**3D-Printed Dual-Band Antenna Design for ISM Band Biomedical Systems**

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***Abstract –*** This study presents the development, fabrication, and evaluation of a dual-band biomedical antenna designed for operation at 2.45 GHz and 5.8 GHz within the ISM bands. The antenna is produced using 3D printing technology, employing PLA material known for its biocompatibility, lightweight characteristics, and ease of fabrication. With overall dimensions of 35×35×1.7 mm³, the rectangular patch design is compact and ideal for biomedical applications such as wearable and implantable systems. To enhance performance, a microstrip line with inset feeding is incorporated, ensuring efficient power transfer and impedance match over the selected bands. Detailed analyses are conducted to assess the radiation behaviors of the antenna, including bandwidth, gain, and efficiency. Additionally, SAR simulations evaluate the safety of antenna for use near the human body, confirming compliance with international health standards. The SAR analysis demonstrates that the antenna performs safely under standard usage conditions. Experimental results align closely with simulations, validating the antenna's dual-band functionality and effectiveness. This work emphasizes the capacity of 3D printing as a cost-efficient and adaptable method for producing innovative biomedical devices, particularly for wireless communication in healthcare systems.

*Keywords –* *Dual-Band Antenna, 3D Printing, PLA, SAR, ISM Bands, Biomedical.*

1. INTRODUCTION

Wireless communication systems have become integral to modern technology, significantly influencing various aspects of daily life. Among these, the Wireless Body Area Network (WBAN) has emerged as a rapidly expanding domain within wearable technology, offering applications in healthcare, fitness, defense, public safety, and personal communication. Antennas serve as essential components in ensuring stable and efficient communication between wearable devices and external systems like smartphones or medical monitoring equipment [1, 2]. The Industrial, Scientific, and Medical (ISM) frequency bands, particularly at 2.45 GHz and 5.8 GHz, have gained prominence in wireless communication due to their global availability, license-free operation, and low power requirements. These characteristics make ISM bands ideal for biomedical applications such as health monitoring, remote diagnostics, and medical telemetry. Devices leveraging these frequencies can achieve continuous data transmission with fewer regulatory limitations [3]. Modern wireless communication systems increasingly demand multiband antennas capable of operating across multiple frequencies with minimal hardware complexity. This is especially critical for IoT and wearable applications, where size, cost, and efficiency are paramount. For ISM band applications, compact and power-efficient antenna designs are essential, particularly for body-centric devices that must operate near or directly on the human body. Antennas in these settings must account for potential interference from body tissues and surrounding materials, ensuring reliable performance in biomedical environments [4, 5].

The demand for miniaturized, efficient, and reliable antennas capable of operating at different frequencies has significantly increased, particularly for wireless communication in ISM bands. Antennas for these applications must be small, lightweight, and conformal to the device's surface, while also providing adequate isolation and radiation efficiency. Furthermore, the antennas must be able to operate reliably in harsh environments, such as extreme temperatures and humidity. Microstrip antennas, or patch antennas, have become a preferred choice for biomedical applications owing to their small form factor, lightweight design, and seamless integration into wearable devices [6]. Additionally, microstrip antennas are relatively inexpensive, making them an attractive choice for many applications. Microstrip antennas are also compatible across a broad spectrum of wireless devices, making them an ideal solution for many applications. However, conventional printed circuit board (PCB) manufacturing methods and substrate materials used in the production of these antennas pose problems in terms of environmental sustainability. In recent years, the use of environmentally friendly alternatives instead of commonly used materials has encouraged researchers [7].

The emergence of 3D printing technology has opened new avenues for antenna fabrication, particularly for biomedical applications. 3D printing allows for the design and manufacturing of complex, customized antenna geometries that traditional fabrication techniques cannot easily achieve. The ability to produce antennas with intricate structures, as well as incorporating lightweight and biocompatible materials, makes 3D printing an attractive option for wearable and biomedical antenna applications. Among these materials, Polylactic Acid (PLA) stands out due to its biodegradable and non-toxic properties, combined with its cost-effectiveness and ease of processing. As an environmentally friendly material, PLA has garnered attention for use in 3D-printed antenna substrates, offering low dielectric losses that make it ideal for high-frequency applications [8].

This paper emphasizes the development and performance analysis of a dual-band biomedical antenna optimized for 2.45 GHz and 5.8 GHz ISM band operations. PLA is used for dielectric substrate and the proposed antenna is fabricated through additive manufacturing, leveraging its biocompatibility and processing advantages. The analysis emphasizes key performance metrics, including radiation efficiency, impedance matching, and radiation patterns, ensuring compliance with the rigorous demands of biomedical applications. Furthermore, Specific Absorption Rate (SAR) evaluations are conducted to ensure the antenna operates safely when used near the human body. The findings confirm that the 3D-printed antenna effectively supports dual-band communication, offering a reliable and efficient solution for biomedical devices. By combining the advantages of ISM band frequencies, microstrip technology, and modern 3D printing, this work demonstrates a promising pathway for developing advanced wearable communication systems.

1. ANTENNA DESIGN

The antenna with dual-band capabilities presented in this study is designed and simulated using CST MWS software to ensure optimal performance at the ISM frequencies of 2.45 GHz and 5.8 GHz. The design process includes optimization to achieve precise dimensions for linear performance and efficient impedance matching. The antenna utilizes a PLA substrate having a relative permittivity (𝜀r) of 2.8, chosen for its biocompatibility and ease of fabrication. The total dimensions of the antenna are 35×35×1.7 mm3 as illustrated in Fig. 1. Copper tape is used as the conductive material for its cost-effectiveness and high conductivity. A modified ground plane with dimensions of 35×26.3 is implemented to enhance the reflection coefficient. The radiating patch features a 180° rotated U-shaped slot, which facilitates the generation of the higher frequency band while contributing to size reduction. Additionally, the ground plane includes a rectangular slot measuring 3mm×20 mm, designed to improve impedance matching and expand the bandwidth. For excitation, a microstrip inset feed line is implemented, having a feed width of 3.1 mm and length of 14.6 mm, ensuring effective power transfer and stable dual-band operation. This compact and sustainable design supports ISM band applications with effective performance in dual-band operations.

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Fig. 1. The proposed dual-band 3D printed antenna: (a) Top view, (b) Bottom view

1. Design Methodology

The design methodology of the proposed antenna follows a systematic approach to achieve efficient performance at the target 2.45 GHz and 5.8 GHz frequencies. The design process starts with selecting an appropriate substrate material, ensuring optimal electrical and mechanical properties. For this study, a biodegradable material PLA with a dielectric constant of 2.8 and a thickness of 1.7 mm was selected. PLA's eco-friendly nature and suitability for 3D printing make it an ideal choice for this design.

The design of the presented antenna begins by utilizing traditional patch antenna equations to determine the initial dimensions of the patch. These equations serve as the foundation for the optimization process and are essential for achieving efficient resonance at the target frequencies [9]. Firstly, the patch width (*Wp*) can be calculated using the following equation:

(1)

Here, 𝑐 denotes the velocity of light in free space (3×10 8 m/s), *fr ​* denotes the resonant frequency and εr ​ indicates the substrate's relative dielectric constant. This equation provides the fundamental width of the patch, which is essential for establishing resonance at the desired frequency. Next, the effective dielectric constant (𝜀eff) is calculated to account for the effects of the substrate height (ℎ), dielectric constant (εr), and the calculated patch width (*Wp*). This is given by the equation:

(2)

The effective permittivity considers the impact of the substrate’s physical properties on the overall behaviour of the antenna, ensuring more accurate predictions of the its performance. Once 𝜀eff is known, the effective length (𝐿eff) of the patch can be computed using the formula below.

(3)

The real patch length (𝐿p) is then determined by adjusting the effective length for the fringing fields at the sides of the patch, using the length extension (Δ𝐿) calculated as:

(4)

Finally, the patch length is given by:

(3)

These equations provide the starting dimensions for the patch antenna. For the 2.45 GHz frequency, the patch dimensions are calculated to be approximately 53.2 mm in width and 41 mm in length. For the 5.8 GHz frequency, the corresponding patch dimensions are approximately 25.4 mm wide and 20.5 mm long. Proposed antenna dimensions are generally suitable for the 5.8 GHz frequency, but additional modifications are necessary to achieve dual-band operation.

The design process progressed through several stages to improve the performance of antenna. The traditional antenna design was first developed, followed by the inclusion of the inset feed. This modification was made to improve impedance matching, resulting in better power transfer and reducing reflection losses. A partial ground plane was then added to enhance the radiation performance and enhance the total performance of the antenna. As mentioned by Ahmad, et al. [10], incorporating slots into the radiating element of the antenna can enable the generation of multiple resonances at different frequencies. This was followed by the addition of U-slot and ground slot structures that are crucial in extending the effective length of the antenna and thus achieving resonance at both frequencies. The proposed antenna design offers optimum performance for both resonant frequencies, making it suitable for dual-band biomedical applications.

1. RESULTS AND DISCUSSION

The substrate of the antenna is fabricated with Ultimaker 2+ commercial 3D printer using FDM (Fused Deposition Modelling) technique. The ground and patch parts of the antenna are formed by adhering copper tape on the produced substrate. Finally, the antenna prototype was created by soldering the SMA connector. The manufactured antenna model is illustrated in Fig. 3, highlighting its compact design and key features such as inset feed, partial ground plane and slot structures. This fabrication method provides a strong yet lightweight structure, making the antenna ideal for wireless communication applications.

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Fig. 2. Manufactured prototype of the dual-band 3D printed antenna: (a) Top view, (b) Bottom view

To evaluate the performance of the fabricated antenna, return loss measurements were carried out using the Keysight N5224A PNA Microwave Vector Network Analyzer. These measurements are critical for assessing the antenna’s impedance matching and resonance behavior at the target frequencies. The results, as presented in Fig. 3, show a strong agreement between the simulated and experimental results, verifying the precision of the design. Both results are almost identical, confirming that the antenna operates as expected and delivers efficient performance in the 2.45 GHz and 5.8 GHz ISM bands.



Fig. 3. Comparison of simulated and measured return loss

The radiation characteristics of the antenna were examined through 3D radiation patterns at the resonant frequencies of 2.45 GHz and 5.8 GHz. As depicted in Fig. 4, at 2.45 GHz, the antenna exhibits bidirectional radiation in the *xz*-plane (*E*) and omnidirectional radiation in the *yz*-plane (*H*). In contrast, at 5.8 GHz, the radiation pattern becomes directional in the *xz*-plane, while maintaining omnidirectionality in the *yz*-plane. The antenna demonstrates reliable performance across both the 2.45 GHz and 5.8 GHz ISM frequency ranges, with peak gains of 3.5 dBi and 3.92 dBi, respectively.

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Fig. 4. 3D radiation patterns of the proposed 3D printed antenna (a) at 2.45 GHz (b) at 5.8 GHz.

Fig. 5 depicts the current flow distribution across the antenna. At 2.45 GHz, the current primarily accumulates around the perimeter of the slots, as depicted in Fig. 5(a). Conversely, at 5.8 GHz, the highest current concentration is observed near the patch edges and U-shaped slot, as shown in Fig. 5(b).

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Fig. 5. Surface current distributions of the proposed 3D printed antenna (a) at 2.45 GHz (b) at 5.8 GHz.

1. SAR Analysis

The human body can be influenced by the near-field radiation emitted by biomedical antennas, making it crucial to consider the power absorbed by the body. Reactive near-field energy, which is non-radiating, accumulates around the antenna and can result in heating effects in nearby lossy materials, including human tissue. Specific Absorption Rate (SAR) is a widely recognized metric for quantifying the electromagnetic power absorbed by biological tissues. According to FCC and IEEE standards, the maximum allowable SAR value is 1.6 W/kg, averaged over 1 gram of tissue [11, 12]. A three-layer numerical phantom was developed as shown in Fig. 6.

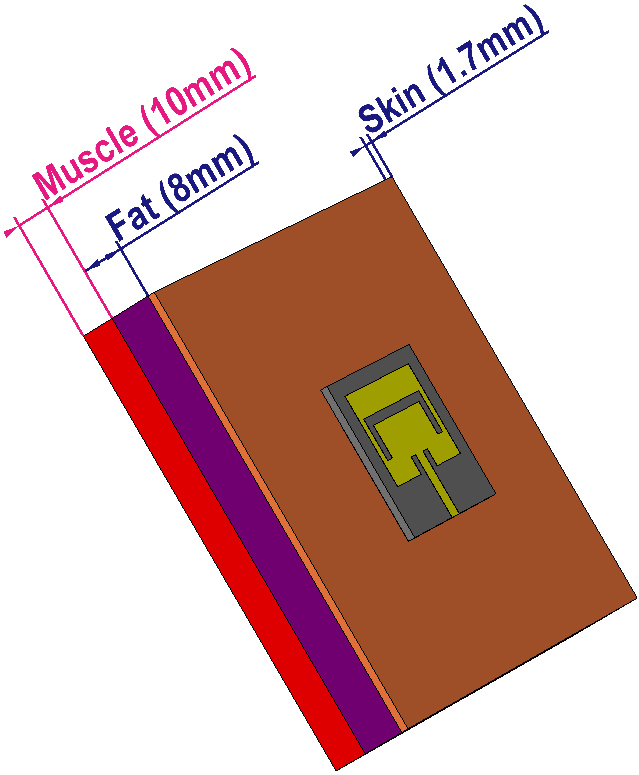


Fig. 6. Numerical model of the proposed 3D printed antenna on a three-layer tissue model

The phantom consisted of layers representing skin, fat, and muscle. The electrical properties at the operating frequencies, along with the thickness of each layer, were derived from [11]. At an input power of 0.1 W, the SAR values are 0.754 W/kg at 2.45 GHz and 0.316 W/kg at 5.8 GHz. These values are significantly lower than the maximum safety limit, ensuring the safety of the tissues.

1. CONCLUSION

This study emphasizes the design and performance evaluation of a dual-band antenna intended for biomedical uses, specifically tuned to the 2.45 GHz and 5.8 GHz ISM band frequencies. The antenna, prototyped using a biodegradable Polylactic Acid (PLA) substrate and 3D printing technology, demonstrated excellent performance for wireless communication in healthcare and other wearable applications. Its small size, dual-band operation, and efficient radiation characteristics make it a promising solution for modern biomedical devices. Simulation and experimental results confirm that the antenna provides good impedance matching, low return loss, and stable performance at the target frequencies. The radiation characteristics confirm that the antenna operates efficiently in both the 2.45 GHz and 5.8 GHz bands, with peak gains of 3.5 dBi and 3.92 dBi, respectively. Additionally, SAR analysis revealed that the antenna operates well within the safety limits for human tissue, ensuring its safe use in wearable devices. The low SAR values at both frequencies indicate minimal risk of harmful heating effects on the human body.

In conclusion, the proposed 3D-printed antenna offers a compact, efficient, and environmentally friendly solution for biomedical and wearable applications, providing reliable communication without compromising safety. The use of 3D printing technology and eco-friendly materials like PLA opens new possibilities for designing sustainable antennas in the healthcare and IoT industries.

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