RESEARCH ARTICLE

Design of Ultra-Wideband (UWB) Microstrip Patch Antenna for Biomedical Telemetry Applications

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Abstract

The emergence of ultra-wideband (UWB) technology, following the FCC's allocation of the 3.1-10.6 GHz spectrum for unlicensed use, has significantly advanced short-range wireless communication, particularly in biomedical telemetry. This paper proposes a compact UWB microstrip patch antenna (32×32×1.6 mm³) designed for biomedical applications such as brain tumor detection, cancer screening, and health monitoring. The antenna incorporates a miniaturized radiating patch with stair-step and serrated slot structures, as well as a defected ground configuration to enhance impedance bandwidth and reduce electromagnetic interference. It achieves effective operation across the 2.48-10.8 GHz range and integrates multiple band-notch features to suppress unwanted signals from WiMAX, WLAN, 5G, and satellite services. With its compact footprint, wide bandwidth, and selective rejection characteristics, the proposed antenna is well-suited for microwave medical imaging and wearable biomedical systems.

Keywords: ultra-wideband (UWB), microstrip patch antenna, telemetry device, biomedical application.

1 Introduction

Ultra-wideband (UWB) technology has attracted considerable interest in recent years, primarily for its capability to deliver high data rates over short distances while maintaining low power consumption. In 2002, the Federal Communications Commission (FCC) approved the unlicensed use of the 3.1-10.6 GHz frequency band for UWB applications, thereby paving the way for extensive research and development in this domain. This wide spectrum availability has enabled the design of compact and efficient antennas, particularly for biomedical telemetry and other applications, where reliable and safe wireless communication is essential [1–4]. Despite the wide range of applications enabled by UWB technology, a significant challenge remains electromagnetic interference with existing narrowband communication systems that operate within or adjacent to the UWB spectrum. Notable examples include IEEE 802.16 WiMAX at 3.5 GHz (3.3-3.7 GHz), IEEE 802.11a WLAN at 5.2 and 5.8 GHz (5.15-5.82 GHz), and X-band satellite downlink services at 7.1-7.9 GHz. Furthermore, the rapid deployment of 5G networks introduces additional spectral overlap, particularly within the C-band (3.3-4.2 GHz) allocated for fixed satellite services, the 3.3-3.8 GHz band for 5G cellular

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communication, and the 4.5-5.5 GHz range used for lower-band 5G applications [5–8]. These overlaps can severely degrade UWB system performance if not addressed through proper interference mitigation. Therefore, the integration of band-notch functionality into UWB antenna design has become crucial to ensure coexistence with these licensed systems while maintaining reliable and interference-free communication, especially in sensitive biomedical environments.

Recent advancements in microelectronics and medical technologies have significantly increased interest in biotelemetry devices. These devices, designed for applications such as glucose monitoring, retinal prostheses, and intracranial pressure (ICP) monitoring, require reliable wireless communication with external systems, necessitating the use of implantable antennas. However, antenna design for such devices faces critical challenges including tissue-induced signal loss, stringent size constraints, biocompatibility, and spectrum licensing. While the Medical Implant Communication Service (MICS) offers a globally license-free band for biomedical use, access to Industrial-Scientific-and-Medical (ISM) bands—such as 902-928 MHz and 2400-2483.5 MHz in the United States is regulated and varies by region [9]. Due to space limitations, implantable components must be miniaturized, often compromising radiation performance at lower frequencies. To overcome this, higher-frequency or multi-band designs are explored to enhance functionality. For example, Huang et al. [10] proposed a triple-band system supporting data transmission, wireless powering, and wake-up control, while Das et al. [11] demonstrated wireless power and data communication for a leadless pacemaker. However, their design presents several challenges, including miniaturization, biocompatibility, bandwidth enhancement, detuning, and patient safety. Multipath interference and polarization mismatch further affect performance, prompting research into circularly polarized antennas to improve reliability and reduce bit error rates. Antennas used in IMDs must maintain stable performance within the human body and meet specific absorption rate (SAR) limits. As biomedical telemetry evolves, these technologies not only enhance diagnostic accuracy and treatment effectiveness but also reduce hospitalization time, offering both healthcare and economic benefits [12–14].

To address the challenges, this paper proposes a compact UWB microstrip patch antenna with dimensions of $32\times32\times1.6$ mm^3, tailored for biomedical applications such as brain tumor detection, cancer screening, and health monitoring. The antenna features a miniaturized radiating patch incorporating stair-step and serrated slot geometries, along with a defected ground structure to enhance impedance bandwidth and mitigate electromagnetic interference. It operates efficiently over a wide frequency range of 2.48-10.8 GHz and integrates multiple band-notch characteristics to suppress interference from coexisting systems, including WiMAX, WLAN, 5G, and satellite services. Owing to its compact size, broad bandwidth, and interference rejection capabilities, the proposed design is a strong candidate for microwave medical imaging and wearable biomedical telemetry systems.

The structure of the paper is as follows: Section II provides a review of related work. Section III describes the proposed antenna design in detail. Section IV presents and discusses the simulation results. Finally, Section V concludes the paper.

2 Related Work

Several studies have focused on designing low-profile ultra-wide band (UWB) antennas with broad impedance bandwidths for biomedical applications. For instance, a compact planar microstrip antenna with stair-step and open-slot modifications was developed to cover 3.06-11.4 GHz, though it lacked band-notch functionality [1–6]. The UWB frequency range of 3.1-10.6 GHz overlaps with several existing wireless communication systems, such as the wireless local area network (WLAN), which operates in the 5.15-5.825 GHz band. This spectral overlap can lead to mutual interference, highlighting the need for UWB antennas with integrated notch-band characteristics to suppress unwanted signals. In response, various notch-band UWB antennas have been developed over recent years [15–21]. While [17–19] introduced single, dual, and triple notch bands respectively, these designs generally lack sharp frequency selectivity. Later works, such as [20, 21], achieved better notch-band performance; however, [20] experienced instability in return loss when tuning the notch frequency, and [21] had limited controllability over the notched band. Furthermore, none of these existing designs employ differential feeding structures, which can offer improved performance in certain applications.

Flexible UWB antennas fabricated on substrates such as Rogers RT/duroid 5880 have also been proposed, achieving bandwidths of 3.5-14 GHz, particularly for breast cancer detection [22]. In addition to

UWB designs, multi-band and triband antennas have been investigated for operation in ISM, MICS, and MedRadio bands. A five-band skin-implantable system integrated with biosensors and dummy electronics is presented in [9], while a compact triple-band antenna of 254 mm^3 successfully operates in MICS and ISM bands [10]. Miniaturized loop and patch antennas tailored for in-body environments have demonstrated effective impedance matching and size reduction, such as a 7×7×0.2 mm^3 antenna with -12 dBi gain at 2.45 GHz [23]. Simulation-based optimization has been employed to enhance miniaturization without sacrificing performance, achieving coverage from 5-10 GHz [24]. The influence of substrate materials has also been analyzed, with prototypes on FR4, polyester, and fleece achieving wide bandwidths (3-12 GHz) and return losses up to -49 dB [25]. The impact of human tissue on antenna performance remains a significant concern. Studies report degradation up to -7 dB when antennas are implanted in human limbs, underscoring the importance of biocompatible and efficient designs [26]. Additionally, variations in impedance properties due to the dielectric nature of internal tissues such as the lungs have been observed in torso models [27]. Research has also explored off-body and on-body antenna designs for wireless body area networks (WBANs), including triband and ring-slot configurations with favorable VSWR and radiation patterns [28]. In [29], the importance of WBAN in remote patient monitoring is emphasized, along with a discussion on architectural limitations and future enhancements using Software Defined Networking (SDN), Energy Harvesting (EH), and Blockchain technologies. In [30], various WBAN protocols and technologies for healthcare monitoring are compared, with emphasis on communication parameters, security, energy efficiency, and mobility to identify optimal solutions for medical applications.

Despite substantial progress, existing studies face limitations such as incomplete UWB coverage and the absence of integrated band-notch features to mitigate interference from WiMAX, WLAN, and 5G signals. Furthermore, ensuring patient safety remains paramount in the design of implantable medical devices, particularly the antennas.

3 Antenna Configuration and Parametric Analysis

To design an efficient microstrip patch antenna (MPA), careful selection of substrate material and design parameters is essential, as single-element MPAs typically suffer from low gain and narrow bandwidth. The substrate not only provides mechanical support but also influences electromagnetic behavior by stabilizing fields and facilitating displacement currents, which are crucial for sustaining wave propagation. To enhance radiation efficiency, reduce antenna size, and achieve band rejection for WiMAX, WLAN, 5G, and satellite applications, a low-loss dielectric material is preferred. In this work, Rogers RT/duroid 5880 is selected for its low dielectric constant ($\varepsilon_r \approx 2.2$) and suitability for high-frequency applications. The proposed UWB antenna is designed with a resonance frequency of 6.5 GHz and compact dimensions of $32 \times 32 \times 1.6$ mm^3. A 3mm wide quarter-wave transformer feed line with 50-ohm impedance is used to ensure efficient power transfer. Both the microstrip line and ground plane are implemented on the same substrate to optimize overall antenna performance.

As part of the antenna design procedure, the radiating patch length (L_p) and width (W_p) are calculated based on the specified resonant frequency (f_r), dielectric constant (ε_r), and substrate height (h), using the following standard equations. Patch width (W_p) can be calculated as:

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$$W_p = \frac{c}{2f_r\sqrt{(\varepsilon_r+1)/2}}, \tag{1}$$

Patch length (L_p) can be calculated as:

$$\varphi = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left[1+12\frac{h}{W_p}\right]^{-1/2}, \tag{2}$$

$$\phi = \frac{c}{2f_r\sqrt{\varphi}}, \tag{3}$$

$$\Delta = 0.412h \cdot \frac{(\varphi+0.3)\left(\frac{W_p}{h}+0.264\right)}{(\varphi-0.258)\left(\frac{W_p}{h}+0.8\right)}, \tag{4}$$

$$L_p = \phi - 2\Delta. \tag{5}$$

where c is the speed of light (3x10^8). The feed line width and inset length of the antenna were determined using standard microstrip transmission line theory, and were calculated using the following expressions:

$$\psi = \frac{7.48 \times h}{e^{\left(Z_o\frac{\sqrt{\varepsilon_r+1.41}}{87}\right)}} - 1.25 \times t \tag{6}$$

$$\sigma = \frac{L_p}{\pi}\cos^{-1}\left(\sqrt{\frac{Z_o}{\omega_{in}}}\right) \tag{7}$$

Table 1. The physical dimensions of the proposed antenna are presented below.

Parameters	Dimensions (mm)	Parameters	Dimensions (mm)
Frequency f_r	1–14 GHz	Patch height, H_s	0.035
Substrate height, h	0.8155	Patch length, L_p	12.94
Dielectric constant, ε_r	0.8149	Patch width, W_p	16.35
Substrate length, L_s	32	Fid-line length, L_f	9
Substrate width, W_s	32	Fid-line width, W_f	4.971

where ψ represents the width of the microstrip feed, inset length is denoted as σ, input impedance is Z_o, ω_{in} is input resistance. The width of the ground plane is denoted as W_g and the length of the ground plane is L_g can be calculated as following equations:

$$W_g = 6h + W_p \tag{8}$$

$$L_g = 6h + \alpha \tag{9}$$

After determining the dimensions of the radiating patch, feed line, and ground plane, the antenna was modeled and simulated using CST Microwave Studio (CST MWS). The initial antenna geometry, shown in Figure 1, is based on a Rogers RT/duroid 5880 substrate with a thickness of 1.6 mm and overall dimensions of 32×32 mm^2. A rectangular radiating patch measuring 16.35×12.94 mm^2 is placed on the top surface, while the ground plane, measuring 9.07×32 mm^2, features a stair-step structure and a circular slot to enhance bandwidth. Both the patch and ground are made of 0.035 mm thick annealed copper. The antenna supports a UWB frequency range from 3.1 GHz to 12.88 GHz, maintaining a VSWR below 2, indicating good impedance matching and suitability for UWB applications. Final optimized parameters obtained through iterative tuning in CST are summarized in Table 1.

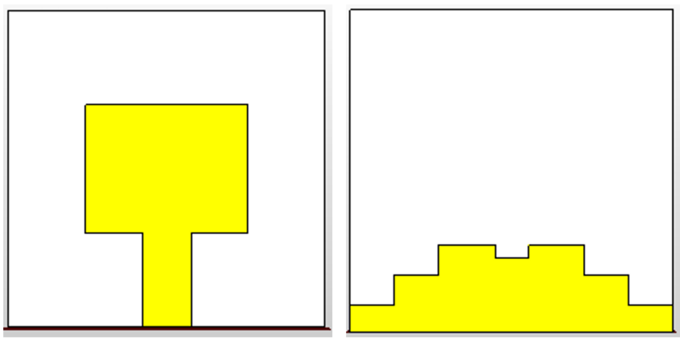

Figure 1. Geometry of initial patch antenna.

Figure 2 The proposed UWB antenna is specifically designed for biomedical applications, featuring three strategically placed slots to introduce band-notch characteristics targeting existing communication bands. The top slot suppresses WiMAX interference by introducing a notch between 3.1-4.3 GHz, while the middle and bottom slots reject WLAN (4.5-5.8 GHz) and satellite (8.02-8.7 GHz) bands, respectively. The antenna operates over a wide bandwidth of 2.4-10.88 GHz, achieving a radiation efficiency of 77%. It provides a minimum return loss of -19.28 dB across the UWB band and a maximum return loss of -1.61 dB at the notch frequencies, confirming strong band-rejection capabilities. These characteristics make it highly suitable for next-generation biomedical telemetry systems.

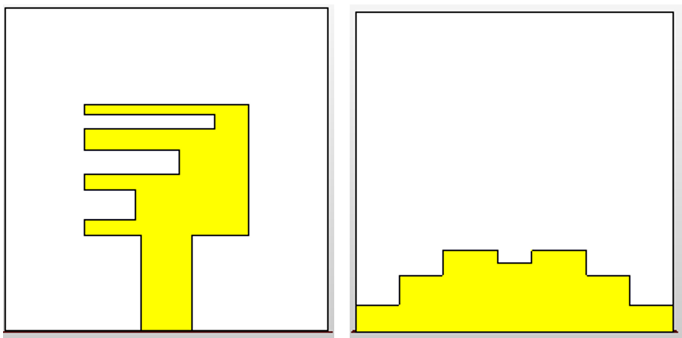

Figure 2. Geometry of proposed patch antenna.

4 Result Analysis

The proposed ultra-wideband microstrip patch antenna was simulated using CST Microwave Studio (CST MWS). The simulated results are presented and analyzed in this section. The antenna design utilizes the optimally tuned parameters listed in Table 1.

The simulated S-parameter ($|S_{11}|$) response of the proposed antenna, as depicted in Figure 3, covers a frequency range of 0–12 GHz, with resonance observed between 2.46 GHz and 10.88 GHz, closely aligning with the UWB spectrum. The antenna exhibits two intentional band-notches to mitigate electromagnetic interference with existing narrowband services operating within the UWB range. The first notch, spanning from 3.21 GHz to

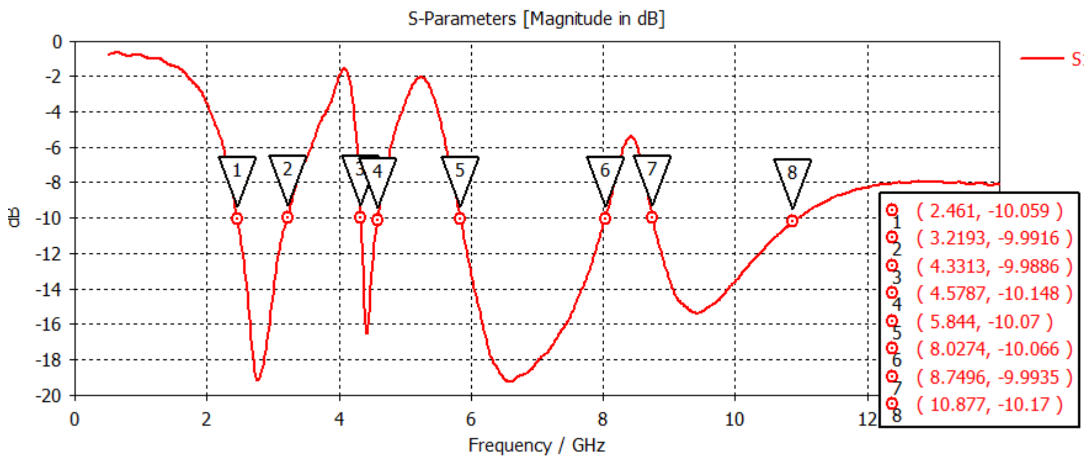

Figure 3. Return loss (S11) parameter for proposed UWB Micro-strip antenna.

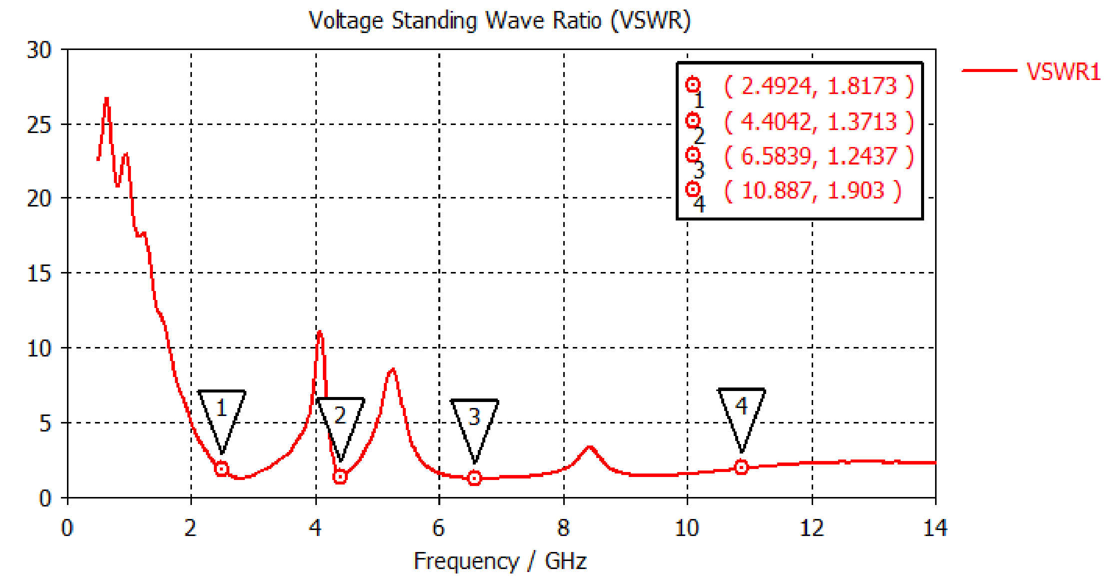

Figure 4. VSWR plot for parameter for proposed UWB Micro-strip antenna.

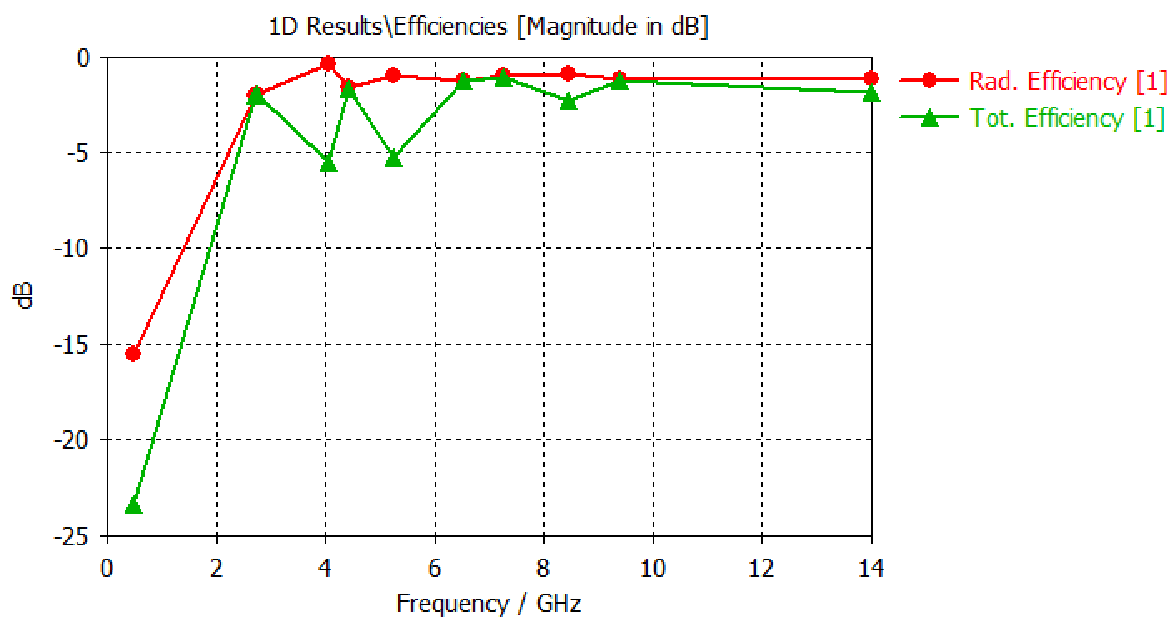

Figure 5. Radiation efficiency plot of Proposed UWB micro-strip antenna.

4.33 GHz, effectively suppresses interference from IEEE 802.16 WiMAX (3.3–3.7 GHz) and ongoing 5G services within the C-band (3.3–4.2 GHz), particularly the 3.3–3.8 GHz band allocated for 5G cellular communication. The second notch, covering 4.5–5.8 GHz, targets the lower 5G frequency band (4.5–5.5 GHz). The antenna achieves good impedance matching ($|S_{11}| < -10$ dB) at eight resonant frequencies: 2.46, 3.22, 4.33, 4.58, 5.84, 8.03, 8.75, and 10.88 GHz. These multiple resonances and notched characteristics validate the antenna's UWB performance and its suitability for interference-free biomedical and wireless communication applications.

Figure 4 shows the simulated VSWR of the proposed UWB antenna from 0 to 14 GHz. Favorable impedance matching (VSWR < 2) is achieved at 2.49, 4.40, 6.58, and 10.88 GHz, with a minimum VSWR of 1.24 at 6.58 GHz, confirming efficient power transfer and reliable broadband performance for UWB applications. Fig. 5 shows the radiation and total efficiency of the proposed UWB antenna. The radiation efficiency remains near 0 dB across most of the band, while the total efficiency stays above -2 dB after 3 GHz, confirming good performance with minimal losses across the UWB range.

5 Conclusion

In this work, a compact UWB microstrip antenna has been designed, simulated, and analyzed for biomedical and wireless communication applications. The proposed antenna achieves a wide operating bandwidth ranging from 2.46 GHz to 10.88 GHz, covering the essential UWB spectrum. It exhibits stable impedance matching multiple resonant frequencies and integrated band-notch characteristics to suppress interference from existing narrowband systems such as WiMAX and 5G sub-6 GHz bands. The top slot introduces a notch between 3.1-4.3 GHz to suppress WiMAX interference, while the middle and bottom slots create notches at 4.5-5.8 GHz and 8.02-8.7 GHz to reject WLAN and satellite bands, respectively. This antenna operates effectively over the 2.4-10.88 GHz range, fully covering the UWB spectrum with a radiation efficiency of 77%. Achieving a peak return loss of -19.28 dB and efficient rejection at interference bands, this antenna offers a compact, reliable, and interference-resilient solution, making it a strong candidate for next-generation wearable biomedical and UWB communication systems.

Data Availability Statement

Data will be made available on request.

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Conflicts of Interest

The authors declare no conflicts of interest.

Ethical Approval and Consent to Participate

Not applicable.

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