearability without compromising its operational characteristics is essential for integrating it into wearable medical devices. Further advancements in miniaturization techniques and low-cost manufacturing could allow wearable antennas to be produced at scale, making them more accessible for widespread use in healthcare applications. Wearable antennas for biomedical applications hold great promise in revolutionizing healthcare systems by providing continuous, non-invasive monitoring. With continued research and technological advancements, these devices will become increasingly sophisticated, efficient, and user-friendly.

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