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REGULAR ARTICLE

Compact Omnidirectional UWB Trapezoidal-Slot Antenna Design for IoT Applications

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(Received 05 August 2025; revised manuscript received 15 December 2025; published online 19 December 2025)

This paper presents the design and performance analysis of a compact ultra-wideband (UWB) antenna optimized for smart industrial applications. The proposed antenna achieves broad impedance bandwidth from 2 GHz to 10 GHz with omnidirectional radiation characteristics, making it suitable for diverse industrial environments requiring robust and seamless connectivity. Fabricated on a compact 30 mm × 25 mm FR4 epoxy, the antenna incorporates an *L*-shaped slot in the ground plane to enhance impedance matching and bandwidth without increasing its physical size. Experimental results demonstrate strong agreement with simulated data, showing |S11| values below – 10 dB across the UWB range and stable gain levels from 2 dBi to 4 dBi. Three-dimensional radiation pattern measurements were conducted to assess the antenna's performance comprehensively, confirming consistent omnidirectional coverage across key frequencies and ensuring reliable device communication in varied orientations. The proposed UWB antenna's compact size, omnidirectional radiation, and broad bandwidth make it a promising solution for smart industrial systems, where spatial constraints and high-performance wireless connectivity are paramount.

Keywords: Ultra-wideband antenna, Trapezoidal monopole, Smart industrial applications, Omnidirectional radiation.

DOI: 10.21272/jnep.17(6).06015 PACS number: 84.40.Ba

1. INTRODUCTION

The Ultra-Wideband (UWB) technology, initially conceptualized in the 1960s through impulse-response analysis of linear time-invariant systems, has advanced considerably, especially after its initial deployment in military sectors for secure communication and radar applications [1]. For several decades, UWB was limited to governmental and defense-related operations. However, regulatory developments in the early 2000s led the federal communications commission to allocate the 3.1–10.6 GHz spectrum for civilian use in indoor wireless communication systems. This regulatory shift spurred substantial research interest, catalyzing industry initiatives like the WiMedia Alliance, which promoted seamless device interoperability in personal area networks [2]. Despite these efforts, the rise of alternative standards like IEEE 802.11ac eventually led to a decline in UWB research and development activities. Recently, UWB has regained attention for its capabilities in high-precision positioning and reliable signal propagation, which are highly advantageous for tracking and localization in industrial environments [3]. Unlike conventional positioning technologies such as GPS, which is limited by line-of-sight constraints, or Wi-Fi and Bluetooth, which offer comparatively lower accuracy in indoor applications, UWB enables optimized performance. Its ultrashort pulse-based communication facilitates high data throughput, resilience to multipath interference, and immunity to frequency-selective fading, which are critical for robust, high-security transmission in complex environments [4].

UWB-based indoor positioning systems for industrial applications necessitate antennas that exhibit broad bandwidth, omnidirectional radiation patterns, and compact form factors to facilitate seamless integration within spatial constraints. Recent research has focused on innovative miniaturization techniques to meet these requirements [5]. For instance, biconical antennas have been employed to achieve directional radiation with minimized back emissions, although their larger size can hinder compact integration [6]. Additionally, large ground planes have been shown to effectively shield the

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Cite this article as: G.Ch. Ram et al., *J. Nano- Electron. Phys.* 17 No 6, 06015 (2025) https://doi.org/10.21272/jnep.17(6).06015

body or surrounding equipment from electromagnetic interference, thereby enhancing performance; however, this design approach often results in increased dimensions and reduced flexibility, which are critical for wearable devices in industrial settings [7]. Efforts to develop compact, flexible antennas have led to the introduction of unidirectional designs that operate effectively within the 0.55-3 GHz frequency range while adhering to regulatory limits on specific absorption rates [8]. Such configurations are particularly advantageous for on-body industrial applications, ensuring user safety without compromising antenna performance. Furthermore, precision imaging applications have spurred the design of compact antennas capable of operating in the 1.1-1.9 GHz and 1-4.3 GHz bands [9]. These antennas are essential for automated inspection and asset tracking systems, where reliable performance is paramount for operational efficiency in smart industrial environments [10].

Advancements in multi-band and implantable antennas have also been noteworthy, with designs incorporating split ring resonators and meander line loading to achieve narrowband performance suitable for biotelemetric applications [11]. The integration of artificial magnetic conductor structures in circularly polarized monopole antennas has been explored to enhance gain and SAR performance, making them suitable for high-density wireless environments typical of industrial applications [12]. Fractal-inspired antenna designs, such as Koch curve configurations, have demonstrated significant miniaturization while maintaining broad operational bandwidths, offering the adaptability required for various industrial IoT applications [13]. However, designing compact, wideband, omnidirectional antennas for UWB in industrial environments presents significant technical challenges. These challenges include strict constraints on antenna size, and stable performance across diverse operating conditions. An omnidirectional radiation pattern is particularly crucial in industrial settings to ensure uniform coverage and reliable signal reception, regardless of device orientation. Addressing these requirements is essential to establish robust UWB connectivity in applications like asset tracking, automated process monitoring, and wireless sensor networks, which are integral to the infrastructure of smart industrial systems [14, 15].

In this work, we propose a compact UWB planar antenna with omnidirectional coverage to enable reliable communication between devices across diverse locations in the frequency range of 2 GHz-10 GHz. The design process follows a two-step approach: first, a rectangular radiator is established as the primary structure, providing a compact and efficient configuration; second, an *L*-shaped slot is incorporated into the ground plane to enhance bandwidth and improve impedance matching across the targeted frequency range. This streamlined design method yields an antenna capable of supporting robust connectivity in smart industrial applications, addressing the demands of IoT-driven environments.

2. ANTENNA DESIGN

The proposed UWB antenna design, as illustrated in Fig. 1, combines the benefits of a planar trapezoidal monopole with a quarter-wave open slot in the ground plane, providing broad impedance bandwidth and an omnidirectional radiation pattern, making it well-suited for smart industrial applications. Fabricated on an FR4 substrate with a dielectric constant of 4.3 and a thickness of 1 mm, the antenna achieves compact dimensions and stable radiation characteristics across a frequency range of 2 GHz to 10 GHz. A 50-ohm coaxial feed is used to directly connect the feed line to the base of the trapezoidal monopole, ensuring efficient energy transfer. The main radiating element is a planar trapezoidal monopole, whose width gradually increases from the base to the top. This trapezoidal shape provides a broadband impedance profile due to the gradual width transition, which improves the impedance bandwidth over a standard rectangular monopole by allowing a smoother impedance transition, especially at the beveled bottom edges. To further extend the impedance bandwidth, a quarter-wave open slot is introduced asymmetrically in the ground plane below the trapezoidal monopole.

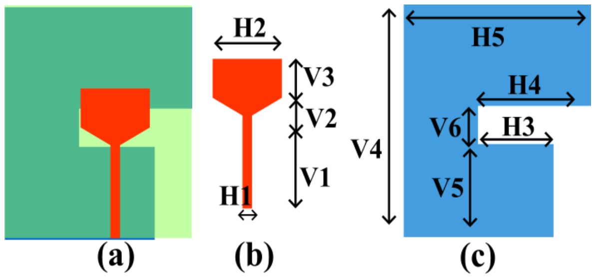

Fig. 1 – (a) The configuration of the proposed UWB trapezoidal antenna (b) Top view of trapezoidal antenna (b) bottom view of proposed antenna

This slot, with a length designed to be approximately a quarter wavelength at the lowest operating frequency, introduces an additional resonance, enhancing the low-frequency response and supporting the UWB profile. The optimized geometrical parameters are $V_1 = 12.1$, $V_2 = 4.3$, $V_3 = 9.8$, $V_4 = 30$, $V_5 = 8.2$, $V_6 = 3.5$, $H_1 = 1.8$, $H_2 = 11.2$, $H_3 = 13.6$, $H_4 = 7.5$, and $H_5 = 25$ (all dimensions are in mm).

3. RESULT AND DISCUSSION

To validate the design, a fabricated model of the compact UWB antenna underwent rigorous 3D measurement in an anechoic chamber as shown in Figure 2. The experimental setup confirmed the antenna's functionality, verifying its compact form and suitability for spatially constrained environments typical of smart industrial applications.

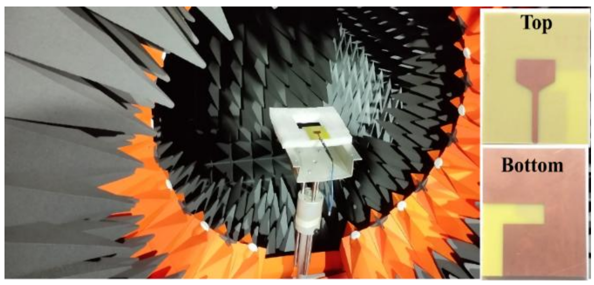

Fig. 2 – Photograph of the fabricated UWB trapezoidal antenna with 3D experimental setup

The measured and simulated *S*-parameter results (Fig. 3) demonstrated strong impedance matching across the entire frequency range, with |S11| maintained below – 10 dB, indicating efficient signal transmission with minimal reflection losses. Minor discrepancies observed between simulated and measured data, particularly at lower frequencies, are likely attributable to fabrication tolerances and the experimental setup; however, overall correspondence between data sets validates the effectiveness of the design.

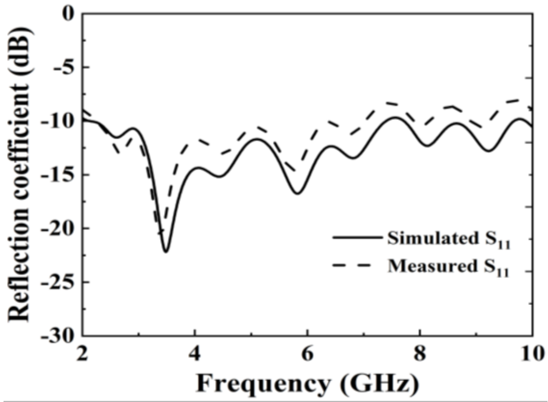

Fig. 3 – Simulated and measured *S*-parameters of the proposed UWB antenna

Radiation pattern measurements at 2 GHz, 6 GHz, and 10 GHz (Fig. 4) reveal a near-omnidirectional pattern, essential for ensuring consistent connectivity across various orientations in industrial environments. Simulated and measured azimuthal and elevation patterns (Figs. 5-7) confirm stable omnidirectional coverage across the UWB range, further supporting the antenna's reliability in smart industrial settings where communication with devices across multiple positions is required. The antenna achieves an average gain of approximately 3 dBi across the frequency range (Fig. 8), with stable gain values from 2 dBi to 4 dBi, effectively balancing connectivity with low power consumption in dense industrial settings. The incorporation of an *L*-shaped slot in the ground plane significantly enhanced the antenna's bandwidth, achieving the desired wideband characteristics. Comparative simulations without this modification demonstrate the slot's role in optimizing impedance matching without increasing the overall antenna size.

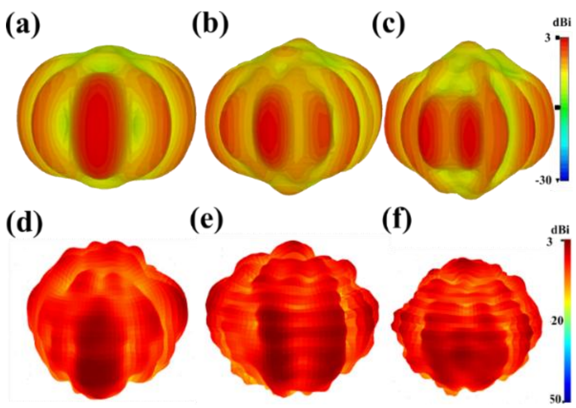

Fig. 4 – The simulated and measured 3D radiation patterns for 2 GHz (a, d), 6 GHz (b, e), and 10 GHz (c, f)

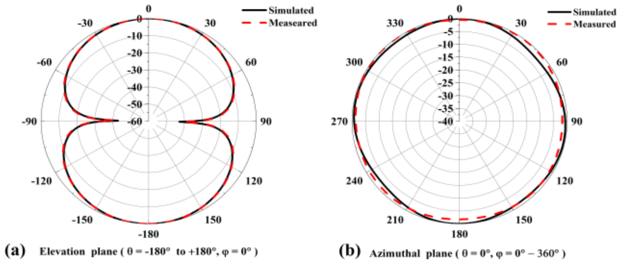

Fig. 5 – Radiation patterns at 2 GHz

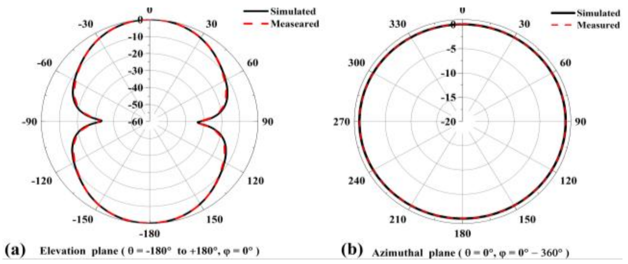

Fig. 6 – Radiation patterns at 6 GHz

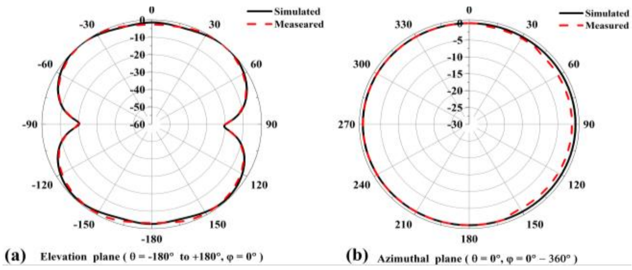

Fig. 7 – Radiation patterns at 10 GHz

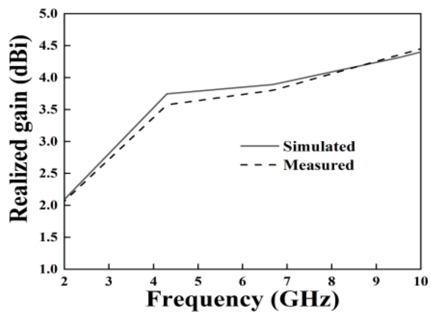

Fig. 8 – Simulated and measured gain for proposed antenna

The broad |S11| bandwidth achieved through this modification underscores the practical benefits of the ground plane configuration in maximizing performance across the UWB range while maintaining compactness.

Compared with similar UWB antenna designs, the proposed structure offers distinct advantages in size, omnidirectional coverage, and broadband impedance matching, making it highly adaptable for smart industrial applications. This performance profile aligns well with the operational demands of IoT-enabled smart industries, where reliable connectivity across spatially distributed devices is critical. The proposed compact UWB antenna, therefore, represents an effective solution for robust, energy-efficient communication within the expanding domain of smart industrial environments.

4. CONCLUSION

This paper presented the design and analysis of a compact UWB antenna tailored for smart industrial applications. The antenna, characterized by a compact form factor of 30 mm × 25 mm, achieves a wide impedance bandwidth from 2 GHz to 10 GHz, with |S11| values consistently below – 10 dB, indicating effective impedance matching and minimal signal reflection. Experimental results demonstrated a peak gain of 4 dBi and an average gain of approximately 3 dBi, ensuring reliable connectivity. The measured omnidirectional radiation patterns at key frequencies, including 2 GHz, 6 GHz, and 10 GHz, confirm the antenna's suitability for robust communication across multiple device orientations in complex industrial environments. Overall, the proposed UWB antenna provides an efficient solution for smart industrial systems, meeting the requirements for low-profile and high-performance wireless communication.

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Компактна всеспрямована надширокосмугова трапецієподібна щілинна антена для застосувань Інтернету речей

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У цій статті представлено аналіз конструкції та продуктивності компактної надширокосмугової (UWB) антени, оптимізованої для інтелектуальних промислових застосувань. Запропонована антена досягає широкої смуги пропускання імпедансу від 2 ГГц до 10 ГГц з характеристиками всеспрямованого випромінювання, що робить її придатною для різноманітних промислових середовищ, що потребують надійного та безперебійного з'єднання. Виготовлена на компактній епоксидній смолі FR4 розміром 30 мм × 25 мм, антена має L-подібний паз у заземленій площині для покращення узгодження імпедансу та смуги пропускання без збільшення її фізичних розмірів. Експериментальні результати демонструють сильну відповідність змодельованим даними, показуючи значення |S11| нижче –10 дБ у всьому діапазоні UWB та стабільні рівні посилення від 2 дБі до 4 дБі. Були проведені тривимірні вимірювання діаграми спрямованості для комплексної оцінки продуктивності антени, що підтверджує стабільне всеспрямоване покриття на ключових частотах та забезпечує надійний зв'язок між пристроями в різних орієнтаціях. Компактний розмір, всеспрямоване випромінювання та широка смуга пропускання запропонованої UWB антени роблять її перспективним рішенням для інтелектуальних промислових систем, де просторові обмеження та високопродуктивне бездротове з'єднання є першочерговими.

Ключові слова: Надширокосмугова антена, Трапецієподібний монополь, Інтелектуальні промислові застосування, Всеспрямоване випромінювання.