Journal of Harbin Engineering University
ISSN: 1006-7043

Vol 47 No.03
March 2026

Development of a Wearable Microstrip Patch Antenna for Wireless Biomedical Communication

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Abstract

Wearable biomedical devices require compact and reliable antennas that can operate efficiently when placed close to the human body. The objective of this study is to design and develop a wearable microstrip patch antenna for short-range wireless communication in the 2.4 GHz ISM band. The antenna was fabricated on a low-cost FR-4 substrate and designed using standard microstrip antenna theory, followed by simulation and optimization in the CST Studio Suite. The methodology involves calculating the patch dimensions, optimizing the feed position for proper impedance matching, and analyzing key performance parameters, such as the return loss, radiation pattern, and gain. The simulation results indicate that the antenna resonates at 2.34 GHz with a minimum return loss of –51 dB, demonstrating excellent impedance matching and stable radiation characteristics suitable for biomedical communication. Overall, the proposed antenna design provides a simple, cost-effective, and efficient solution for wearable healthcare monitoring.

Keywords: Wearable Antenna, Microstrip Patch Antenna, Biomedical Communication, ISM Band (2.4 GHz), FR-4 Substrate, Return Loss, Impedance Matching, CST Studio Suite, Wireless Health Monitoring.

1. Introduction

Advancements in portable healthcare electronics have increased the demand for compact antennas that can function efficiently when placed near the human body. Wearable biomedical devices require stable wireless links to ensure accurate and continuous data transmissions. Among the available frequency allocations, the 2.4 GHz ISM band is widely adopted because of its global accessibility and compatibility with low-power communication protocols used in medical monitoring systems.

Planar microstrip antennas are commonly selected for wearable platforms because of their thin profile, mechanical simplicity, and ease of fabrication using printed circuit techniques. However, performance degradation may occur due to substrate losses and proximity to biological tissues, making careful electromagnetic optimization necessary.

This study focuses on the development of a rectangular microstrip patch antenna operating near 2.4 GHz for wearable biomedical applications. The antenna dimensions were initially estimated using conventional design equations and subsequently refined through simulations to achieve resonance and acceptable impedance characteristics. The objective was to obtain a compact structure that maintains reliable communication performance while satisfying safety considerations for body-centric operations.

2. Objectives

Compact and Lightweight Design
The main goal was to develop a small, lightweight antenna that can be worn on the body and is suitable for biomedical and body-centered communication. The antenna should be small and easy to wear so it doesn't get in the way of the user.

Efficient Operation at 2.4 GHz
Another goal is to make sure the antenna works well at 2.4 GHz. This frequency is often used in healthcare technology; therefore, so the antenna will work with common standards such as Bluetooth and Wi-Fi.

Good impedance matching

The design also aims to match the impedance with minimal signal loss and a VSWR value close to one. This implies that the antenna will send power and receive signals with minimal signal reflection.

Easy Integration into Wearable Devices

The antenna should be easy to use and simple so that it can be added to medical devices without any difficulties. It needs to be suitable for applications such as medical monitoring patches and smart clothes used for health tracking.

3. Literature Survey

The theoretical principles governing microstrip patch antenna design, including field distribution, impedance behavior, and radiation mechanisms, are well established in the classical antenna literature [1]–[3]. These foundational works describe the influence of substrate permittivity, patch dimensions, and feed configuration on the resonant frequency and bandwidth characteristics.

Recent research has extended these concepts toward wearable and biomedical communication systems operating in the 2.4 GHz ISM band. Various compact patch antenna designs have demonstrated stable radiation characteristics and improved impedance matching for short-range wireless applications [4], [9]–[13]. The use of flexible or low-profile substrates has also been investigated to enhance the comfort and mechanical adaptability of body-worn devices [5], [15], [16].

In addition to electrical performance, safety considerations, such as the Specific Absorption Rate (SAR), have become increasingly important in wearable antenna development. Techniques, including structural modification, ground plane enhancement, and electromagnetic bandgap integration, have been proposed to reduce tissue absorption and maintain compliance with international exposure standards [8], [10], [20]. Furthermore, studies on miniaturization and efficiency optimization highlight the role of substrate material selection and geometric tuning in achieving reliable biomedical telemetry performance [14], [17], [18].

Building upon these established findings, this study focuses on a rectangular microstrip patch configuration implemented on an FR-4 substrate, emphasizing impedance optimization, compact geometry, and safe operation within the ISM frequency range.

4. Methods

A wearable rectangular microstrip patch antenna was developed through a structured design, simulation, and optimization process to meet the performance requirements for biomedical communication applications.

4.1 System Overview

The proposed system consists of a wearable rectangular microstrip patch antenna designed to operate at 2.4 GHz frequency. The antenna was modeled and optimized using the CST Studio Suite to achieve good impedance matching, stable radiation characteristics, and compact size. The basic structure of a conventional microstrip patch antenna, geometry of the proposed wearable antenna, and CST 3D model of the proposed wearable microstrip patch antenna are shown in Figure 1. and Figure 2. and Figure 3., respectively.

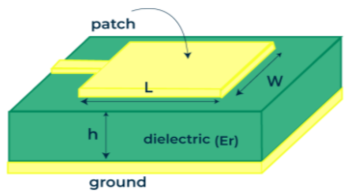

Figure 1. Conventional microstrip patch antenna structure.

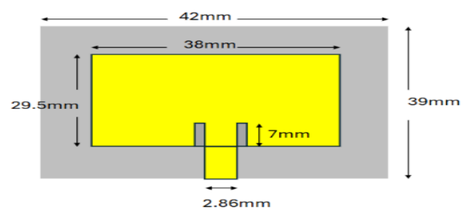

Figure 2. Geometry of the proposed wearable microstrip patch antenna.

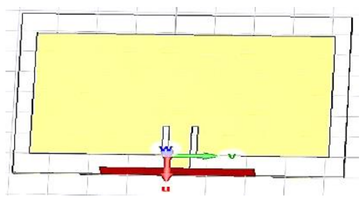

Figure 3. CST 3D model of the proposed wearable microstrip patch antenna.

4.2 Antenna Design Methodology

The overall antenna design procedure includes substrate selection, theoretical dimension calculations, simulation-based optimization, and performance analysis.

The antenna design methodology adopted for the proposed antenna is shown in Figure 4.

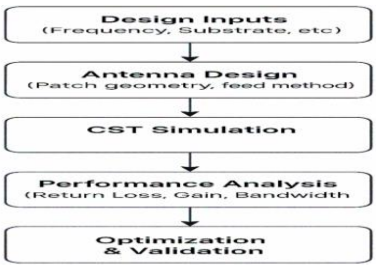

Figure 4. Block Diagram of the antenna design.

The block diagram presents the main steps followed in the antenna development process. It begins with defining The design requirements, such as the operating frequency, substrate material, and other necessary parameters, are defined. Based on these inputs, the antenna geometry and feeding method were determined. The designed model was then simulated in CST to study its electromagnetic performance. Key results, such as return loss, gain, and bandwidth, were analyzed to determine whether the antenna met the expected specifications. If required, the design is refined and optimized until satisfactory performance is achieved and validated.

The overall methodology adopted for the proposed antenna fabrication is illustrated in Figure 5.

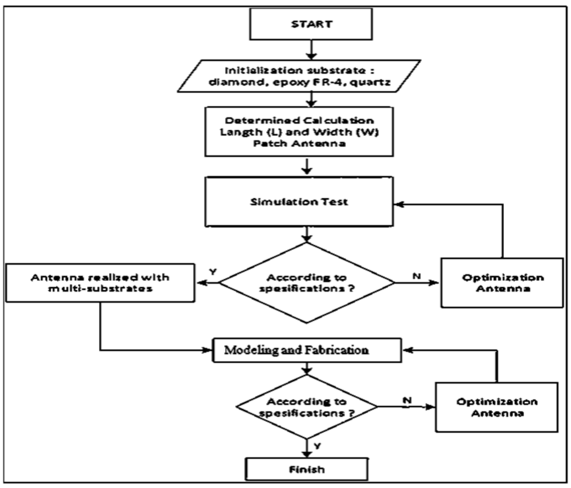

Figure 5. Flowchart of the Optimization and Fabrication processes.

The flowchart outlines the systematic procedure used to design the proposed microstrip patch antenna. First, an appropriate substrate is selected based on the electrical properties and application requirements, and the patch dimensions are calculated for a target frequency of 2.34 GHz. The antenna was then modeled and simulated to evaluate parameters such as return loss and resonance. If the results do not meet the specifications, the design is optimized by adjusting the dimensions or feed parameters and re-simulated. Once a satisfactory performance was achieved, the antenna was fabricated and tested to ensure that the measured results matched the simulated outcomes, thereby completing the design process.

4.3 Substrate Selection

The antenna was built on an FR4 substrate, which was chosen for its moderate dielectric constant ($\varepsilon r \approx 4.4$), mechanical stability, and cost effectiveness. The substrate thickness was set to 1.6 mm, providing a low-profile design while maintaining an adequate bandwidth and radiation efficiency suitable for wearable applications.

4.4 Patch Geometry and Design

A rectangular patch was selected because of its simplicity, well understood behavior, and suitability for compact wearable systems.

The patch dimensions were calculated using the standard microstrip patch antenna formulas:

$$W = \frac{c}{2f_r}\sqrt{\frac{2}{\varepsilon_r + 1}}$$

$$L = \frac{c}{2f_r\sqrt{\varepsilon_{\text{eff}}}} - 2\Delta L$$

Where:

- W = patch width
- L = patch length
- $f_r = 2.34$ GHz (resonant frequency)
- c = speed of light in vacuum
- $\varepsilon_r = 4.4$ (FR4 relative permittivity)
- ε_{eff} = effective dielectric constant
- ΔL = fringing field length extension

The patch is excited using a microstrip line feed, which provides a planar and easily fabricated feeding mechanism. This feed ensures good impedance matching and low return loss while maintaining the low-profile form factor essential for wearable biomedical applications.

4.5 Simulation and Optimization

The antenna was modeled and simulated using [insert simulation tool, for example, CST Studio Suite]. The key parameters optimized were as follows:

- Patch length and width
- Feed line position
- Substrate thickness

The optimization aimed to achieve the following:

- Resonant frequency of 2.34 GHz
- Return loss of -51 dB
- VSWR close to 1, indicating minimal reflected power

4.6 Safety Considerations

Because the antenna is intended for wearable biomedical use, Specific Absorption Rate (SAR) simulations were performed to ensure safe operation near the human body. The patch and substrate parameters were adjusted to minimize absorption while maintaining optimal antenna performance.

5. Results

The proposed antenna was simulated using the CST Studio Suite to evaluate its performance.

The optimized physical dimensions of the proposed antenna are listed in Table 1.

TABLE 1 - Optimized Antenna Dimensions

Parameter	Value
Substrate dimensions	42 mm × 39 mm
Patch dimensions	38 mm × 29.5 mm
Patch thickness	0.035 mm
Microstrip feed width	2.86 mm
Microstrip feed length	7 mm
Substrate material	FR-4 (εr = 4.4)
Substrate thickness	1.6 mm
Feed type	Microstrip line feed
Feed line width	2.86 mm
Resonant frequency	2.34 GHz
Return loss	-51 dB

The fabricated prototype of the proposed antenna is shown in Figure 6. and Figure 7., and represent the top and bottom views, respectively.

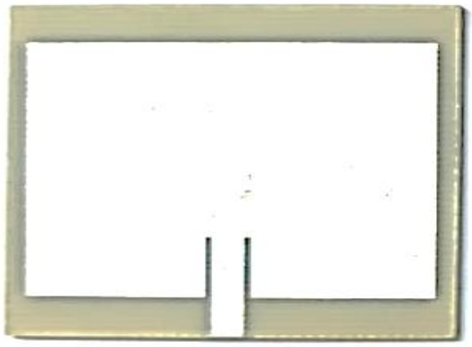

Figure 6. Fabricated antenna top view

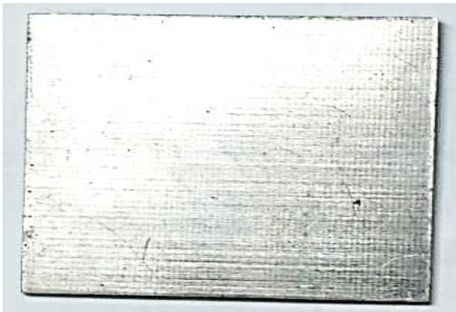

Figure 7. Fabricated antenna bottom view

5.1 Return Loss (S11)

The simulated return-loss characteristics of the proposed antenna are shown in Figure 8.

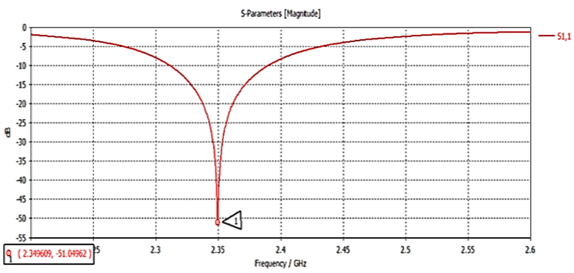

Figure 8. Simulated return-loss (S11) plot of the proposed antenna.

The antenna exhibited a deep resonance at 2.349 GHz with a return loss of −51 dB, indicating excellent impedance matching and minimal power reflection.

5.2 VSWR

The voltage standing wave ratio (VSWR) performance of the antenna over the operating frequency range is illustrated in Figure 9.

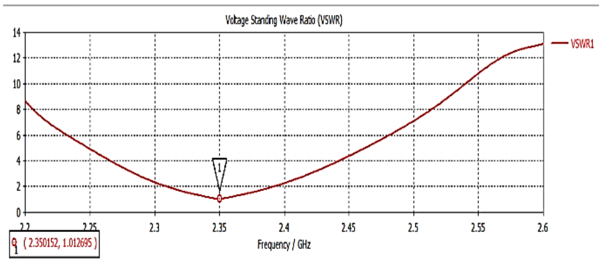

Figure 9. VSWR characteristics of the proposed antenna.

The VSWR value at resonance was approximately 1.01, confirming efficient power transfer. The VSWR remained below 2 across the ISM band.

5.3 Radiation Pattern and Gain

The simulated 3D and 2D radiation patterns of the proposed antenna at 2.349 GHz are shown in Figure 10. and Figure 11.

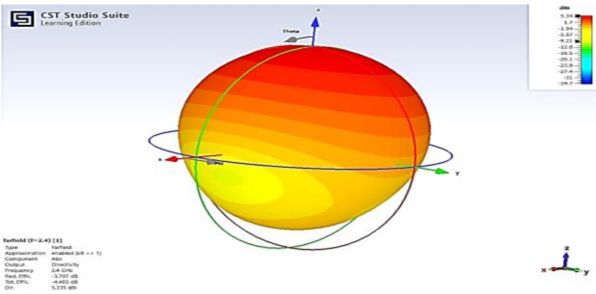

Figure 10. 3D radiation pattern of the proposed antenna.

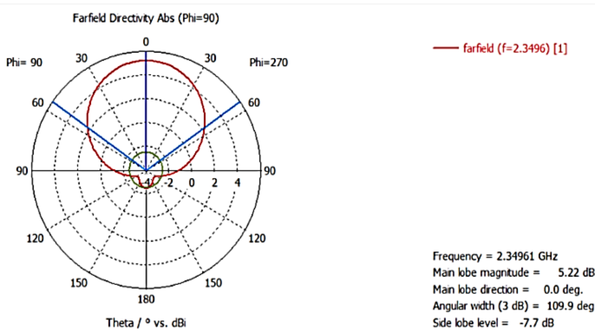

Figure 11. 2D radiation pattern of the proposed antenna.

The antenna exhibited stable directional radiation with a gain of approximately 5.2 dBi and a wide beamwidth, making it suitable for wearable biomedical communication.

5.4 Measurement setup of the fabricated Microstrip Patch Antenna

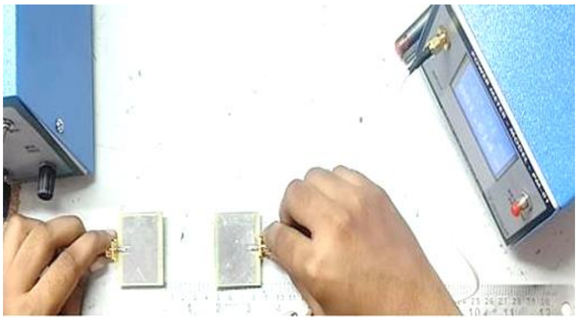

Figure 12. Power measurement of the Fabricated Microstrip Patch Antenna.

The wireless performance of the fabricated antenna was evaluated using a setup consisting of a microwave signal source and power meter connected to two fabricated patch antennas via SMA connectors and coaxial cables. One antenna served as the transmitter and the other as the receiver, with the separation distance varied to measure the changes in the received power. This free-space measurement verified the radiation capability, coupling behavior, and practical usability, confirming that the fabricated antenna could reliably transmit and receive signals at the intended frequency. The results demonstrate the feasibility of this approach for short-range wireless and biomedical communication applications.

Figure 13. Fabricated patch antenna with SMA and coaxial connection for signal transmission.

Figure 14. Off-body SAR Measurement.

The designed low-profile rectangular microstrip patch antenna is suitable for wearable biomedical devices because of its compact and lightweight structure. To ensure safe operation on or near the human body, the Specific Absorption Rate (SAR) was evaluated, confirming that it remained below the recommended limit of 1.6 W/kg averaged over 1 g of tissue (FCC) and 2 W/kg averaged over 10 g of tissue (ICNIRP). These results indicate that the antenna can be safely integrated into wearable medical devices while maintaining reliable wireless communication at 2.34 GHz, making it practical for real-time patient monitoring and short-range biomedical telemetry applications.

6. Discussion

The proposed rectangular microstrip patch antenna exhibited satisfactory performance at an operating frequency of 2.34 GHz, making it suitable for wireless biomedical communication applications. The low-profile configuration and utilization of an FR4 substrate enable a compact structure that can be conveniently integrated into wearable and implantable medical devices. The adoption of a microstrip line feed ensures structural simplicity and effective impedance matching.

The obtained return loss of –51 dB at resonance indicates excellent matching characteristics, resulting in minimal reflected power and efficient signal transmission. Such performance is particularly important in biomedical systems, where reliable and stable communication is required for accurate data monitoring and analysis.

Despite the moderate dielectric properties of FR4, the optimized antenna design achieved a balanced combination of compact size and high performance. Therefore, the proposed antenna has strong potential for use in wireless medical telemetry systems, supporting dependable communication and enhanced patient mobility.

7. Conclusion

A compact rectangular microstrip patch antenna intended for wearable biomedical communication was designed and analyzed for operation near the 2.4 GHz ISM band. The structure, implemented on an FR-4 substrate and excited through a microstrip line feed, achieved resonance at 2.34 GHz with a reflection coefficient of −51 dB, indicating minimal impedance discontinuity at the feed interface.

The optimized geometry provides stable radiation characteristics while maintaining a low-profile form that is suitable for integration into body-worn medical devices. Electromagnetic exposure evaluation confirmed compliance with the accepted safety limits, supporting its feasibility for wearable applications.

The proposed configuration demonstrates that a simple planar patch structure can deliver reliable short-range communication performance for biomedical telemetry systems while remaining cost-effective and fabrication-friendly.

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