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A Compact Ultra-Wideband Antenna for Wearable and Implantable Medical IoT Devices

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ABSTRACT: This paper presents a novel approach to enhancing the radiation efficiency and performance of miniaturized antennas for medical Internet of Things (IoT) and AI-assisted healthcare systems. The proposed design is an ultra-wideband (UWB) antenna with a rectangular patch fed by a 50 Ω microstrip line and a stair-step rectangular slot, improving impedance matching and ensuring stable radiation. Operating across 3.1–16.7 GHz, the antenna enables high-data-rate, short-range communication for healthcare applications such as real-time transmission of biomedical signals (ECG, EEG, SpO_2), wireless connectivity with wearable and implantable devices, and secure integration with AI-driven diagnostic and monitoring systems. The antenna geometry was designed and analyzed using CST Microwave Studio, with comprehensive simulation results confirming its suitability for advanced medical IoT applications.

KEYWORDS: Ultra-Wideband (UWB), Compact antenna, Medical IoT, Wearable/Implantable devices.

I. INTRODUCTION

The rapid expansion of the medical Internet of Things (IoT) is transforming healthcare by enabling continuous monitoring of patients through connected devices such as wearable sensors, intelligent implants, and remote monitoring systems [1], [2]. These devices collect critical physiological data, including ECG, EEG, heart rate, oxygen saturation (SpO_2), and body temperature. Integrating artificial intelligence (AI) into these systems allows real-time data analysis for early anomaly detection, assisted diagnosis, and personalized treatment planning [12].

Wireless antennas play a crucial role in ensuring reliable communication in these devices. However, designing miniaturized antennas for wearable or implantable applications presents challenges such as reduced radiation efficiency, impedance mismatch, and distortion of transmitted signals [3], [4]. [5]. additionally, these antennas must operate reliably in close proximity to the human body, which can introduce significant signal losses and detuning effects [2], [6].

Ultra-wideband (UWB) antennas provide a promising solution, offering high-data-rate transmission over short distances with low power consumption [1], [7]. They cover several frequency bands essential for medical IoT applications: 2.36–2.40 GHz (MBAN) for patient monitoring, 2.4–2.48 GHz (ISM/Bluetooth Low Energy, ZigBee) for wearable sensors and automated drug delivery systems[14], 3.1–10.6 GHz (UWB) for high-speed body area network communications[9], [10], and 5 GHz and 6 GHz Wi-Fi bands for telemedicine and hospital networks[5], [15].

Despite these advantages, miniaturization often compromises radiation efficiency and impedance matching [6], [8]. To address these challenges, this work proposes an innovative UWB antenna design consisting of a rectangular patch fed by a 50 Ω microstrip line with a stair-step rectangular slot on the radiating element. This configuration improves impedance matching, stabilizes radiation across the UWB spectrum, and ensures reliable data transmission for medical IoT devices[7], [9], [13].The proposed antenna is suitable for continuous patient monitoring, wireless implant communications, and integration with AI-driven diagnostic systems[12].

The antenna geometry was carefully designed and simulated using CST Microwave Studio (Computer Simulation Technology), and detailed design methodologies, simulation approaches, and performance results are presented and thoroughly discussed in this paper [11].

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II. DESCRIPTION OF THE ANTENNA

The studied microstrip antenna has modified rectangular patch geometry, as illustrated in Figure 1. The patch is designed to enhance bandwidth performance and overcome the typical limitations of conventional microstrip antennas, making it suitable for medical IoT applications that require reliable, wideband wireless communication.

The main patch has dimensions of Lp = 12 mm (length) and Wp = 15 mm (width) and is printed on an FR-4 substrate with a dielectric constant of $\varepsilon r = 4.4$, thickness h = 1.5 mm, and overall dimensions L = 25 mm and W = 20 mm.

To further improve performance, a rectangular slot of 6 × 9 mm² is etched on the radiating patch. The antenna is excited using a 50 Ω microstrip feed line with a width of wf = 2.9 mm.

A partial ground plane is implemented on the bottom side of the substrate. The ground plane has a height of Lm = 11 mm and spans the full substrate width (W = 20 mm). This compact design approach has been shown to provide stable radiation characteristics and wideband performance in IoT-oriented antennas [4], [7]. Such features are essential for the reliable operation of medical IoT devices, including wearable health monitors, biomedical telemetry systems, and remote patient sensors [8], [13]. Moreover, slot loading and partial ground techniques have been widely validated in recent UWB antenna designs to achieve compactness and enhanced performance [10], [11], [14], [15]

Parameter	L	W	Wp	Lp	Lf	Wf	W1	L1	Lm
Value (mm)	25	20	15	12	12	2.9	6	9	11

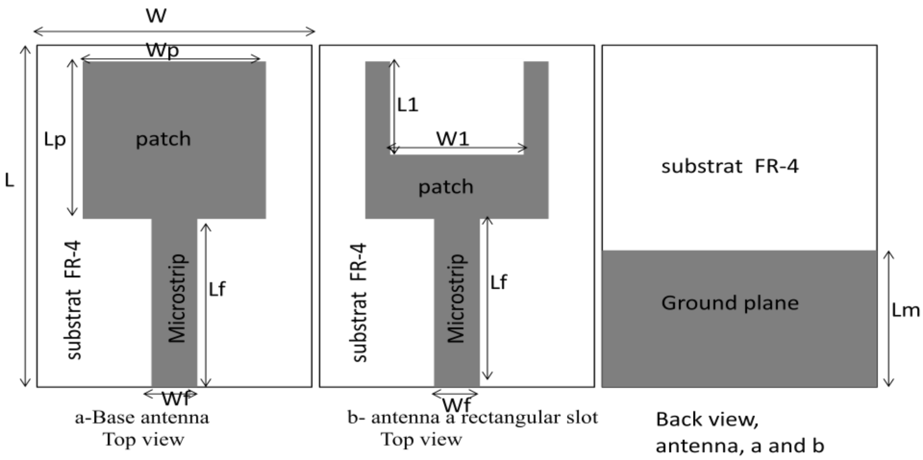

Fig1. Geometry of the proposed microstrip antenna

To achieve antenna miniaturization and enhanced bandwidth, stair-step structures are introduced between the feed line and the patch. These steps improve impedance matching, broaden the operational frequency band, and facilitate the emergence of additional resonances. The step height is defined as g = 2mm, with step widths of s = 3mm and s/2 = 1.5mm. A parametric study is performed using simulation software to optimize the proposed antenna configuration, as illustrated in Figure 2, with the corresponding results presented in Table 2.

parametre	L	W	Wp	Lp	Lf	wf	W1	L1	Lm	S	g
Value (mm)	25	20	15	12	12	2.9	6	9	11	3	2

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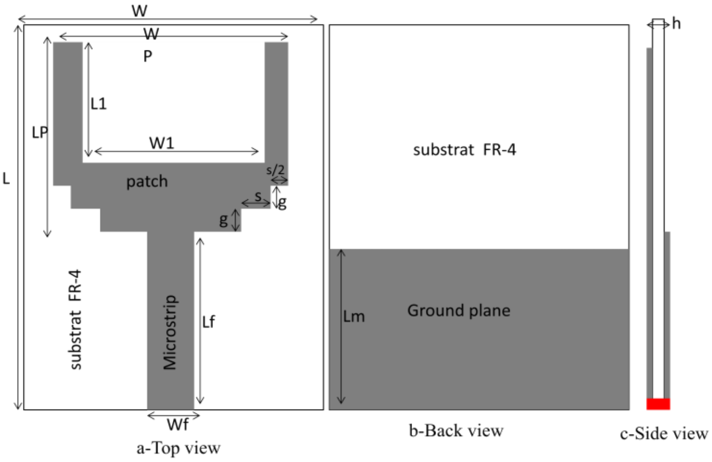

Fig.2: Geometry of the proposed antenna

Figure 3 illustrates the return loss of the base antenna, showing a wide operating band from 3 GHz to 9.7 GHz. Two resonances are observed at 5.3 GHz and 8.8 GHz, with S11 values of -17.6 dB and -20.1 dB, respectively. These results are compared to a single rectangular patch antenna incorporating a partial-mass slot to assess the influence of this modification on the antenna's behavior. The obtained bandwidth in this case remains nearly identical to that of the base antenna. It is important to note that the inclusion of the slot does not significantly affect the antenna's bandwidth or introduce new resonances [1], [3].

This frequency range is suitable for medical Internet of Things (IoT) applications, such as remote patient monitoring and wearable healthcare devices, and can support AI-assisted healthcare systems for real-time data analysis and diagnostics [4], [7]. In particular, the resonances at 5.3 GHz and 8.8 GHz fall within bands that can accommodate various medical IoT communication standards, ensuring reliable connectivity and efficient data transfer [8], [15].

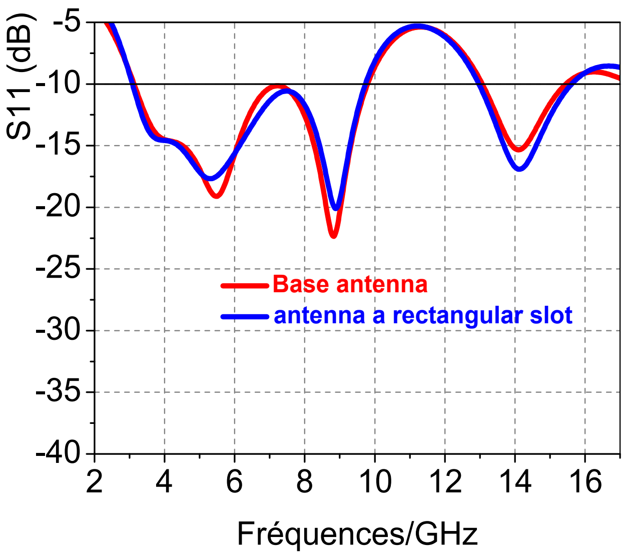

Fig.3: Return loss coefficient of the base antenna

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III. PARAMETRIC STUDY

The adopted procedure for this parametric study is to vary only one parameter at a time while keeping all others constant, in order to analyze its effect on the antenna characteristics[1], [3]. Different sets of parameter values are simulated to cover a broad range of variations. For reference, a baseline antenna is selected with the parameters listed in Table 2 [4], [5]. First, the return loss is evaluated as a function of frequency for different values of the step height. This parameter significantly influences the bandwidth of the proposed antenna and contributes to the appearance of a third resonance [6], [7]. The widest bandwidth is achieved when g = 2 mm, as illustrated in Figure 4. After determining the optimal value of the step height, the impact of the step width is investigated. Figure 5 presents the return loss as a function of frequency for various widths. It is observed that the widest frequency band is obtained when the step width is S = 3mm [11].

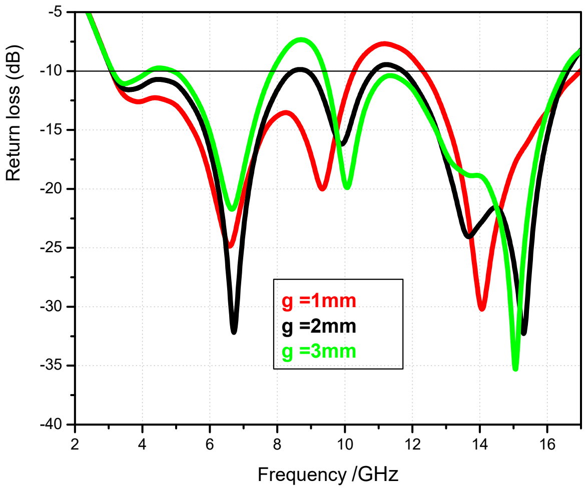

Fig.4: Return loss as a function of the height of steps

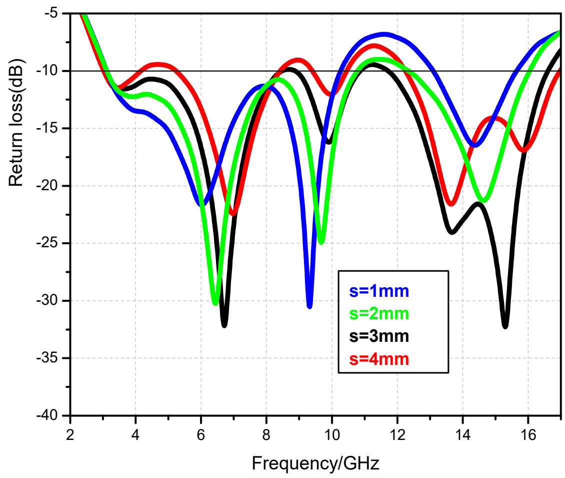

Fig.5: Return loss as a function of stair treads' width

Figure 6 presents the variation of the S11 parameter as a function of the ground plane length. It can be observed that changing the ground plane length Lm between 9mm and 12mm results in a shift of the S11 response. The optimal bandwidth is achieved for Lm = 11mm, as illustrated in the figure.

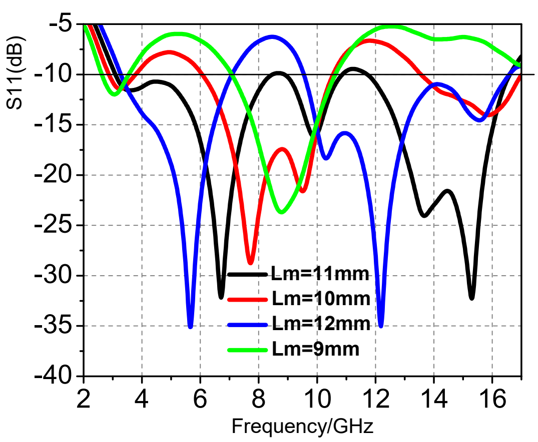

Fig.6: Return loss as a function of the length of the ground plane

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Figures 7 and 8 present the return loss as a function of frequency for different slot widths. It can be observed that variations in the slot dimensions have only a minor influence on the reflection coefficient.

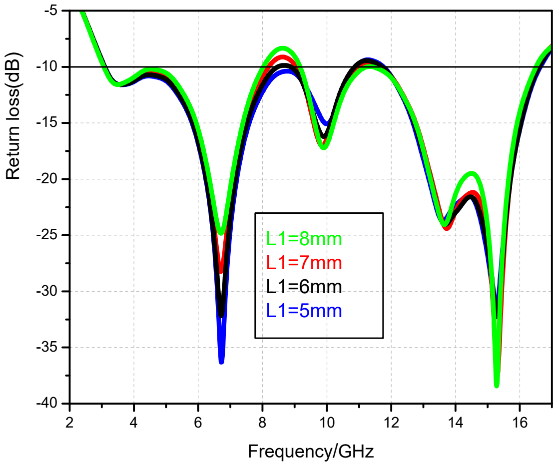

Fig.7: Return loss as a function of the gap length

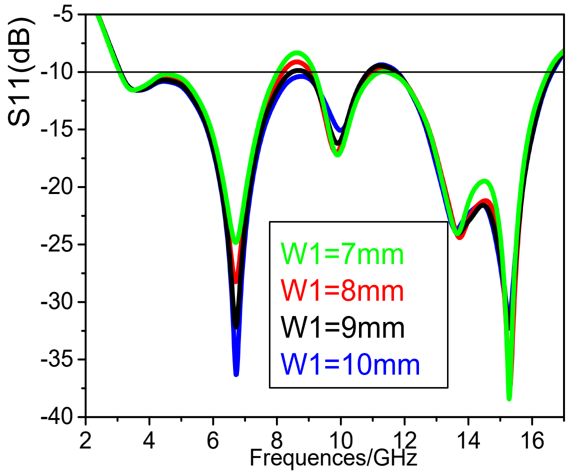

Fig.8: Return loss as a function of slot width

Figure 9 presents a comparison of the return loss between the base antenna and the proposed stepped antenna. The proposed antenna achieves a return loss of –10 dB at 3–16.7 GHz, corresponding to a relative bandwidth (BR %) of 139%. Three resonance modes are observed, centered at 6.7 GHz, 10 GHz, and 15 GHz. The obtained bandwidth also covers the ultra-wideband (UWB) range of 3.1 GHz to 10.6 GHz, as defined by the FCC for wireless communications.

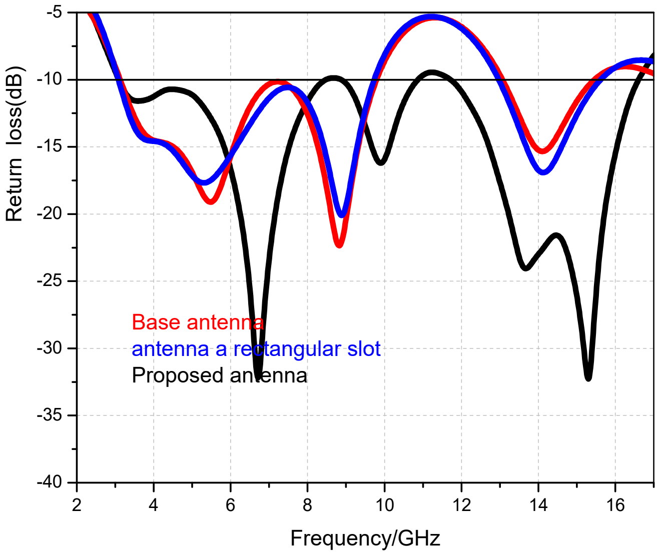

Fig.9: Comparison of S11 of the proposed antenna and the base antenna

The photographs of prototype antenna are depicted in Figure. 10. The designed prototype antenna was measured with the ZVL 13.6GHz Rohde& Schartz vector network analyzer.

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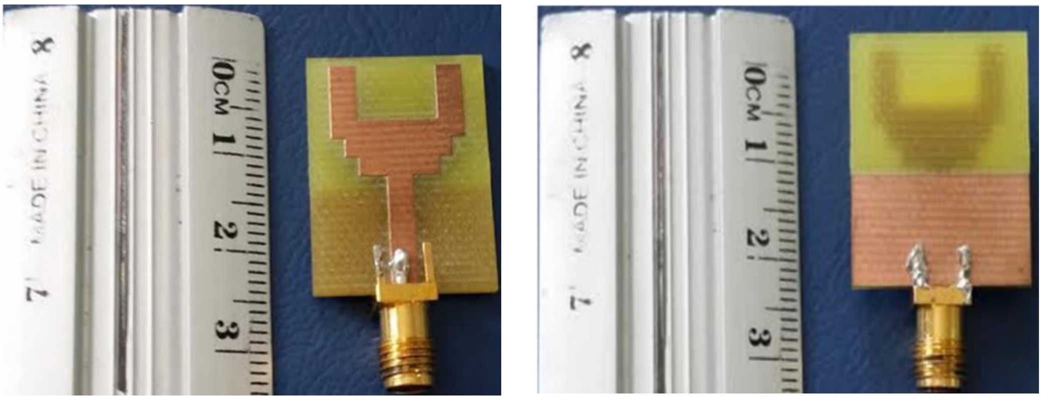

(a) (b)

Fig.10: Photographs of the proposed antenna (a) top view, (b) bottom view

The measured and simulated results are presented in Figure 11. This figure shows good agreement between simulated and measured results. The antenna covers the frequency band of 3 GHz – 16.7 GHz, as predicted in simulations, with resonant frequencies at 6.7 GHz, 10 GHz, and 15 GHz respectively. The measured result of the proposed antenna confirms its capability to support the UWB system [1], [3. In addition, this wideband coverage allows the antenna to be suitable for several Artificial Intelligence (AI) and Internet of Things (IoT) applications. For example, the antenna can support, IoT and AI-assisted smart devices operating at 2.4 GHz ISM band (2.4–2.48 GHz) and 5 GHz WLAN/WiFi bands (5.15–5.85 GHz) [4], [5]. Intelligent healthcare and wearable IoT systems using UWB (3.1–10.6 GHz). AI-based wireless sensing and imaging systems in the 6–10 GHz range[8], [9]. High-speed IoT communication and AI-driven data processing in the 15 GHz band for emerging beyond-5G applications [10], [12]. Thus, the proposed antenna not only meets UWB requirements but also demonstrates strong potential for AI- and IoT-oriented wireless technologies across multiple frequency bands[13], [15].

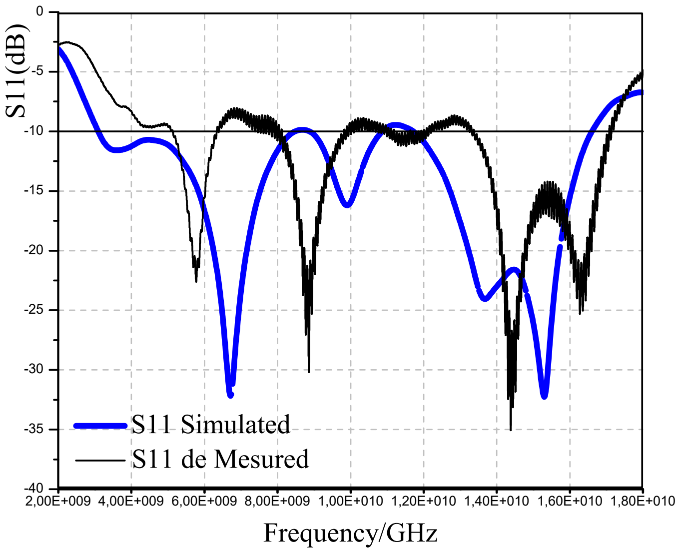

Fig.11: Comparison of the simulated and experimental return loss of the proposed antenna

Figure 12 shows the group delay of the proposed UWB antenna, which remains stable between −1 ns and +1 ns across the entire operating band (3.1–16.7 GHz). This stability ensures minimal distortion of transmitted impulses, supporting reliable mobile UWB operation [1], [3]. Such performance also benefits IoT and AI applications:

3.1–16.7 GHz: Enables high-data-rate communications, precise localization, and synchronized IoT networks for real-time AI analytics [4], [5], 6.7 GHz: Ideal for smart home and industrial IoT systems, supporting edge-AI tasks like anomaly detection, energy optimization, and environmental monitoring [6], [7], 10 GHz: Supports low-latency video

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and image transmission for drones, surveillance, and autonomous robots, facilitating AI-based event recognition and object classification [8], [9], 15 GHz: Enables high-resolution radar sensing, short-range imaging, and predictive maintenance in industrial settings, providing fine-grained telemetry for real-time AI diagnostics [10], [12]. In summary, the proposed UWB antenna offers stable temporal performance and a versatile platform for next-generation IoT and AI systems, combining precise positioning, robust data transfer, and seamless integration with intelligent applications [13], [15].

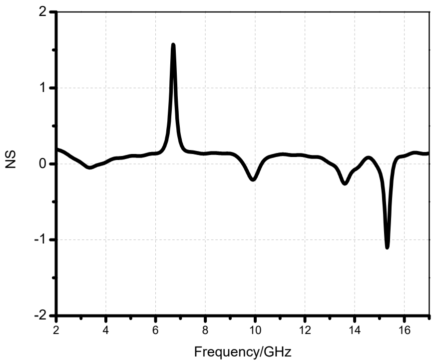

Fig.12: group delay

The figure.13, below show the different types of radiation patterns for several frequencies: 3GHz, 6.7GHz, 10GHz, 15GHz and 16GHz. We note that the radiation patterns are almost bidirectional

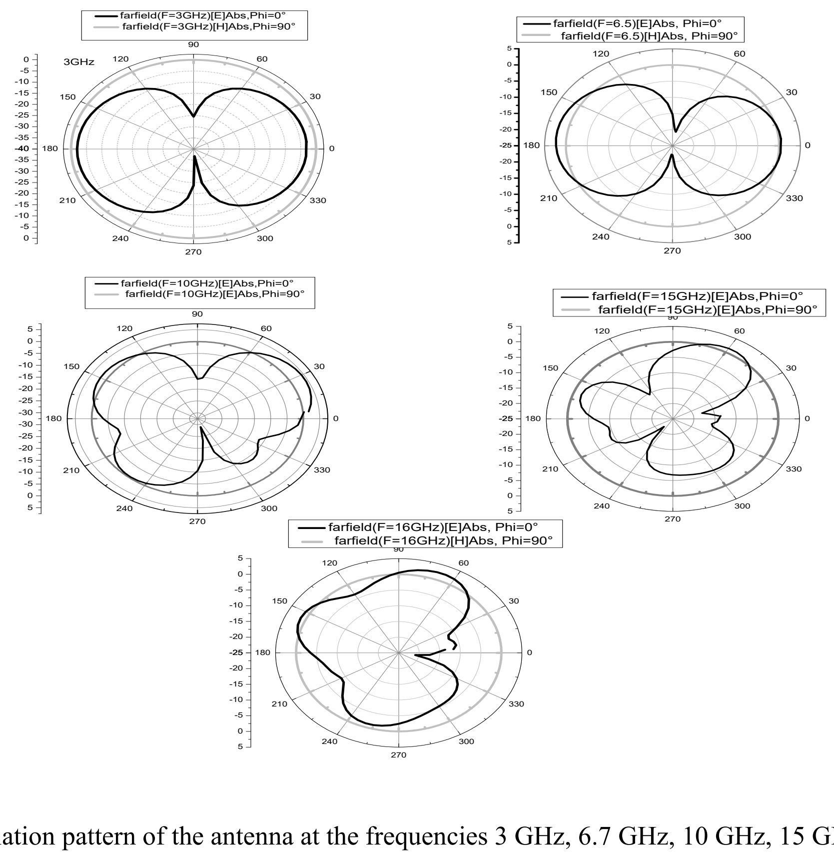

Fig.13: Radiation pattern of the antenna at the frequencies 3 GHz, 6.7 GHz, 10 GHz, 15 GHz and 16 GHz

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The figure.14 gives the variation of the gain of the proposed antenna. It varies between -2 and 3.15dBi throughout the frequency band. Table.3, Values of the gain for frequencies that it gives.

Frequency/GHz	3	6.7	10	15	16
Gain/dBi	-2	1.33	3.15	2.32	1.78

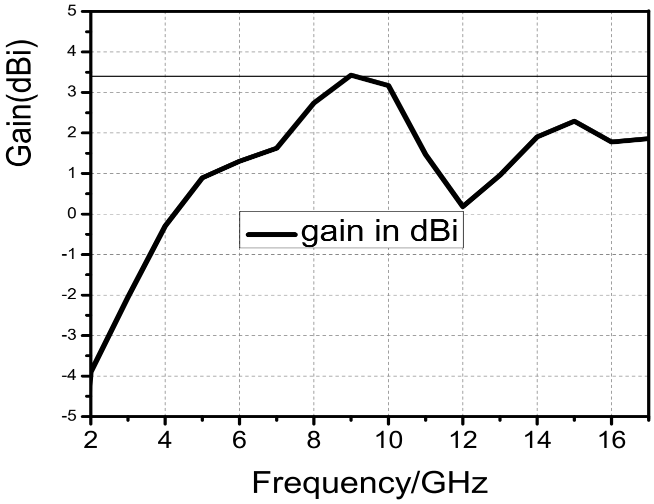

Fig.14: Gain antenna

IV. CONCLUSION

In this paper, a novel ultra-wideband (UWB) microstrip antenna was designed and analyzed for medical Internet of Things (IoT) and AI-assisted healthcare applications. The proposed antenna features a rectangular patch with a stair-step rectangular slot, fed by a 50 Ω microstrip line, and incorporates a partial ground plane to enhance bandwidth, impedance matching, and radiation stability. Simulation results demonstrated that the antenna operates efficiently across the 3.1–16.7 GHz band, covering critical frequencies for biomedical signal transmission (ECG, EEG, SpO_2), wearable and implantable device communication, and integration with AI-driven monitoring systems. The compact geometry, stable radiation characteristics, and wideband performance confirm the suitability of this design for continuous patient monitoring, high-data-rate wireless communication, and advanced healthcare IoT applications. Future work may include experimental validation, optimization for body proximity effects, and integration into fully functional wearable or implantable medical devices.

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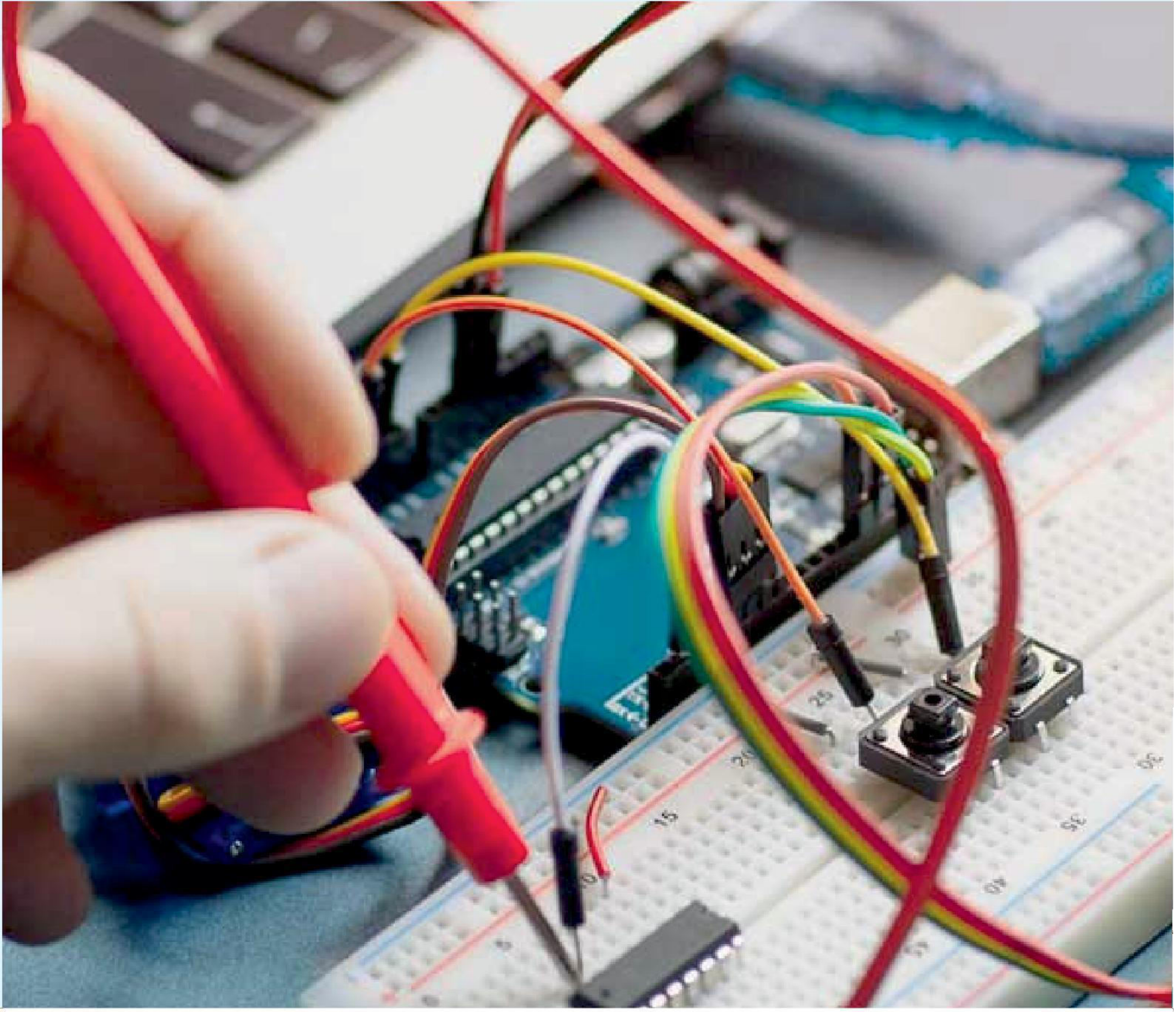

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