Design of a Compact Dual-Band Microstrip Antenna for ISM and 5G Use

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***Abstract*—This paper presents a compact, dual-band, and flexible wearable antenna designed for modern wireless applications, specifically targeting the Industrial, Scientific, and Medical (ISM) band and the sub-6 GHz 5G NR band. The antenna operates effectively across two frequency ranges: 2.4442–2.5200 GHz and 3.6400–3.7652 GHz, and exhibits a low-profile geometry with dimensions of $40 \times 11.3 \times 3\ \mathrm{mm}^3$. The structure is realized on a felt substrate characterized by a relative permittivity (ε_r) of 1.63 and a dielectric loss tangent ($\tan\delta$) of 0.044. A comprehensive parametric study was conducted to optimize performance parameters including impedance bandwidth, reflection coefficient, and gain. The proposed antenna achieves peak gains of 3.4287 dB and 4.1617 dB at 2.48 GHz and 3.71 GHz respectively, with well-defined 2D and 3D radiation characteristics. These results, combined with its compact and conformal profile, make the antenna a promising candidate for integration into wearable systems and emerging on-body communication technologies.**

***Index Terms*—Wearable antenna, dual-band, ISM band, 5G NR, high-gain, flexible substrate, felt material.**

I. Introduction

The evolution of wearable electronics has necessitated the development of advanced antenna systems capable of supporting multiple wireless standards within compact and flexible form factors [1]. As applications expand across domains such as biomedical sensing, personal communication, and body-centric data transmission, there is an increasing demand for antennas that can efficiently operate over multiple frequency bands, particularly within the ISM and sub-6 GHz 5G NR spectra [3]. Achieving reliable performance in such scenarios requires antennas with dual-band functionality, low-profile geometry, and mechanical conformability [5]. Recent advancements have emphasized the use of flexible dielectric substrates and optimized geometries to ensure stable electromagnetic performance [6]. These design considerations are critical for seamless integration into wearable platforms, enabling consistent radiation characteristics, minimal power loss, and robust connectivity in on-body environments [4].

The mechanical characteristics of substrate and conductive materials are pivotal in determining the suitability of antennas for wearable application. Rigid substrates, such as FR4, while common in traditional antenna designs, are ill-suited for integration into wearable systems due to their inflexibility and inability to conform to curved or dynamic body surfaces. This lack of adaptability can lead to discomfort and functional limitations during use. To ensure reliable performance and user comfort, wearable antennas must employ flexible substrates that can endure bending and movement without degrading their electromagnetic behavior. Consequently, the integration of soft, deformable materials is a fundamental requirement for enabling antennas to operate effectively in wearable and on-body environments [6].

Recent research in wearable antenna engineering has focused on achieving dual-band operation within compact and conformal geometries to support emerging standards such as the 2.45 GHz ISM band and sub-6 GHz 5G NR [3]. Various radiating structures have been proposed to realize frequency-selective characteristics while maintaining mechanical flexibility, including modified planar monopoles, slot-loaded patches, folded dipole configurations, and shorted asymmetric grounds. Techniques such as impedance matching through stubs, defected ground structures (DGS), and parasitic element coupling have been employed to enhance bandwidth and minimize reflection losses [5]. Furthermore, the integration of high-permittivity, low-loss flexible substrates has enabled reliable electromagnetic performance under bending and stretching conditions, which is critical for maintaining stable S_{11} and gain profiles in on-body developments[[7]. These designs aim to optimize radiation efficiency, minimize SAR levels, and ensure robust performance across both frequency bands under dynamic environmental and mechanical stresses.

A dual-band antenna utilizing a folded patch configuration has been reported in [8], targeting frequency ranges of 1.7-1.9 GHz and 2.4-2.5 GHz, making it suitable for general wireless communication systems. In [9], a compact on-chip antenna designed for 2.4 GHz and 5 GHz WLAN applications is presented. This design is implemented using a cost-effective CMOS process and incorporates a meandered monopole structure alongside a parasitic element, resulting in efficient impedance matching and satisfactory radiation characteristics across both bands. Another contribution, detailed in [10], introduces a fabric-based WLAN antenna developed for integration into smart clothing. The antenna features an overall radiating area of $56 \times 51 mm^2$, supported by a $76 \times 71 mm^2$ ground plane, and has a thickness of 3mm. Gain measurements, conducted using the gain transfer technique with a standard horn antenna, report a peak gain of 6.82 dB. Additionally, the antenna achieves radiation and total efficiency levels exceeding 90% withing the operating band, confirming its viability for wearable systems.

This paper presents a high-performance, dual-band wearable antenna designed specifically for operation in the 2.45GHz ISM and sub-6GHz 5G NR frequency ranges. The antenna exhibits effective resonance across two targeted bands:2.4442–2.5200 GHz and 3.6400–3.7652 GHz, making it suitable for low-power medical, industrial, and next-generation mobile communication applications [1]. The design utilizes a flexible felt substrate characterized by a relative permittivity (ε_r) of 1.63 and a dielectric loss tangent ($\tan\delta$) of 0.044, enabling excellent mechanical flexibility along with stable RF behavior. Despite its compact dimensions of $40 \times 11.2 \times 3\ \mathrm{mm}^3$, the antenna achieves impressive peak gains of 3.4287 dB and 4.1617 dB at 2.48 GHz and 3.71 GHz. Extensive parametric studies were conducted to optimize key performance factors such as impedance bandwidth, return loss, and radiation characteristics under structural deformation [5]. These results confirm the antenna's potential for integration into wearable communication systems that demand compactness dual-band capability, and robust performance under dynamic conditions.

II. Antenna Design

The physical structure of the developed dual-band antenna is presented in Figure 1, showcasing both front layout. To accommodate wearable use, the antenna is implemented on a soft felt substrate with a low relative permittivity (ε_r) of 1.63 and a dielectric loss tangent ($\tan\delta$) of 0.044, enabling both electrical stability and physical flexibility. The total profile thickness is 3mm, suitable for seamless integration into fabric-based or body-mounted platforms. The antenna design incorporates a truncated ground plane, which assists in optimizing current distribution and impedance matching across the operating frequencies. A standard 50-ohm microstrip feedline is used to excite the radiating patch. The compact dimensions $40 \times 11.2 \times 3\ \mathrm{mm}^3$ support miniaturization without sacrificing performance.

TABLE I
Parameters of Antenna

Parameter	Dim. (mm)	Parameter	Dim. (mm)
L	40	W	11.3
L1	30	W1	2.8
L2	10	W2	0.3
L3	28.2	W3	3.3
L4	15.4	W4	0.3
L5	7.36	W5	2.7
L6	7.36	W6	1.8
L7	27.2	W7	1.6
L8	7.36	W8	0.4
L9	11.8	W9	6.1

Full-wave simulations were conducted using Ansys HFSS to evaluate key characteristics. The antenna delivers dual-band resonance, covering 2.4442–2.5200 GHz and 3.6400–3.7652 GHz, aligning with ISM and 5G NR bands, respectively. It also achieves substantial peak gain values of 3.4287 dB and 4.1617

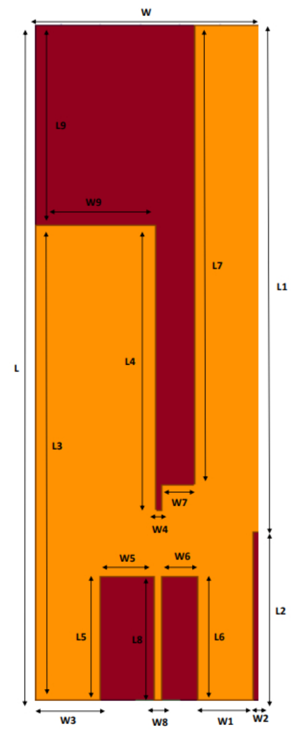

Fig. 1. Simulated reflection coefficient S_{11} response of the proposed dual-band antenna.

dB at 2.48 GHz and 3.71 GHz , indicating strong radiative efficiency and suitability for low-profile, body-centric wireless systems.

A. Design Evolution

Iteration 1 marks the initial enhancement of a wearable antenna, inspired by the design in [11], which originally functioned at a single frequency of 2.4 GHz and exhibited a gain of 2.5 dB. To improve performance, slots were introduced into the original patch configuration. This led to the creation of Iteration 1, which still operated as a single-band antenna, now resonating around 2.48 GHz.

With the aim of achieving dual-band functionality and enhancing both bandwidth and gain, additional structural changes were implemented. In Iteration 2, a horizontal slot was etched into the patch to optimize impedance matching. This modification resulted in resonance peaks at 2.4425 GHz with a return loss of -10.19 dB and at 2.5116 GHz with -10.06 dB, while a deeper resonance at 2.48 GHz showed a return loss of -22.83 dB, indicating strong impedance matching in the ISM band.

However, the design remained limited to a single operating band. To move toward dual-band behavior, Iteration 3 further modified the horizontal slot, forming two distinct radiating elements. This enabled a new resonance at 3.87 GHz with a significant return loss of -21.97 dB, indicating strong performance at a higher frequency band.

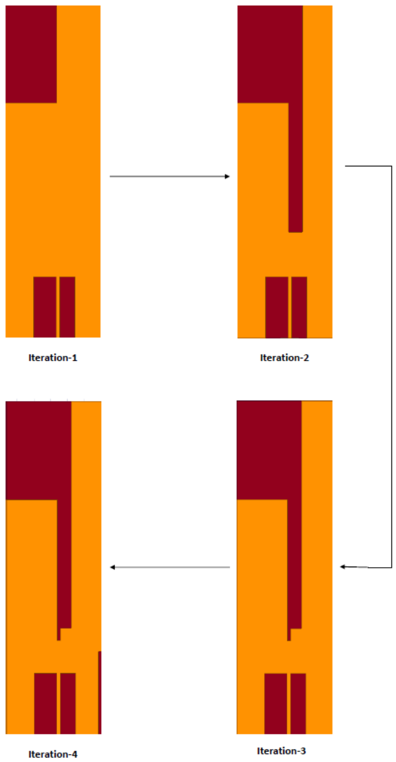

Fig. 2. Simulated reflection coefficient S_{11} response of the proposed dual-band antenna.

This led to the final modification–Iteration 4–demonstrated robust dual-band performance with sharp dips at 2.48 GHz and 3.87 GHz, making it suitable for ISM and sub-6 GHz 5G applications. The optimized slot structure played a critical role in achieving strong impedance matching and radiation performance in both frequency bands.

III. RESULTS AND ANALYSIS

The following section discusses Reflection Coefficient Analysis, Gain Analysis, Current Distribution, 2D/3D Radiation Pattern and Parametric Analysis of the antenna design.

A. *Reflection Coefficient Analysis*

The simulated reflection coefficient S_{11} response of the proposed dual-band antenna, as depicted in Figure 5, demonstrates efficient impedance matching across two distinct frequency ranges. The antenna exhibits resonant behavior at 2.48 GHz and 3.71 GHz with corresponding return loss values of -29.2559 dB and -20.3468 dB, respectively. These deep notches indicate strong radiation at both targeted frequency bands, aligning with the ISM and sub-6 GHz 5G NR requirements. The measured bandwidths are sufficiently broad to accommodate minor de-tuning effects due to bending or fabric variation, which is critical in wearable applications. Overall, the S-parameter analysis confirms the antenna's dual-band functionality and its potential for integration into compact, flexible communication modules.

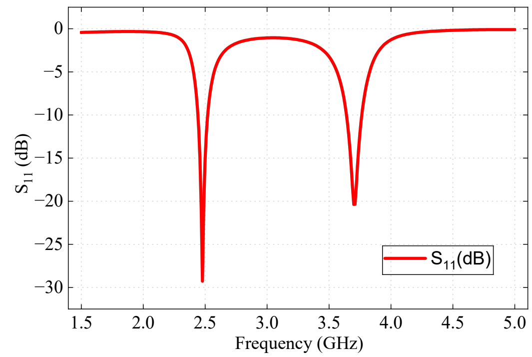

Fig. 3. Simulated reflection coefficient S_{11} response of the proposed dual-band antenna.

B. *Gain Analysis*

The simulated gain response of the proposed antenna, as depicted in Figure [4], spans the 0–8 GHz frequency range. The antenna maintains a positive gain (above 0 dB) approximately between 0.9 GHz and 5.2 GHz, indicating efficient radiation across this broad operational band. Within this range, two distinct gain peaks are observed at 2.48 GHz and 3.71 GHz, achieving values of 3.43 dB and 4.16 dB, respectively.

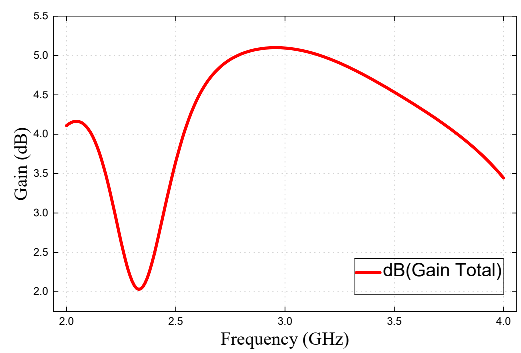

Fig. 4. Gain Total of the Dual Band Antenna

C. *Current Distribution*

The simulation image represents the surface current density distribution (Jsurf) in a planar electromagnetic structure, modeled using Ansys 2024 R2. The color gradient map illustrates variations in surface current density ranging from 2.2×10^6 to 9.99×10^7. High current concentrations, indicated by red and dark red regions, are observed along the conducting paths, suggesting efficient current flow in these segments. Conversely, the blue regions represent areas of minimal surface current, likely due to geometrical discontinuities or material boundaries that inhibit conduction. The distribution pattern reveals how the electromagnetic filed interacts with structural features, such as edges, bends, and transitions. This visualization is crucial for analyzing current crowding effects, optimizing conductor geometry, and ensuring thermal reliability in high-frequency circuit designs.

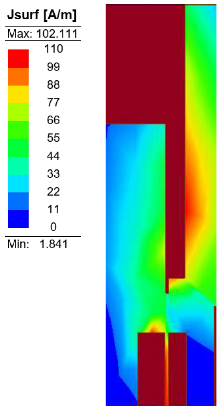

Fig. 5. Gain Total of the Dual Band Antenna

D. 2D/3D Radiation Pattern

TABLE II
RESULTS AT RESONANCES

Parameter	At 2.48 GHz	At 3.71 GHz
S_{11}	-29.2559 dB	-20.3468 dB
Gain	3.4287 dB	4.16 dB
VSWR	0.5987 dB	1.6744 dB
Front to Back Ratio	7.8878 dB	10.6383 dB

IV. CONCLUSION

This work presents a compact and flexible dual-band antenna demonstrates excellent potential for next-generation wearable and body-centric wireless systems. By leveraging a low-permittivity felt substrate and a carefully optimized truncated ground structure, the design achieves stable impedance matching and efficient radiation within the 2.4 GHz ISM band and sub-6 GHz 5G NR range. Full-wave simulation results verify dual-band operation with peak gains of 3.4287 dB and 4.1617 dB at 2.48 GHz and 3.71 GHz, respectively. The antenna's low-profile form factor, robust performance, and conformal characteristics make it well-suited for seamless integration into smart textiles and on-body communication platforms, paving the way for reliable and unobtrusive wireless connectivity in wearable applications.

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