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Design of a High-Gain, Slotted Ultra-Wideband Antenna with T-shaped slots for Millimeter-Wave Applications

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Abstract: Millimeter wave (mmWave) is a crucial frequency range for fifth-generation (5G) mobile communication, characterized by wide bandwidth and higher data rates. Antenna components will be small, wideband, and high-gain for use in 5G systems. This study presents the design and simulation of an ultra-wideband rectangular antenna with T-shaped slots, developed using an evolutionary-oriented method for 5G mmWave applications. The antenna dimensions are tiny, with a width of 17 mm and a length of 16 mm. The suggested antenna is constructed utilizing a Rogers RT5580 substrate with a thickness of 0.254 mm. The operating bandwidth of the antenna element is between 25.45 GHz and 44.25 GHz, including 5G frequency ranges. The results show a steady end-fire radiation pattern with a gain of more than 9.5 dBi across the whole frequency range. The suggested antenna's improvements and benefits for 5G specs, bandwidth, and small size are supported by the most recent study in the field. The suggested antenna element works well with large radio communities and 5G multi-input multi-output (MIMO) applications.

Keywords: Millimeter wave, ultra-wideband antenna, Rogers RT5580, high-gain, small slotted antenna

1. Introduction

Microstrip patch antennas are very popular in wireless communications because they are small, cheap, and easy to assemble [1]. Applications include satellite communications, radar systems, mobile devices, and 5G networks, which depend on microstrip patch antennas[2]. Notwithstanding their benefits, they have some drawbacks as well, including poor efficiency, restricted power gain, and narrow bandwidth, which result from surface wave losses, substrate restrictions, and impedance mismatching and hence influence general performance [3][4]. Higher frequencies, such as millimeter-wave bands, cause further problems like significant path loss and air absorption, which further weaken signal power [5]. Recent research has concentrated on creating small antenna designs that keep their operational frequency and performance while improving efficiency and bandwidth, hence overcoming these restrictions.

More and more recent studies are looking at ways to make different kinds of antennas smaller while still keeping their working frequency and other performance measures [6]. So, the amount and speed of data are going up, as well as the number of people [7]. This is true for high-flow apps like 5G mobile technologies, cameras, sensor systems, wearable tech, smartphones, high-quality video streaming, managing home appliances, and sending big files. A lot of new studies have been done in the millimeter-wave range (30–300 GHz), which has been used to make antennas wider. The good thing about this range is that it can handle very fast communication[8]. Recently, the millimeter-wave frequency has gotten a lot of attention from businesses and international standards groups. This is because it has a lot of useful features for fast data transfer rates. Nevertheless, mm-wave communication is very hard to use because of transmission problems, such as heavy route loss and rain. This has sparked a lot of interest in millimeter-wave antenna design studies for a wide range of uses, such as 5G wireless communication, monitoring, and security, highlighting the urgent need for new solutions[9].

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Moreover, fifth-generation (5G) communication technologies are crucial to the Internet of Things (IoT). The increasing demand for higher data rates for IoT devices underscores the importance of compact antennas with sufficient bandwidth, driving the development of innovative solutions in antenna design [10]. As technology advances, the demand for communication systems with increased data rates and spectrum efficiency is rising. In this situation, ultra-wideband (UWB) radio technology presents a viable alternative for high-data-rate wireless networking across small distances [11]. However, they may be insignificant when a single antenna is utilized for many communication systems inside one handheld device for significant data transfers. Currently, a prevalent trend is using an ultra-wideband antenna, which offers comprehensive coverage by accommodating both long and short-range transmissions [12].

Researchers aim to develop wideband high-gain antennas that are compact and simplified to operate effectively in the millimeter wave bands. [13]. Reference [14] presents a wideband antenna working within the frequency range from 26.4 GHz to 31.6 GHz, with dimensions of 20×20 mm^2. The antenna provides a substantial gain of 8 dBi. Wideband performance and high gain are achieved using elliptical-shaped patches and slots. A distinct wideband antenna exhibiting a frequency range of 24.9 GHz –30 GHz and performing at 28 GHz is presented in [15]. The antenna is compact and features an 8.25 dBi gain. These works provide wideband capabilities and high gain yet exhibit complex geometric structures [16], [17]. Reference [18] presents a geometrically compact and efficient antenna. The design dimensions are 15×30 mm^2, and it features a simple structure with helical-inspired patches. The study presents a bandwidth of 26 GHz–29 GHz, achieving a maximum gain of 5.9 dBi. In [19], the authors introduce a slot-loaded rectangular patch antenna with a center frequency of 28 GHz and a bandwidth ranging from 26.6 GHz to 29 GHz. The antenna is small, measuring just 14×14 mm^2, and has a gain of 8.2 dBi. Vivaldi antenna is also present in [20] with dimensions 5.5×12 mm^2, producing a good bandwidth from 22.5 to 45 GHz with gain ranging from 5.5 to 8 dBi. In [21] a single dipole antenna is provided and provides a maximum gain of 6.2 dBi within its operational bandwidth, which ranges from 25.2 to 32.8 GHz.

This study presents an Ultra-Wideband (UWB) antenna design with a maximum gain of 9.5 dBi operating between 25.45 GHz and 44.25 GHz. A crucial development that greatly increases bandwidth lowers surface current losses and improves impedance matching is the proposed antenna's rectangular patch with four symmetrically positioned T-shaped slots. This special arrangement shows better performance in return losses, frequency responsiveness, overall gain, and radiation efficiency by maximizing operational capacity by means of many resonant modes. This work uses an evolutionary design strategy that maximizes the antenna structure to get increased radiation efficiency and greater gain, thus fitting for mm-wave uses. Emerging technologies like huge 5G MIMO systems and compact satellite communication depend especially on the wide frequency coverage of the antenna as high data rates, enhanced spectral efficiency, and miniaturized designs are fundamental for the next-generation wireless networks.

2. The development of the proposed antenna

This study employs a design approach based on the dominance of rectangular patch antennas. The designed antenna features a rectangular patch that incorporates T-shaped slots, allowing for precise control of its radiation characteristics. The antennas are made using Rogers RT5880 substrate, measuring 17 mm in width, 16 mm in length, and 0.254 mm in thickness. They have a relative dielectric permittivity (εr) of 2.2 and a loss tangent ($\tan \delta$) of 0.0009, which are highly beneficial for millimeter-wave applications. For uses like 5G and satellite communication, these characteristics assist in reducing signal loss and guaranteeing effective performance in high-frequency areas, thereby optimizing the conditions. This design utilizes inset feeding as the selected approach among different feeding techniques in microstrip patch antennas to achieve optimal matching impedance between the feeding line and the radiating part. The patch is 9.5 × 3.95 mm^2 and is connected to a microstrip line that is 0.52 mm wide and 7.75 mm long, operating at 50 Ω. The dimensions of the proposed antenna are tailored to get the required bandwidth. CST Studio Suite 2018 is used for the design and simulation of the proposed antenna. The simulation setup comprises an adaptive mesh refinement technique to guarantee result correctness and a frequency domain solver.

Figure 1 illustrates the geometry of the proposed antenna. Table 1 presents the appropriate parameter values for the proposed antenna.

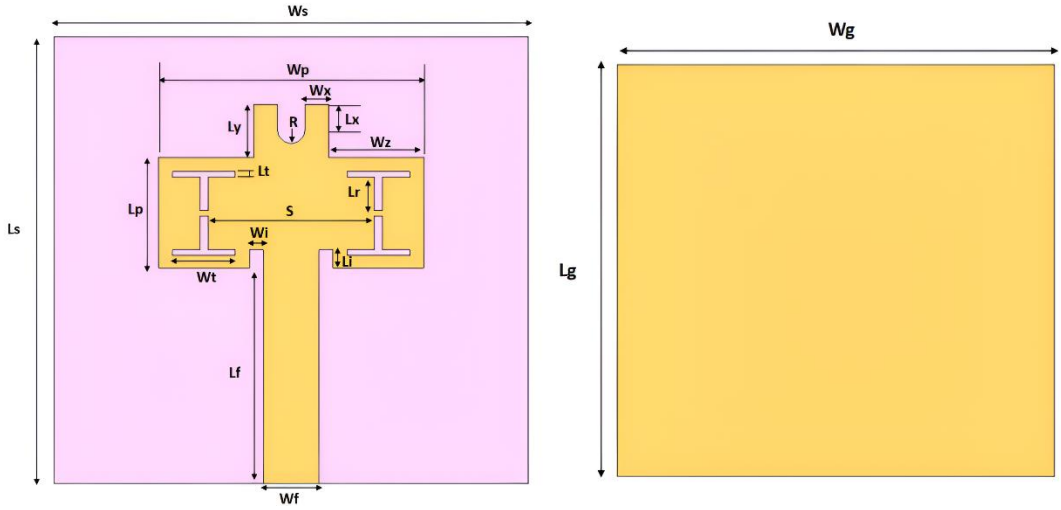


Fig. 1 The structure of the proposed UWB antenna (a) front view and (b) back view

Table 1 Optimized physical parameters of the suggested UWB antenna

Parameter	Value (mm)	Description	Parameter	Value (mm)	Description
Wg	17	Width of the ground	Li	0.65	Length of the inset feed gap
Lg	16	Length of the ground	S	5.95	Distance between T-slots
Ws	17	Width of the substrate	Lr	1.2	Length of the vertical T-slot
Ls	16	Length of the substrate	Wt	2.27	Width of the horizontal T-slot
Hs	0.254	Thickness of the substrate	Lt	0.2	Length of the horizontal T-slot
Wp	9.5	Width of the patch	Wx	0.83	Width of a tuning element
Lp	3.95	Length of the patch	Lx	0.92	Length of a tuning element
Wf	2.05	Width of the feedline	Ly	1.92	Length of upped radiator
Lf	7.75	Length of the feedline	Wz	3.42	Distance from upped radiator to side
Wi	0.52	Width of the inset feed gap	R	1.1	Radius of a circular structural element

The evolution of the designed antenna transpires in three steps. The first step is referred to as the initiation step. In this step, the process commences with the fundamental building of a rectangular patch antenna, using a complete ground plane radiator to ensure enough signal ground and a steady feed. The rectangular patch's initial dimensions were calculated using formulas provided in [22], [23]. In Step 2, four symmetric T-shaped slots are included at the corners of the patch to enhance its appearance. Better surface current distribution made possible by the T-shaped design helps to minimize current concentration close to edges and thus lower losses. Apart from that, the slots improve the matching between the antenna and the feed line and thus widen the bandwidth, therefore guaranteeing a better power transmission. This enhancement in current distribution and impedance matching helps the antenna to be very gainful and efficient. Consequently, Step 3 involves incorporating a U-shaped element just above the radiating patch.

This improves other antenna features by enabling more resonance modes and facilitating precise gain and radiation properties adjustments. The evolution steps of the proposed antenna are shown in Figure 2. Figure 3 illustrates the simulation results of three steps of the design process.

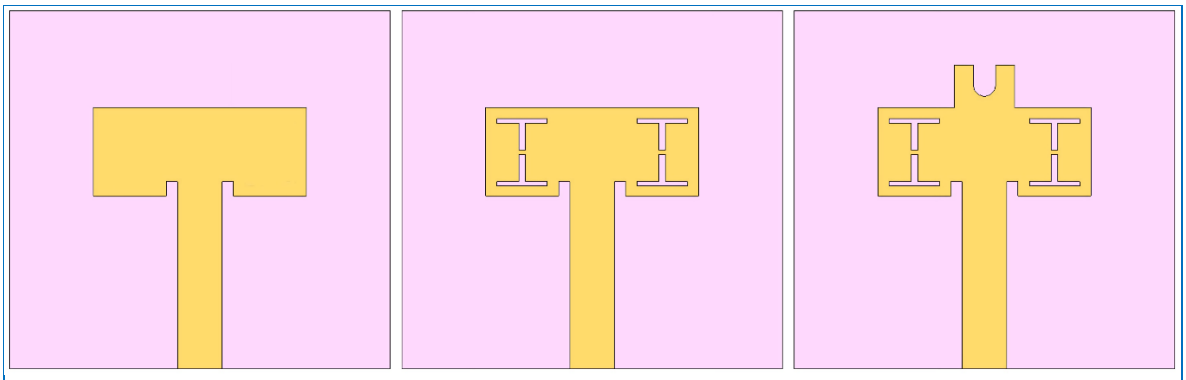


Fig. 2 The evolution design steps of the proposed UWB antenna (a) First step (b) Second step (c) Final step

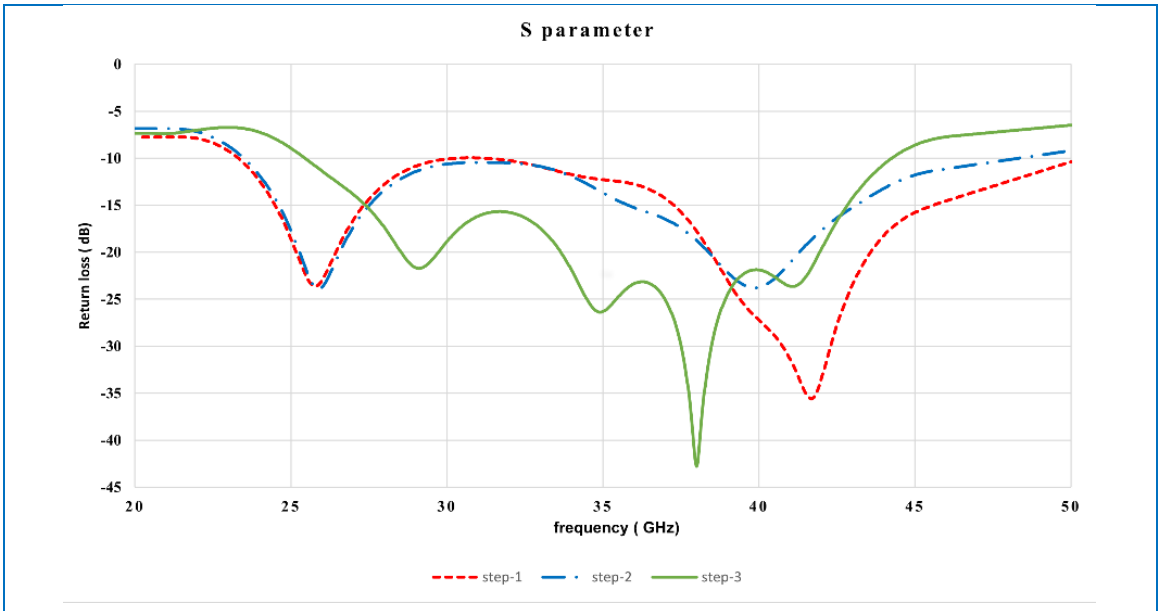


Fig. 3 Simulation results of design process steps of UWB antenna

3. Simulation results of the proposed antenna

The suggested antenna is constructed with Rogers RT5580 substrate with a thickness of 0.254 mm. The antenna demonstrates a bandwidth of 18.8 GHz, spanning from 25.45 GHz to 44.25 GHz. The return losses reach a minimum of approximately -42.78 dB at a frequency of 38 GHz, as shown in Figure 3. This indicates that the antenna efficiently absorbs energy and transfers it to the transmission medium with low losses, thus improving its efficiency. Figure 4 illustrates the antenna's return losses. Figure 5 illustrates the voltage standing wave ratio (VSWR), which remains below 2 within the operating frequency band, achieving a minimum value at 38 GHz. The findings demonstrate that the antenna is effectively designed to provide optimal matching with the transmission line, operating efficiently across its designated frequency band from 25.45 GHz to 44.25 GHz.

The reduction in antenna size for the desired bandwidth necessitates thoroughly examining antenna gain as a critical parameter. The proposed antenna demonstrates steady gain, achieving a maximum of 8.9 dBi at 29 GHz and 9.5 dBi at 38 GHz. A high-gain antenna signifies effective radiation concentration in specific directions, hence improving its ability for extensive transmission and reception. A significant issue with microstrip antennas is their inherently low efficiency, which limits gain; nonetheless, this design attained high gain by enhancements in the antenna's overall structure that increase radiation efficiency. It demonstrates radiation efficiency of 92% and 94% radiation efficiency at 29 GHz and 38 GHz resonant frequencies, respectively. The distribution of surface currents is analyzed across all resonant frequencies. The radiating patch's edges have a higher current density than its center at resonant frequencies. The current initially flows to the feed line before proceeding to the patching part, with a higher current density observed at the edges of the slots. Likewise, the current flow is primarily at the ground plane's peripheries. The distribution of surface current demonstrates the meticulous design of the antenna, allowing effective radiation direction at each frequency and ensuring the achievement of the desired gain without signal loss or dispersion, thus enhancing the antenna's overall efficiency. This results making it highly efficient for massive MIMO (Multiple-Input Multiple-Output) systems that require antennas with high gain and low interference. Moreover, the antenna's small size and improved directivity make it perfect for satellite communications, in which dependable signal transmission in space applications depends on steady and high-gain antennas. These developments place the suggested antenna as a good contender for next-generation wireless communication systems as they provide a competitive advantage over conventional designs in terms of bandwidth, efficiency, and application flexibility. Figure 6 presents the surface current density at resonance frequencies. Table 2 shows the simulation results of the proposed antenna at two operating frequencies.

Table 2. Simulation results of the proposed UWB antenna

Operating frequency	Return loss	Directivity	Gain	Radiation efficiency	Overall bandwidth
29 GHz	-21.76 dB	9.72 dBi	8.9 dBi	92%	18.8 GHz
38 GHz	-42.78 dB	9.76 dBi	9.5 dBi	94%	

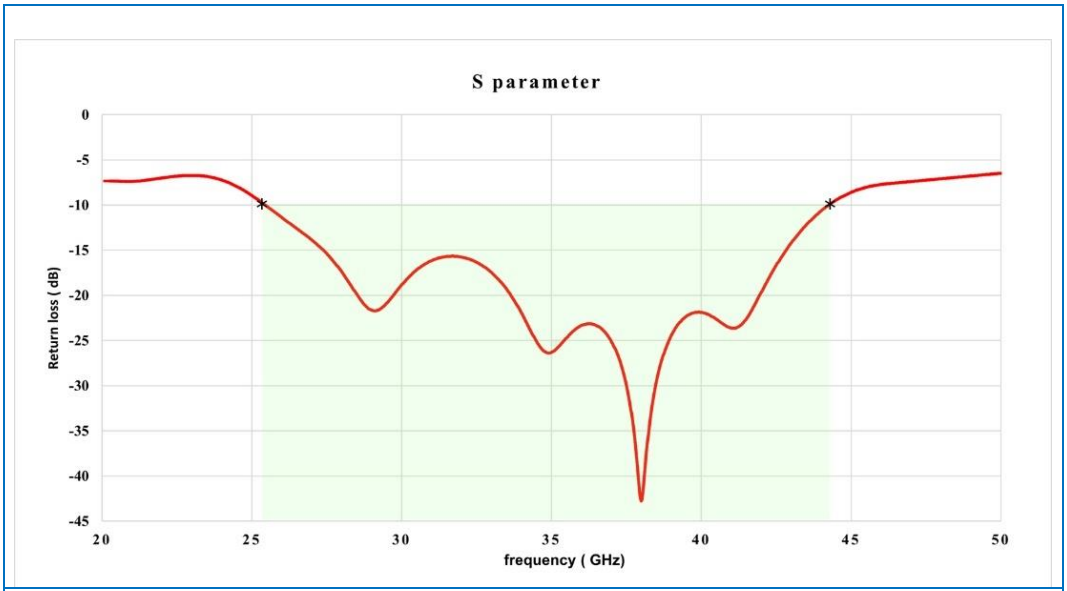


Fig. 4 Return loss results of proposed UWB antenna

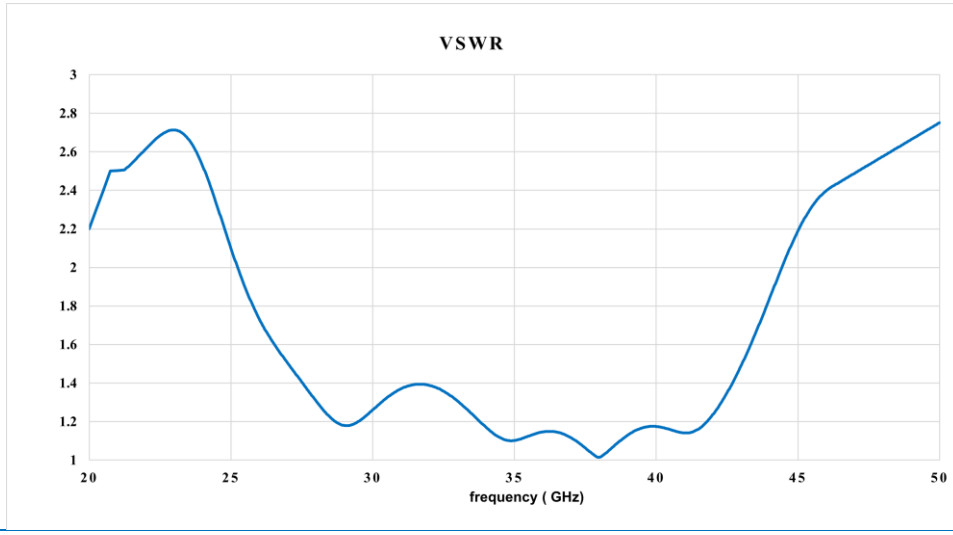


Fig. 5 VSWR of proposed UWB antenna

The radiation pattern within the Ultra-Wideband antenna is analyzed through simulation at frequencies of 29 GHz and 38 GHz. The suggested antenna attains a narrow beam at both resonance frequencies, signifying focused radiation in a specific direction. This is crucial for applications necessitating high-precision radiation, especially at millimeter frequencies. The side lobe has minimal values, indicating that side radiation is significantly constrained, hence minimizing interaction with adjacent systems. Moreover, the increased directivity ensures effective energy steering, thus improving the antenna's overall performance and proving it appropriate for wideband applications. Figure 7 illustrates the antenna's two-dimensional and three-dimensional radiation patterns across various planes.

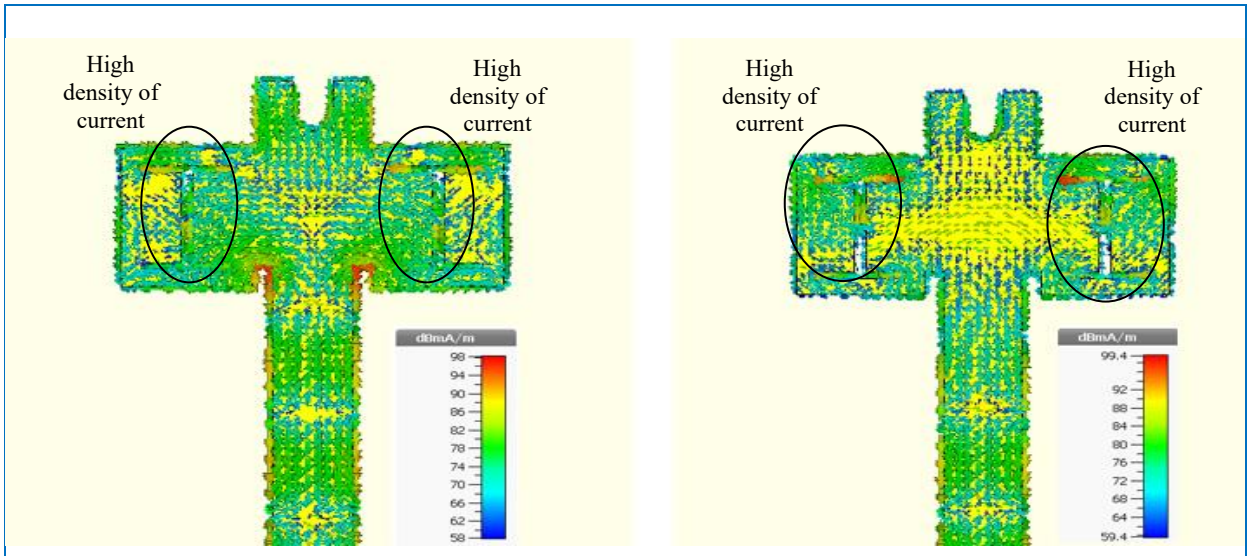


Fig. 6 Current distribution result of the proposed UWB antenna at (a) 29 GHz , (b) 38 GHz

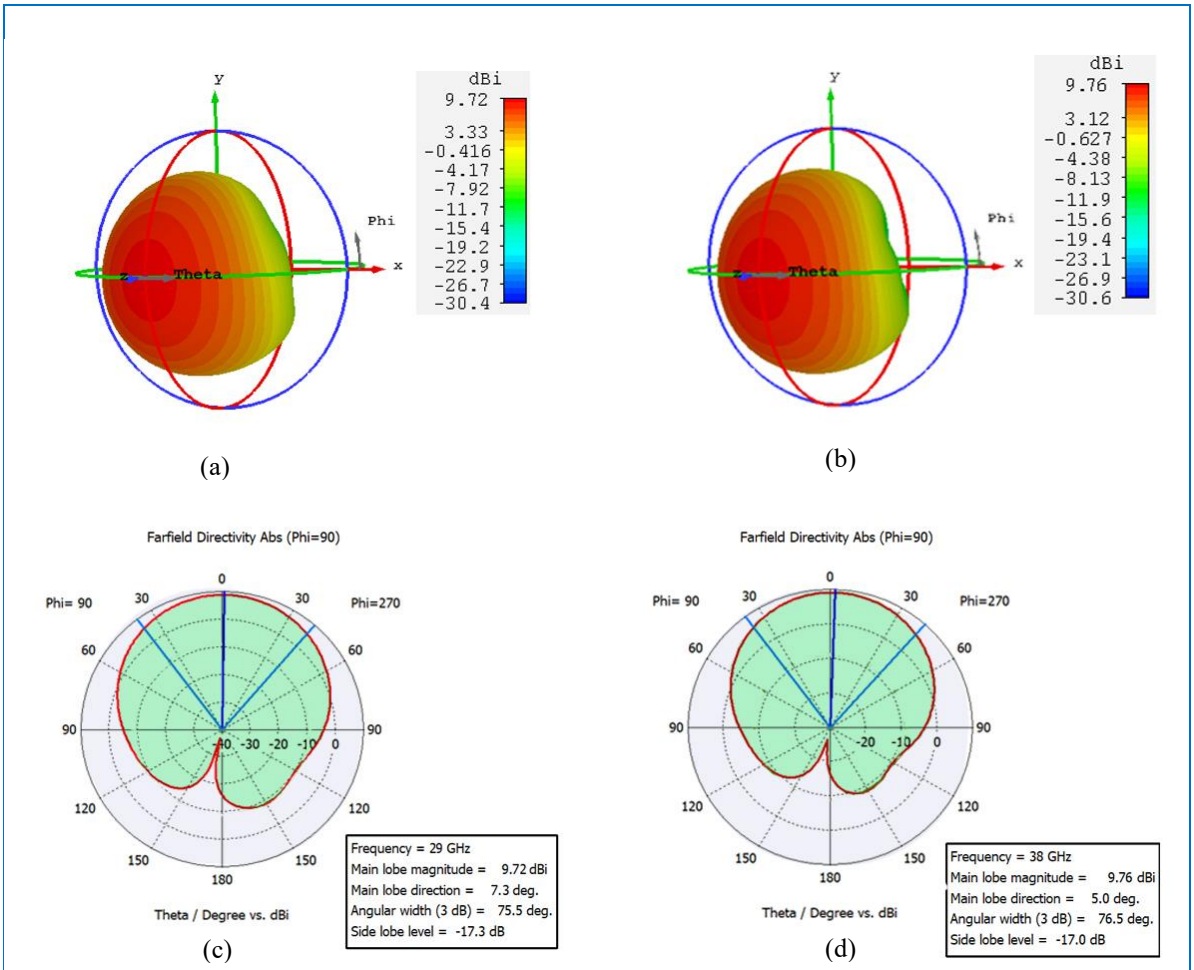


Fig. 7 Far-field simulation result of the proposed UWB antenna. (a) 3D form at 29 GHz (b) 3D form at 38 GHz (c) 2D form at 29 GHz (d) 2D form at 38 GHz

Compared to previous studies, the suggested design demonstrated exceptional results in gain and bandwidth, significantly enhancing the antenna's overall performance. This design's exceptional performance renders it an appropriate selection for millimeter-wave communication applications, as it exhibits an optimal balance between high gain and extensive bandwidth coverageThis design's T-slot shape essentially creates many resonant modes, therefore extending the operating bandwidth and guaranteeing low signal degradation. Careful placement of these slots improves impedance matching, hence lowering return losses and enabling improved power transfer. Moreover, the T-slots help to minimize surface current concentration, thus cutting losses and raising radiation efficiency. Furthermore, the reduced dielectric loss of Rogers RT5880 substrate guarantees high-frequency stability, hence enhancing gain and bandwidth. Table 3 presents a detailed comparison between the antenna developed in this research and many other efforts in millimeter waves, emphasizing the significant performance enhancements attained. This superior combination of wide bandwidth (18.8 GHz) and high gain (9.5 dBi at 38 GHz) surpasses conventional microstrip antennas, making the proposed design more efficient and reliable for millimeter-wave applications.

Table 3. Comparison presented antenna with other works

Reference	Antenna dimensions (mm^2)	Operating Frequency (GHz)	Overall bandwidth (GHz)	Peak Gain (dBi)	Radiation efficiency	Methodology
[11]	5×5	28	27.5–28.25	7.6	98%	Y-shaped patch antenna
[14]	20×20	27.5	26.4–31.6	8	80%	Slotted elliptical patch antenna
[15]	12×8.5	28	24.9–30	8.25	96%	E-shaped patch antenna
[16]	15×25	28	26–29	5.9	85%	Helically-inspired patch antenna
[17]	14×14	28	26.6–29	8.2	91.66%	Slot-loaded rectangular patch antenna
Proposed work	17×16	29/38	25.45- 44.25	9.5	92-94%	T-shaped slotted rectangular patch antenna

4. Conclusion

Ultra-wideband (UWB) technology will be essential to the next wireless and mobile communication systems. This results from its ability to provide an exceptionally high data rate derived from the extensive frequency band it occupies. This study presents an innovative rectangular and small UWB radiator for 5G communication technology applications. A comprehensive review of simulation data indicates that this radiator has remarkable performance characteristics, with dimensions of 17×16×0.254 mm^3. It attains a peak gain of 9.5 dBi and has an efficiency rating of 94% at 38 GHz frequency. The antenna also demonstrates favorable results at a frequency of 29 GHz, with a gain of 8.9 dBi and an efficiency of 92%. This antenna has an impressive bandwidth of 18.8 GHz, ranging from 25.45 GHz to 44.25 GHz. The present configuration of the antenna has robust radiation capabilities. The design ensures a steady, uniform radiation pattern with a low-profile structure and superior impedance matching. This antenna's unique design makes it ideal for different communication applications, including satellite, 5G, radar, and other microwave communications. Though these benefits abound, several restrictions still exist. Achieving exact impedance matching throughout the whole frequency range is one difficulty that can call for either more impedance-matching methods or further tweaking. The directed character of the radiation pattern is another possible disadvantage; it may not be ideal for users calling for more coverage. For future research, investigating beam-steering possibilities will help refine the design even further and increase its flexibility for dynamic communication surroundings. Furthermore, it might be dual-band or multi-band functioning to assist many wireless standards. Moreover, further miniaturization methods should be investigated to provide even more small-sized antennas ideal for wearable and IoT uses while preserving great performance.

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Conflicts of Interest: The authors declare no conflict of interest.

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