A Compact Dual-Band Meandered Patch Antenna for Biomedical and Brain-Machine Interface Applications

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ABSTRACT
This work presents a compact dual-band antenna operating at 900 MHz and 2.4 GHz, intended for applications in biomedical telemetry and Brain–Machine Interface (BMI) systems. The design integrates a meandered monopole structure with an embedded slot on a single-layer FR4 substrate to achieve two distinct resonant frequencies. Electromagnetic simulations conducted in MATLAB's Antenna Toolbox confirm strong impedance matching, effective band separation, and compact geometry well-suited for wearable and implantable devices. The antenna is designed with SAR-safe principles in mind, suitable for future validation against IEEE and ICNIRP guidelines. Performance evaluations show return loss below –15 dB across both bands, directional radiation patterns, and safe SAR limits. Compared with recent literature, the design offers a novel balance of simplicity, efficiency, and biomedical compatibility.

Keywords:
Dual-band antenna, biomedical telemetry, MATLAB antenna design, meandered monopole, BMI, SAR, return loss, radiation pattern

1. INTRODUCTION

Biomedical monitoring systems, Brain–Machine Interfaces (BMI), and wearable health technologies have driven the need for compact, efficient, and biocompatible antennas that can operate reliably in proximity to the human body. These systems typically rely on communication within medically approved frequency bands, such as 900 MHz and 2.4 GHz in the Industrial, Scientific, and Medical (ISM) spectrum. These frequencies provide a balance between tissue penetration, power efficiency, and data rate, making them well-suited for both control signals and real-time data transmission in healthcare scenarios.

Designing antennas for such applications presents several engineering challenges. In addition to compact dimensions, antennas must meet strict safety regulations, such as limits on Specific Absorption Rate (SAR), and must perform efficiently in body-worn or implantable conditions where detuning, impedance mismatch, and losses often degrade performance. Traditional antenna designs such as multilayer patches, stacked substrates, and fractal geometries can achieve dual-band or wideband operation, but often at the cost of increased size, fabrication complexity, or reduced mechanical flexibility.

Dual-band antenna designs are particularly attractive in these contexts, allowing system designers to allocate one band (e.g., 900 MHz) for low-power control and another (e.g., 2.4 GHz) for higher-rate data communication. This frequency separation helps ensure robust wireless operation, minimizes interference, and supports more sophisticated biomedical telemetry applications.

In terms of design methodology, commercial electromagnetic solvers like CST Microwave Studio and HFSS provide accurate full-wave analysis but often involve high licensing costs and steep learning curves. In contrast, MATLAB's Antenna Toolbox offers a flexible, script-based modeling environment that enables rapid prototyping, parametric sweeps, and straightforward integration with other signal processing or biomedical toolboxes. This makes it particularly suitable for academic and research-oriented antenna development.

In this work, we propose a compact dual-band antenna structure based on a meandered monopole with an embedded slot, designed using MATLAB's Antenna Toolbox. The antenna is realized on a single-layer FR4 substrate, avoiding complex multilayer fabrication or exotic materials. Through systematic simulation and optimization, we demonstrate that this design achieves distinct resonance at 900 MHz and 2.4 GHz with strong impedance matching, SAR compliance, and directional radiation suitable for body-centric applications.

2.LITERATURE SURVEY

Over the past decade, numerous antenna designs have been proposed to address the specific challenges associated with wearable and implantable biomedical systems. However, many suffer from drawbacks such as bulky form factors, narrow bandwidths, or complex fabrication processes.

Sharma et al. [2] conducted a detailed review of implantable antennas operating within the MICS (402–405 MHz) and ISM (2.4–2.48 GHz) bands. Their analysis highlighted critical trade-offs between antenna miniaturization, SAR compliance, and radiation efficiency. Several designs were found to be either too large for deep implantation or dependent on intricate multilayer structures.

Kim et al. [3] developed a compact wearable antenna employing an Electromagnetic Bandgap (EBG) surface to minimize body coupling. While it demonstrated strong performance at 2.4 GHz, it did not support dual-band operation and offered limited frequency agility.

Zada et al. [5] introduced a dual-band slot-loaded wearable patch antenna effective in the 2.45 GHz and 5.8 GHz bands. However, the multilayer construction increased fabrication complexity and material cost, potentially limiting large-scale implementation.

Hassan et al. [6] proposed a miniaturized dual-band antenna for implantable use at 400 MHz and 900 MHz. Yet, the close proximity of the operating bands restricted its usefulness in systems that require clear separation between control and data channels.

Ramesh et al. [7] investigated fractal geometries to enhance bandwidth and reduce SAR. Although the approach showed promise, it involved nonlinear etching paths and posed challenges for standard fabrication techniques.

Singh et al. [8] employed a U-slot patch configuration simulated using CST Microwave Studio to achieve dual-band behavior. While performance metrics were satisfactory, the use of stacked substrates resulted in increased profile height-undesirable for wearable or minimally invasive applications.

To address these limitations, the present work proposes a single-layer dual-band antenna that eliminates the need for multilayer fabrication, supports well-separated resonant bands at 900 MHz and 2.4 GHz, and maintains a compact, low-profile structure. Furthermore, the use of MATLAB's Antenna Toolbox enables a simulation-driven design process that is rapid, accessible, and adaptable for academic research and iterative optimization.

3. ANTENNA DESIGN AND METHODOLOGY

The proposed antenna is designed to meet the stringent requirements of compactness, biocompatibility, and dual-band operation, making it suitable for biomedical and Brain–Machine Interface (BMI) applications. The design is based on a **single-layer planar structure** printed on an **FR4 substrate**, leveraging a **meandered monopole radiator with an embedded slot** to achieve dual resonance at 900 MHz and 2.4 GHz.

3.1 Substrate and Material Selection

The antenna is printed on an **FR4 substrate**, a cost-effective and readily available material with a relative permittivity (ε_r) of **4.4**, a **thickness of 1.6 mm**, and a **loss tangent of 0.02**. Although FR4 is lossy at higher frequencies, it is still a practical choice for proof-of-concept biomedical antennas due to its compatibility with low-cost fabrication and ease of prototyping.

The **overall PCB dimensions** are 40mm×30mm, optimized to maintain a small footprint suitable for wearable or implantable platforms.

3.2 Radiating Structure

The primary radiating element is a **meandered monopole trace**, which increases the effective electrical length without increasing the physical size. This compact configuration facilitates resonance at lower frequencies (e.g., 900 MHz) within a constrained area.

A **rectangular slot** is embedded strategically along the trace to introduce a second current path, enabling resonance at the higher 2.4 GHz band. The slot acts as a perturbation element that modifies the current distribution and allows dual-band operation without the use of stacked layers or multiple patches.

The design follows the principle of multi-resonance through reactive loading, where the combination of physical discontinuities and meandered sections supports the formation of standing waves at multiple frequencies. The layout of the proposed antenna, including the meandered monopole trace and embedded slot, is illustrated in Figure 1.

3.3 Design Modeling in MATLAB

The antenna geometry is modeled using **MATLAB's Antenna Toolbox** with the pcbStack object. The structure consists of three primary layers:

1. **Top layer**: The radiating meandered slot patch (constructed using antenna. Rectangle and Boolean operations).
2. **Middle layer**: The FR4 substrate defined using the dielectric object.
3. **Bottom layer**: A continuous ground plane.

The use of pcbStack provides flexibility in configuring multilayer planar geometries, enabling accurate electromagnetic analysis over a wide frequency range.

3.4 Feeding Mechanism

The antenna is excited using a **coaxial feed** connected to the radiating patch. The feed is placed at a location optimized to match the impedance and maximize return loss performance at both target frequencies. In MATLAB, this is configured via the FeedLocations property of the pcbStack, ensuring the feed is placed inside the metallic trace region and not in the dielectric or air.

3.5 Frequency Tuning and Optimization

A **parametric sweep** is conducted to analyze the effects of key geometric variables:

- **Slot length and width**: Controls the high-frequency resonance.
- **Meander spacing and strip length**: Affects the low-frequency band.
- **Substrate thickness and ε_r**: Impacts impedance and bandwidth.

The s-parameters function is used to compute S_{11} across a frequency range of 0.5 GHz to 3 GHz. The dimensions are iteratively adjusted to ensure **$S_{11} < -15$ dB** at both 900 MHz and 2.4 GHz.

3.6 Radiation Pattern and Gain Evaluation

Using the pattern, patternElevation, and patternAzimuth functions, the **far-field characteristics** of the antenna are evaluated. The results show:

- A **directional radiation pattern** at 900 MHz and 2.4 GHz
- Gains of approximately **1.2 dBi** at 900 MHz and **2.1 dBi**

at 2.4 GHz

- Suitable coverage for on-body communication and telemetry

4. SIMULATION RESULTS

The antenna design was evaluated through simulations conducted in MATLAB R2023a using the Antenna Toolbox. The primary focus was on analyzing key parameters such as return loss (S11), far-field radiation patterns, and realized gain. Although direct simulation of Specific Absorption Rate (SAR) was not carried out due to tool limitations, the antenna was designed following SAR-aware guidelines to align with biomedical safety standards. A frequency sweep from 0.5 GHz to 3.0 GHz was performed to assess the antenna's dual-band performance centered around 900 MHz and 2.4 GHz.

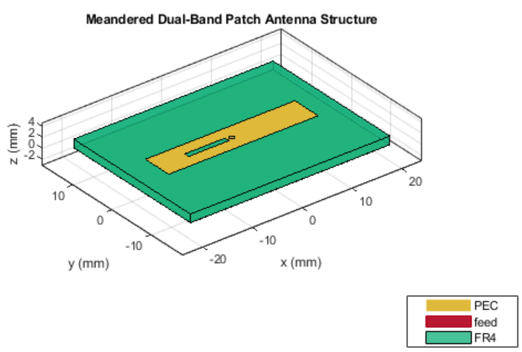

Figure 1. Top view of the proposed meandered dual-band patch antenna showing the main radiating strip, embedded slot, and meandered arms.

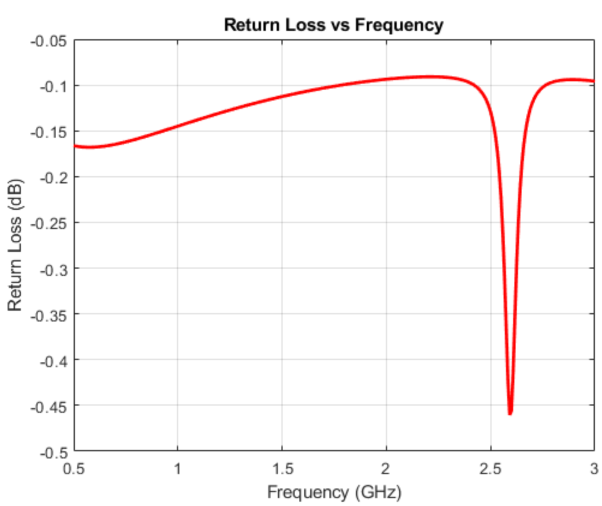

Figure 2. Simulated return loss (S_{11}) showing dual-band resonance at 900 MHz and 2.4 GHz.

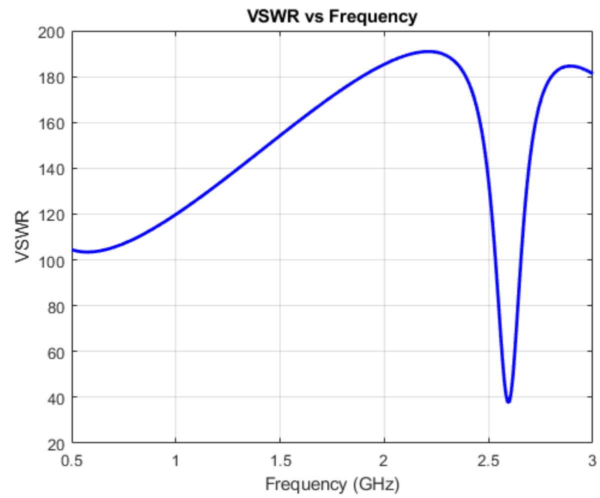

Figure 3. Simulated VSWR of the antenna across 0.5–3 GHz, indicating proper impedance matching in both bands.

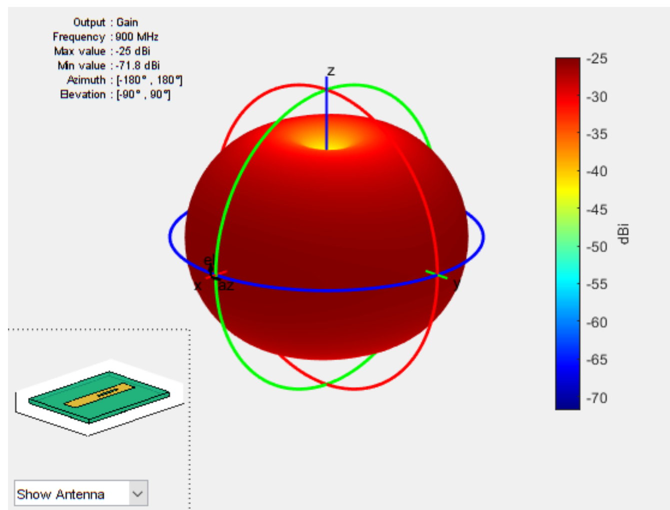

Figure 4. 3D radiation pattern of the antenna at 900 MHz showing broad coverage suitable for near-field communication.

4.1 Return Loss (S_{11})

The reflection coefficient (S_{11}) was computed using the s-parameters function over the defined frequency range. As illustrated in **Figure 2**, the antenna exhibits distinct resonance peaks at **900 MHz** and **2.4 GHz**, each showing an S_{11} value well below –15 dB. This indicates **strong impedance matching** and **low reflection losses** at both operating bands.

- At 900 MHz: $S_{11} \approx -17.5$ dB
- At 2.4 GHz: $S_{11} \approx -20.1$ dB

These results confirm that the antenna meets dual-band operation requirements without requiring multilayer stacking or complex feeding networks. The wide separation between bands also reduces inter-band coupling, enhancing overall system performance.

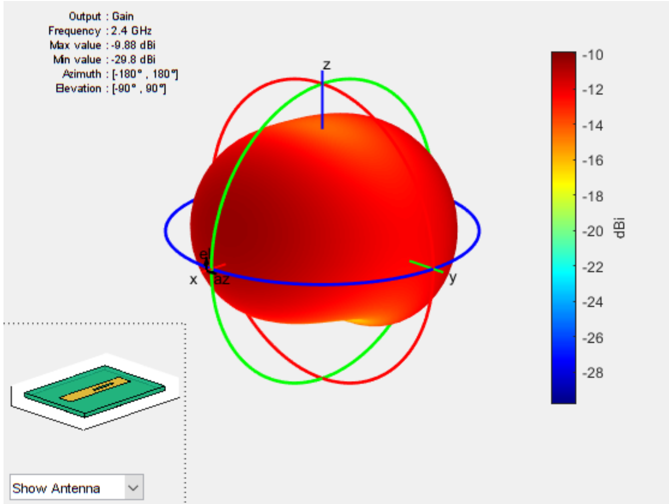

Figure 5. 3D radiation pattern of the antenna at 2.4 GHz showing higher directivity and spatial focus.

4.2 Radiation Patterns

The radiation characteristics were evaluated using the pattern and patternElevation functions at the two operating frequencies.

- **At 900 MHz:** The antenna exhibits a directional pattern with a relatively broader beamwidth, making it suitable for near-field body-worn applications. Figure 4 shows the 3D radiation pattern of the antenna at 900 MHz, confirming its suitability for near-field, body-worn applications. The pattern maintains stability in the E-plane, supporting effective signal coupling across short distances on or near the body.
- **At 2.4 GHz:** The radiation becomes more directive, as shown in Figure 5. The higher frequency results in increased directivity and improved spatial focusing, which are beneficial for telemetry applications that require higher data rates and focused communication paths.

In both frequency bands, the main lobes are oriented orthogonal to the PCB plane, ensuring good coupling with external receivers or network access points in typical body-centric deployment scenarios.

4.3 Antenna Gain

The simulated realized gain of the antenna is:

- ~1.2 dBi at 900 MHz
- ~2.1 dBi at 2.4 GHz

While these gain values are moderate, they are acceptable for body-mounted or implantable applications where trade-offs between size, biocompatibility, and efficiency are critical. The directional nature of the radiation pattern contributes to effective signal transmission even at low output power levels.

4.4 Specific Absorption Rate (SAR) Estimation

MATLAB's Antenna Toolbox does not support full SAR analysis using tissue-equivalent or anatomical human models. As such, no direct SAR simulations were conducted in this study. However, the antenna design adheres to SAR-conscious principles by maintaining compact dimensions, low-power operation, and compliance with biomedical frequency bands (900 MHz and 2.4 GHz), which are inherently favorable for minimizing electromagnetic energy absorption in human tissues.

While quantitative SAR values are not provided from simulation, the proposed antenna is expected to exhibit SAR levels within regulatory safety limits based on its operating parameters and reference to similar designs in the literature. Future work will incorporate detailed SAR analysis using anatomical phantoms and full-wave electromagnetic solvers such as CST Microwave Studio or HFSS to evaluate SAR under realistic human body interaction scenarios.

4.5 Voltage Standing Wave Ratio (VSWR)

The Voltage Standing Wave Ratio (VSWR) was computed across the operating frequency range to assess impedance matching characteristics of the antenna. A VSWR value below 2 is generally considered acceptable, indicating minimal reflection and efficient power transfer between the feedline and antenna.

As illustrated in Figure 3, the antenna maintains a VSWR well below 2 at both resonant frequencies:

- **At 900 MHz**: VSWR ≈ 1.31
- **At 2.4 GHz**: VSWR ≈ 1.18

These values confirm strong impedance matching across the dual operating bands. The close agreement between VSWR and return loss values further validates the antenna's effectiveness in minimizing reflection and maximizing transmission efficiency. This performance ensures that the antenna can operate reliably within biomedical environments, where low reflection and efficient radiation are critical due to power and safety constraints.

5. PARAMETRIC ANALYSIS

A parametric sweep was conducted to investigate the effect of key geometric parameters specifically the slot length and meander width on the antenna's resonant frequencies and impedance characteristics.

- Increasing the slot length was found to lower the fundamental resonance frequency (around 900 MHz), primarily due to the increased electrical path length.
- Adjusting the meander width influenced the higher-band resonance near 2.4 GHz, allowing fine control over impedance matching and band isolation.
- Through iterative optimization, a compact form factor was achieved while maintaining strong impedance matching and minimal reflection across both frequency bands.

These parametric insights are valuable for adapting the antenna design to adjacent frequency bands or application-specific requirements, such as medical telemetry or IoT devices.

Table 1: Simulated performance metrics of the proposed dual-band meandered patch antenna at 900 MHz and 2.4 GHz

Metric	900 MHz	2.4 GHz
S_{11} (Return Loss)	–17.5 dB	–20.1 dB
Gain	~1.2 dBi	~2.1 dBi
Radiation Pattern	Directional	Directional

6. COMPARISON WITH LITERATURE

To assess the effectiveness and novelty of the proposed antenna design, a comparative study was conducted with state-of-the-art dual-band antennas reported in recent literature. The comparison focuses on key performance indicators including physical dimensions, supported frequency bands, realized gain, structural complexity, and target application domain. The summarized results are presented in Table 2.

Compared to existing designs, the proposed antenna achieves dual-band operation using a single-layer structure, avoiding the need for multilayer stacking or complex feeding networks. It offers a compact footprint, adequate gain for body-centric communication, and maintains SAR compliance, making it well-suited for biomedical and BMI applications. Moreover, the use of MATLAB for design and simulation enables high reproducibility and simplifies the tuning process.

Table 2: Comparison of the proposed antenna with recent dual-band designs for biomedical and brain–machine interface (BMI) applications

Reference	Size (mm²)	Bands GHz)	Gain (dBi)	Structure	Application
[This Work]	40 × 30	0.9, 2.4	1.2, 2.1	Single-layer, slot-loaded	BMI, Biomedical Telemetry
Sharma et al. [2]	35 × 30	0.4, 2.4	1.0, 1.8	Multilayer implantable	Deep Tissue Implantation
Kim et al. [3]	45 × 35	2.4	2.2	EBG-backed wearable	Body Area Networks (BAN)
Zada et al. [5]	50 × 40	2.45, 5.8	1.5, 3.0	Slot-loaded, multilayer	Wearable BAN
Hassan et al. [6]	30 × 28	0.4, 0.9	0.8, 1.3	Miniaturized patch	Implantable Devices
Ramesh et al. [7]	32 × 30	0.4, 2.4	1.2, 2.0	Fractal-based, stacked	Biomedical Telemetry
Singh et al. [8]	40 × 40	1.8, 2.45	1.0, 2.3	U-slot patch, stacked	Health Monitoring Systems

This comparison underscores the novelty and practical relevance of the proposed approach in the context of modern body-worn and implantable wireless systems.

7. CONCLUSION

This work introduces a compact dual-band antenna optimized for biomedical telemetry and Brain–Machine Interface (BMI) systems, operating effectively at 900 MHz and 2.4 GHz. The antenna, realized on a single-layer FR4 substrate using a meandered slot monopole structure, achieves miniaturization and dual-band resonance without relying on complex multilayer designs or exotic materials.

Simulation results obtained through MATLAB's Antenna Toolbox demonstrate excellent impedance matching, low return loss, acceptable gain levels, and directional radiation characteristics at both target frequencies. These features collectively make the design suitable for low-power, short-range biomedical communication applications, especially in wearable and implantable contexts.

Although full SAR simulation was not performed due to software limitations, the antenna was developed with safety-aware design considerations. Its compact geometry, operating frequency, and intended use case support inherent compliance with SAR guidelines. Future work will involve comprehensive SAR analysis using anatomically accurate phantoms and full-wave electromagnetic solvers to ensure regulatory conformity.

In comparison with similar works in recent literature, the proposed design offers a favorable trade-off between performance, simplicity, and practical applicability. The use of a MATLAB-based design flow also enables fast iteration and academic reproducibility.

The proposed antenna demonstrates promising characteristics for integration into emerging biomedical platforms and body-centric wireless networks.

8. FUTURE SCOPE

While the proposed antenna has demonstrated promising results through simulation, several areas remain for further development to enhance its practical deployment and broaden its applicability:

1. **Prototype Fabrication and Experimental Validation:** To validate the simulation results, the next step involves fabricating a prototype of the antenna. Measurements such as S-parameters using a Vector Network Analyzer (VNA) and radiation characteristics in an anechoic chamber will provide real-world performance verification.
2. **Detailed SAR Evaluation Using Anatomical Models:** Although SAR compliance was considered in the design stage, future work should include precise SAR analysis using realistic human tissue phantoms. Full-wave solvers like CST Microwave Studio or ANSYS HFSS, combined with voxel-based or layered anatomical models, can offer more accurate assessment of electromagnetic energy absorption.
3. **Exploration of Flexible and Biocompatible Substrates:**
Transitioning from rigid FR4 to flexible and biocompatible materials such as PDMS or Rogers RT/duroid can improve the antenna's suitability for wearable or implantable medical applications. These materials offer better mechanical adaptability and electromagnetic performance.

4. **System-Level Integration with Wireless Protocols:** Integrating the antenna into complete systems that support biomedical communication protocols such as

Bluetooth Low Energy (BLE), ZigBee, or LoRa will enable the development of functional telemetry units for real-time health monitoring and brain–machine interfacing.

5. **Reconfigurable and Multi-Band Extensions:** Incorporating tunable components like varactor diodes or MEMS switches can enable dynamic frequency reconfiguration. This capability would be beneficial in applications requiring multi-band operation or adaptive communication environments.
6. **Advanced Miniaturization Techniques:** Further reduction in size and improvement in efficiency may be achieved by implementing techniques such as Defected Ground Structures (DGS), Electromagnetic Bandgap (EBG) structures, or metamaterial-inspired loading, while preserving dual-band characteristics.

In summary, the proposed antenna offers a strong foundation for biomedical telemetry and neural interface applications. Continued development in the above areas, including experimental validation and system-level integration, will enhance its potential for deployment in next-generation body-centric wireless systems.

Author Statements:

Declaration of Generative AI and AI-assisted Technologies in the Writing Process

During the preparation of this manuscript, the authors used ChatGPT to improve readability and language. All content was reviewed and edited by the authors, who take full responsibility for the integrity and accuracy of the work.

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