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REGULAR ARTICLE

Design and Analysis of an Ultra-Compact Triple-Slotted Hexagonal-Shaped Patch Antenna for IoT Applications in the THz Band

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The rapid advancement of the Internet of Things (IoT) and 5G communication systems necessitates antennas capable of delivering ultra-high data rates and wide bandwidths in the terahertz (THz) frequency band. This paper presents the design and development of a novel graphene-based triple-slotted hexagonal-shaped patch (TSHP) antenna intended for IoT applications in the THz frequency band. The proposed antenna features a compact hexagonal geometry with strategically incorporated slots and a partial ground structure to optimize key performance metrics, including bandwidth, gain, and radiation efficiency. The design process involved rigorous computational simulations to optimize the antenna structure for operation in the THz band, ensuring minimal loss and high precision. The CST Microwave Studio simulation environment is used to investigate the performance of the proposed antenna with an 80 × 60 μm^2 footprint. The simulation results demonstrate a broad bandwidth of 0.86 THz, a low return loss of – 36.76 dB, a high gain of 7.71 dB, and an efficiency of 81.59 %. The use of graphene as a conductive material enhances electrical and thermal performance, enabling the TSHP antenna to meet the stringent requirements of high-speed IoT networks. This work provides a robust foundation for developing efficient THz antennas, advancing the capabilities of next-generation IoT and 5G communication systems.

Keywords: IoT, THz band, Hexagonal shape patch, CST, Triple-slot.

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1. INTRODUCTION

The Internet of Things (IoT) and fifth-generation (5G) communication systems have initiated a wireless revolution by connecting people, data, processes, and infrastructure [1] due to their high data rates, wide bandwidths, and low latency [2]. The Terahertz (THz) band has recently emerged as a beacon of hope for IoT applications, offering unprecedented data rates and bandwidths that surpass those of conventional radio waves [3]. The THz band's rise in popularity for IoT and advanced wireless communication applications is driven by its non-ionizing nature and its ability to penetrate. It has been scientifically proven [4] that THz radiation is almost harmless to human tissue. A microstrip patch antenna (MSA) is employed in the communication system to meet the demands of THz-band applications.

Several researchers have improved the performance of MSA by changing the parameters of the conventional antenna, such as varying the width of the substrate and size of the antenna, adding and cutting slots or grounds [5], and modifying the shape of antenna patches. In [6], the author proposed a hexagonal patch antenna with a DGS structure and a narrow slot of 450 on the patch for a wireless local area network (WLAN). This antenna provides a return loss (S_{11}) of – 30.78 dB with a bandwidth of 30 GHz and a peak gain of about 4.81 dB. The proposed antenna failed to achieve a wide bandwidth and high gain. The researcher in [7] introduced a coplanar waveguide-fed hexagonal antenna with fractal elements. The antenna dimensions were kept at 25 × 25 × 1.588 mm^3 to achieve a bandwidth of 10 GHz, an average gain of 2.35 dB, an efficiency of 95 %, and S11 of – 21 dB. This antenna showed enhanced efficiency, but other performance parameters were not satisfactory. Then, in [8], the author presented a unique proximity-coupled feed circularly polarized hexagonal patch antenna. The antenna was constructed on a 14.2 × 14.2 mm^2 FR4 substrate to achieve S_{11} of – 29dB, a bandwidth of 3.8 GHz, and a gain of 3.4 dB (32 dBm). Finally, authors in [9] proposed a novel fork-shaped plasmonic graphene-based on-chip patch antenna, with a SiO_2/silicon substrate, for wireless Network-On-Chip applications in the THz range. The proposed work showed an S_{11} of – 20 dB with a bandwidth of 0.2 THz, an efficiency of 58.9 %, and a gain of 3.89 dB.

By focusing on the limitations of previous work, this paper proposes a unique triple-slotted hexagonal-shaped patch (TSHP) antenna design for IoT applications in the THz band. The TSHP antenna, which utilizes graphene at the patch and ground (GND) layer for conduction, is expected to overcome the limitations of previous research. The TSHP antenna aims to achieve low S_{11}, wide bandwidth, and improved gain in the THz band, meeting

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the requirements of IoT applications and 5G communication systems. Its primary properties, including compact size, wide bandwidth, and high relative gain, promise improved data transmission capabilities in the THz regime, instilling hope for future advancements in the field.

The rest of the paper is structured as follows: The frequency band of different IoT applications is described in the following sections. The design methodology of the proposed TSHP antenna is described in section 3. Section 4 represents the simulated result of the recommended TSHP antenna. Finally, Section 5 summarizes the work.

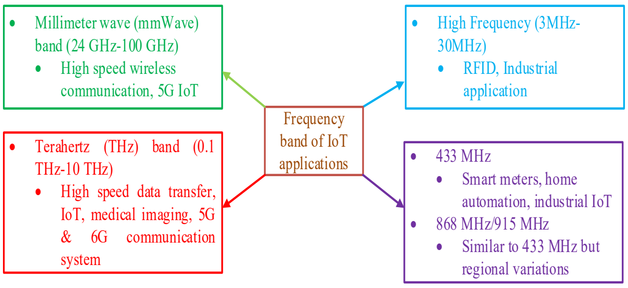

Fig. 1 – Frequency band of different IoT applications

2. THz ANTENNA FOR IoT APPLICATIONS

THz antennas are becoming increasingly crucial in IoT applications due to their wide bandwidth, enabling higher data transmission rates. The THz frequency band supports exceptionally high data rates and wide bandwidth, enabling rapid communication between IoT devices. Fig. 1 shows different IoT applications by frequency band. This paper focuses on an IoT application operating in the THz band, which spans 0.1-10 THz. Some typical IoT applications in the THz band are:

- **High-Speed Communication:** THz frequencies can enable data rates exceeding 100 Gbps, significantly faster than current Wi-Fi technologies. A THz communication system capable of 100 Gbps over a 1-meter distance could revolutionize data transmission in dense IoT environments [10].
- **Environmental Monitoring:** THz sensors can detect chemical signatures with high sensitivity to identify pollutants in the air. This capability can be vital for smart cities, where real-time air quality monitoring is crucial [11].
- **Medical diagnostics:** THz imaging can provide non-invasive analysis of tissues to detect early-stage skin cancers with high resolution. This application can significantly enhance patient monitoring in innovative healthcare systems [12].
- **Smart Manufacturing:** The ability of THz waves to penetrate materials without causing damage makes them valuable for monitoring processes in smart factories. This technology can be used for real-time inspection of materials and products, ensuring quality control without physical contact [13].

This paper focuses on the properties and applications of IoT technology and proposes to design a novel TSHP antenna. The proposed antenna is expected to support the requirements of IoT applications in the THz band..

3. METHODOLOGY

The methodologies used to carry out the research objectives are selecting antenna structures for IoT applications, determining the simulation environment, designing the proposed antenna, and analyzing it. 1st stage of this research involves selecting an antenna structure to obtain the specific bandwidth for IoT applications. The simulation environment stage confirms the specific environment for the design and analysis of the performance of the proposed antenna. The design consideration of the proposed antenna is also discussed. In the analysis stage, the method to analyze the performance and characteristics of the antennas is defined.

3.1 Selecting Antenna Structure for IoT Applications

The main focus of the paper is to design a novel antenna for IoT applications. The antenna must be compact in size and able to operate in the THz band to support high-speed communication. As a procedure for determining the proper antenna structure, first consider the patch shape of the proposed antenna. Several researchers suggested diverse patch forms for improved antenna performance through design and analysis. In the past, various patch shapes, including rectangular, circular [14], elliptical [5,15], triangle [16], and many more, were suggested for operating the antenna in a particular frequency range. We must develop an antenna for IoT applications in the THz band since the current era demands high data rates and large bandwidth. Thus, this paper proposes a triple-slotted hexagonal-shaped patch (TSHP) antenna for IoT applications in the THz band.

The next crucial step is to determine the dimensions of the antenna structure, which are directly related to the antenna's resonant frequency (f_c). It is of utmost importance to obtain a proper resonant frequency for the proposed TSHP antenna in the THz band. The antenna is designed to operate within the range of 1THz to 4THz. Therefore, for the performance assessment of the TSHP antenna, a frequency of 2.50THz is considered the resonant frequency (f_c). The length and width of the proposed antenna are determined by a specific equation based on f_c [17].

$$L = \frac{C}{2f_C\sqrt{\varepsilon_r}} \tag{1}$$

$$W = \frac{C}{2f_C\sqrt{\frac{\varepsilon_r+1}{2}}} \tag{2}$$

where, L is the length, W is the width, f_c is the resonant frequency, ε_r is the dielectric constant of the substrate, and C is the speed of light.

The selection of antenna material is another vital component of antenna design. In antenna design, conductive materials are employed at the patch and GND layers, and insulating materials are used at the substrate layer. Material selection is crucial for operating the antenna at the specified frequency band and achieving the anticipated antenna performance. This work uses graphene at the patch and GND layer as a conductive material because of its amazing and promising qualities, including exceptional electrical conductivity. Its thermal conductivity of 5300 W/m/k is much higher than that of silicon, while its electrical conductivity is 200 times faster. Owing to graphene's exceptional electrical, mechanical, and optical qualities [18], it is utilized as a conductive material to run the suggested antenna in the THz band. Rogers RO3003 is also used at the substrate as an insulator. The antenna material utilized in the antenna's design is displayed in Table 1.

Table 1 – Antenna element

Layer	Material
Ground	Graphene
Substrate	Rogers RO3003
Patch	Graphene
Feed line	Graphene

3.2 Simulation Environment

Designing a patch antenna often involves using specialized simulation software to design and analyze the antenna performance. The most popular antenna design and analysis simulation tools include IE3D, AWR microwave office, FEKO, ADS, Open EMS, 4NEC2, CST-MWS, and HFSS [19]. The computer simulation technology microwave studio (CST-MWS) has been used in this paper as a conducting simulator due to its less complexity in antenna design. CST-MWS contains extensive solvers and capabilities for calculating antenna performance parameters such as return loss, gain, and bandwidth, efficiency, and radiation patterns. Several antenna models were designed and simulated to obtain an efficient antenna design with good performance. Therefore, an antenna with good performance is fabricated. Hence, it will reduce the fabrication costs.

3.3 Design of Proposed TSHP Antenna

Fig. 2 shows the geometric structure of the proposed TSHP antenna. As shown in Fig. 2, the dimension of the substrate and ground layer used in the hexagonal microstrip patch design is $80 \times 60 \times 4$ μm^3 whereas the dimension of the hexagonal radiating patch is $50 \times 40 \times 1.2$ μm^3. The feedline dimensions are kept at $10 \times 7.764 \times 1.2$ μm^3 to maintain a line impedance of about 50 Ω. It is observed from Fig. 2(a) that there are three slots on the patch where the dimensions of slot 1, slot 2, and slot 3 are $10 \times 4 \times 1.2$ μm^3, $4 \times 1.2 \times 1.2$ μm^3, and $4 \times 1.2 \times 1.2$ μm^3, respectively. Furthermore, as shown in Fig. 2(b), we modified the ground layer with horizontal partial grounding. Fig. 2(c) and Fig. 2(d) show the cross-sectional view of the patch and feed line, respectively. Table 2 summarizes the antenna parameters used to design the antenna.

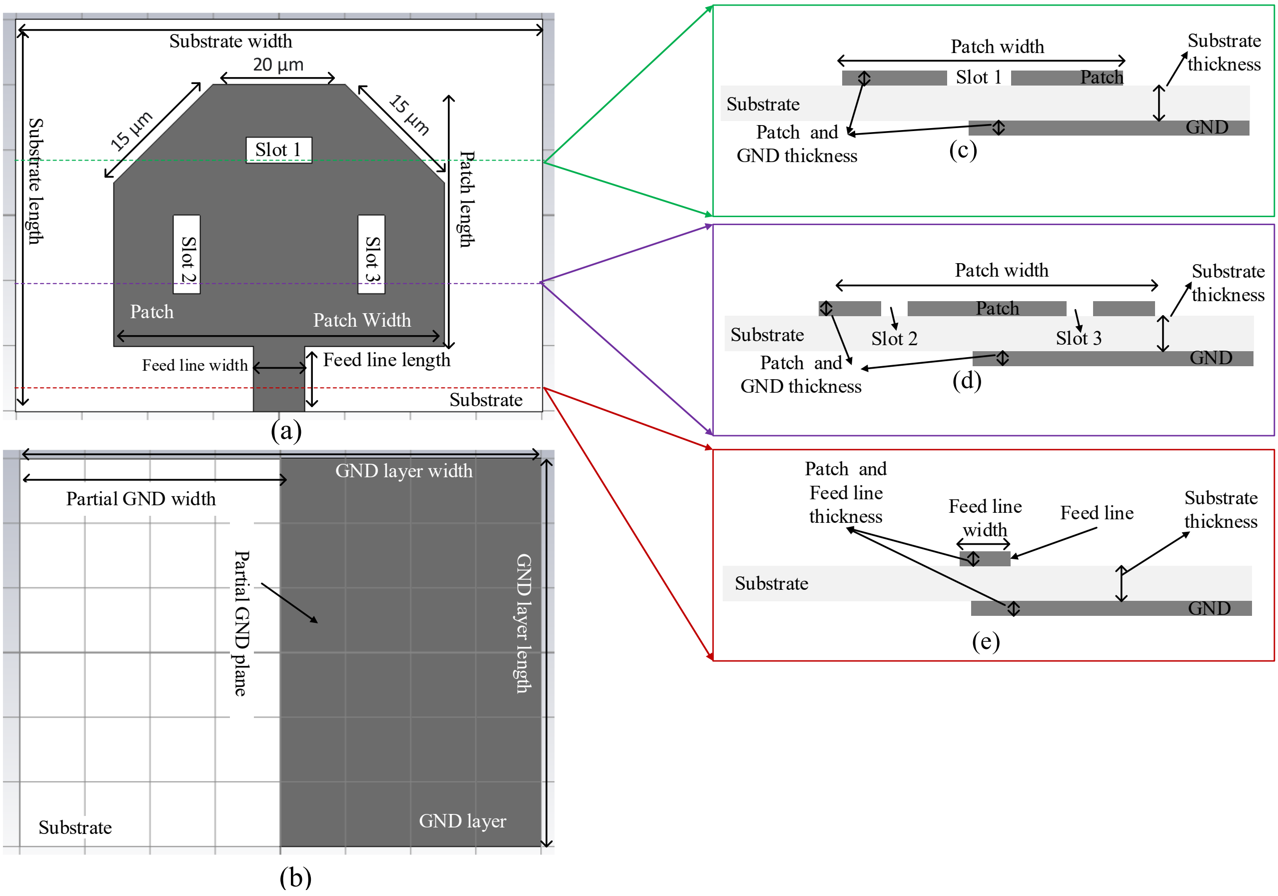

Fig. 2 – Structure of the proposed TSHP antenna (a) Front view (b) Back view (c) Cross-sectional view on the patch (d) Cross-sectional view on the feed line developed interface

3.4 Analysis

This section discusses the techniques for analysis of the TSHP antenna. The performance and properties of the hexagonal patch antenna are investigated based on the evaluation metrics such as resonant frequency (THz), bandwidth, reflection coefficient S_{11} (dB), gain (dB), VSWR, efficiency, and radiation pattern. CST simulation environment was used to design, simulate, and analyze the performance of the antenna.

Table 2 – Parameters of TSHP patch antenna

Parameters	Values (µm)
Substrate length	60
Substrate width	80
patch length	40
Patch width	50
Substrate thickness	4
Patch and GND layer thickness	1.2
Partial GND plane length	60
Partial GND plane width	40
Slot 1 length	4
Slot 1 width	10
Slot 2 length	12
Slot 2 width	4
Slot 3 length	12
Slot 3 width	4
Partial GND plane width	40
Feed line length	10
Feed line width	7.764
Feed line thickness	1.2
Parameters	Values

4. RESULTS AND DISCUSSION

This paper uses the CST-MWS simulator to design and simulate the TSHP antenna, as shown in Figure 2. First, we design the antenna, as shown in Figure 2, based on the design parameter of Table 2 and then simulate it to observe the antenna performance, as discussed in the previous section. Figure 3 to Figure 7 shows the spectra of S_{11}, Voltage Standing Wave Ratio (VSWR), gain, directivity, and gain, respectively.

4.1 Reflection Coefficient (S_{11})

An important metric for assessing an antenna's radiation performance is its return loss. It only takes into account values greater than – 10 dB and always has a negative value. A more minor return loss indicates less power reflected from the antenna. The return loss spectrum is displayed in Fig. 3, with the simulated frequency in THz on the x-axis and the return loss value in dB on the y-axis. The S-parameter, S_{11}, of reflection characteristics at the input port of the antenna was tested for the study.

Fig. 3 clearly shows that the value of the return loss, S_{11}, obtained for the proposed TSHP antenna is -36.76 dB at the operating frequency of 2.48 THz, where the designed value is 2.50 THz. In this instance, we only consider the frequencies for the return loss value of less than – 10 dB. We obtained a lower cutoff frequency at 2.07 THz and a higher cutoff frequency at 2.93 THz, as shown in Fig. 3. Hence, the proposed TSHP antenna offered a bandwidth of 0.86 THz (2.07 THz–2.93 THz). This testifies to the bandwidth enhancement needed for high-speed transmission. The large bandwidth of the suggested TSHP antenna indicates that it could be a game-changer for upcoming 5G mobile communication systems and IoT applications.

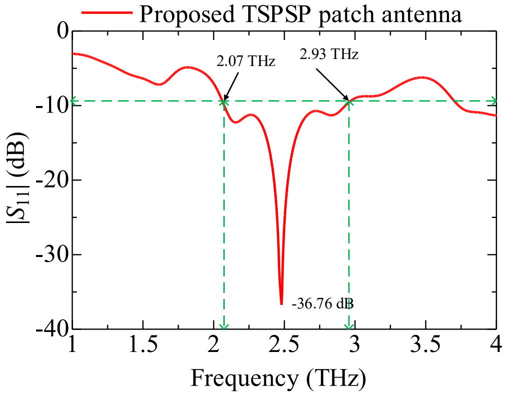

Fig. 3 – Simulated return loss (S_{11}) characteristics

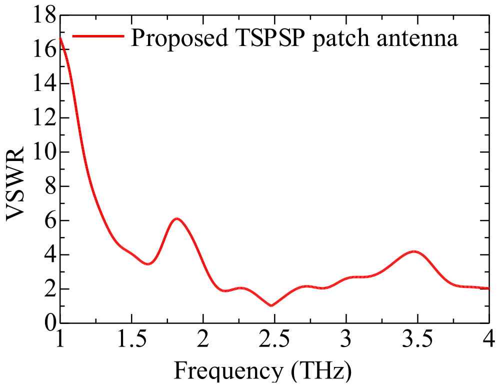

Fig. 4 – VSWR vs. Frequency of the TSHP antenna

4.2 Voltage Standing Wave Ratio (VSWR)

The amount of impedance mismatch between the antenna patch and feeding method is measured using the Voltage Standing Wave Ratio (VSWR). VSWR value is rising with increasing the mismatch level. The perfect match is reached when the VSWR has an absolute minimum value of unity. VSWR is obtained from the return loss of the antenna by using the equations [20]

$$VSWR = \frac{1+10^{\frac{R_l}{20}}}{1-10^{\frac{R_l}{20}}} \tag{3}$$

where, R_l is the return loss of antenna.

Fig. 4 shows the spectra of VSWR with the simulated frequency in THz on the x-axis and the VSWR values on the y-axis. It is observed from this figure that the value of VSWR is 1.03 at resonance frequency 2.48 THz. In this instance, the minimum value of VSWR at the resonant frequency is less than 2, which confirms perfect impedance matching with the TSHP antenna.

4.3 Gain (dB) and Directivity (dB)

Two crucial considerations in evaluating the antenna's performance are directivity and gain. Antenna directivity measures radiated power in a specific direction, while gain measures radiated power in all directions.

Fig. 5 represents the far-field radiation pattern of the proposed TSHP antenna. The plot is a polar plot with fixed Phi = 90°, meaning that it is a cross-sectional view of the radiation pattern in a particular plane. The red line represents the normalized far-field radiation pattern of the antenna at a frequency of 2.48 THz. The peak or maximum directivity of the main lobe is 9.45 dBi. This is the highest gain that the antenna radiates in the main direction. The radiation pattern shows a typical directional pattern often seen with patch antennas, where the main lobe indicates the direction of maximum radiation, and the side lobes indicate lower radiation levels in other directions.

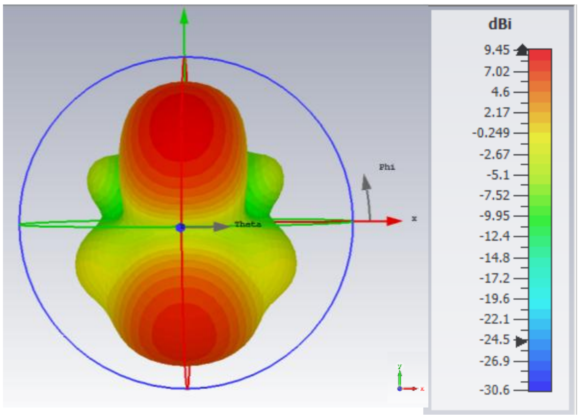

Fig. 5 – Antenna directivity at resonant frequency of 2.48 THz

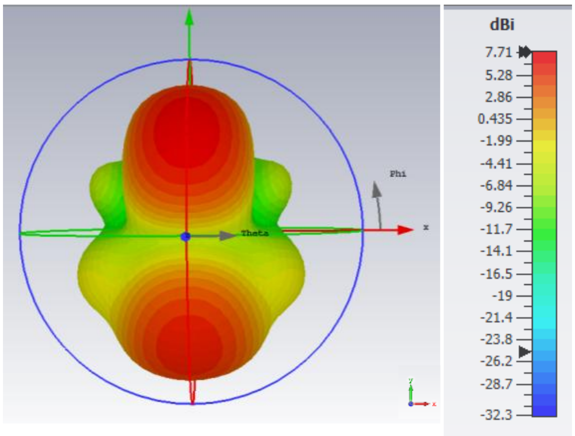

Fig. 6 – Antenna gain at resonant frequency of 2.48 THz

Fig. 6 shows the 3D gain pattern of the proposed antenna. The figure shows the 3D radiation pattern of the antenna, which indicates the gain in various directions. The color scale on the right indicates the gain in dB. Red indicates higher gain, while green, blue, and other cooler colors represent lower gain. The maximum gain of 7.71 dBi indicates that the antenna can effectively concentrate its radiation in specific directions, making it suitable for applications that require focused energy transmission. The lowest gain, represented in blue, goes down to approximately – 32.3 dBi. This 3D gain pattern shows that the proposed patch antenna has a directional nature with multiple high-gain lobes, suitable for applications that require focused energy transmission in particular directions, such as high-frequency communication, radar, or sensing. However, the multiple lobes and variations in gain indicate that the antenna may radiate energy in several directions, which might be helpful for IoT application.

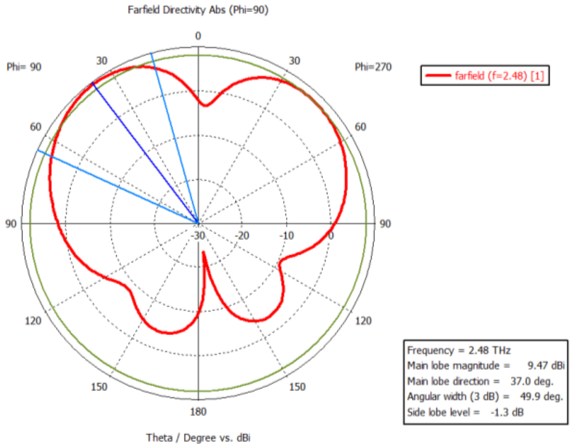

Fig. 7 – Radiation patterns of the *E*-field & *H*- at resonant frequency of 2.48 THz

4.4 Efficiency

Antenna efficiency measures radiated energy of antenna in the air. Antenna efficiency is obtained by using the following relation between the antenna gain and directivity [21],

$$Efficiency = \frac{Gain}{Directivity} \times 100\% \qquad (4)$$

From equation (4), it is observed that efficiency depends on antenna gain and directivity. We obtained the directivity and gain from Fig. 5 and Fig. 6 at resonant frequency of 2.48 THz. The proposed TSHP antenna provides efficiency of 81.59 %. Therefore, we obtained good efficiency with the proposed TSHP antenna, which is suitable for IoT application.

4.5 Radiation Pattern

The radiation pattern of the TSHP antenna at the resonant frequency of 2.48 THz is shown in Fig. 7. The plot represents a typical radiation pattern for the proposed TSHP patch antenna, which generally radiates in a broad, somewhat directional pattern. The pattern is cardioid, with the most substantial radiation occurring in the forward direction and reduced radiation in the backward direction. The main lobe is usually broad, making it suitable for applications that require a wide bandwidth with a high data rate, such as IoT technology. This radiation pattern indicates that the patch antenna operates with a peak directivity of 9.47 dB at a frequency of 2.48 THz. The main lobe is

Table 3 – Simulation results

Parameter	TSHP Antenna
Resonant frequency(THz)	2.48
S_{11} (dB)	-36.76
Bandwidth(THz)	0.86 (860 GHz)
VSWR	1.03
Efficiency	81.59%
Gain(dB)	7.71

directed at 37 degrees with a 3dB angular width of approximately 49.9 degrees. The side lobe level of – 1.3 dB shows secondary radiations, but the main lobe remains dominant. This pattern is typical for the patch antennas used in high-frequency applications that require focused radiation in a specific direction with broad coverage. Table 3 summarizes the simulation result of the proposed TSHP antenna.

4.6 Comparative Analysis

Table 4 compares the performance of some existing antennas with our recommended TSHP antenna. This table demonstrates the compact size of the TSHP antennas. This table also indicates that the proposed antenna addressed the limitation of existing work by exhibiting a reduced S_{11}, high gain, wide bandwidth, and enhanced efficiency, enabling it to function at higher data rates to meet the requirements of IoT applications. The antenna offered by [9] had a compact size but failed to improve another performance parameter compared to the proposed TSHP antenna. Hence, this work advances the design of microstrip patch antennas for THz applications by overcoming the limitations of prior studies, offering a compact, efficient, and high-performance solution. Therefore, the suggested TSHP antenna would be preferable for 5G communication systems and IoT applications in the THz range.

Table 2 – Comparison of antenna performance

Ref.	Ant. Size (um^2)	S_{11} (dB)	BW (THz)	Gain (dB)	Efficiency (%)
[6]	3000 × 3000	– 30.78	0.030	4.81	–
[7]	2500 × 2500	– 21	0.010	2.35	95
[8]	1420 × 1420	– 29	0.038	3.4	–
[9]	46 × 48	– 20	0.20	3.89	58.9
TSHP	80 × 60	– 36.76	0.86	7.71	81.59

5. CONCLUSION

Researchers working in the THz band for IoT applications face several challenges, one of which is the construction of a microstrip patch antenna with a wide bandwidth and quick transmission rate. This work successfully designs and investigates a hexagonal patch antenna with slots on the patch and horizontally partial ground to mitigate the requirements of IoT applications. At the resonance frequency of 2.48 THz, the simulation result received from the CST simulator showed a 0.86 THz (860 MHz) bandwidth with a return loss of – 36.76 dB. The 0.86 THz wide bandwidth of the suggested TSHP antenna allows it to deliver extremely high data rates for IoT applications. In addition, the suggested TSHP antenna shows 81.59 % efficiency and 7.71 dB of gain. The suggested architecture is ideal for IoT applications because it achieves minimal return loss, wide bandwidth, and high gain. Consequently, we validated the concept of the partial ground approach with triple slots on the antenna patch using simulation results, and it confirmed satisfactory antenna performance for IoT applications in the THz band. As a result, in the THz frequency range, the proposed antenna is suitable for Internet of Things applications and future 5G mobile connectivity. Utilizing the suggested TSHP antenna for energy harvesting.

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Проєктування та аналіз надкомпактної трищілинної шестикутної патч-антени для застосувань в IoT у ТГц діапазоні

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Швидкий розвиток Інтернету речей (IoT) та систем зв'язку 5G вимагає антен, здатних забезпечувати надвисокі швидкості передачі даних та широку смугу пропускання в терагерцовому (THz) діапазоні частот. У цій статті представлено проектування та розробку нової графенової трищілинної шестикутної антени (TSHP), призначеної для застосувань IoT в терагерцовому діапазоні частот. Запропонована антена має компактну шестикутну геометрію зі стратегічно вбудованими пазами та частковою заземленою структурою для оптимізації ключових показників продуктивності, включаючи смугу пропускання, коефіцієнт посилення та ефективність випромінювання. Процес проектування включав ретельне обчислювальне моделювання для оптимізації структури антени для роботи в терагерцовому діапазоні, забезпечуючи мінімальні втрати та високу точність. Для дослідження продуктивності запропонованої антени з площею займання 80 × 60 мкм^2 використовується середовище моделювання CST Microwave Studio. Результати моделювання демонструють широку смугу пропускання 0,86 ТГц, низькі втрати на відбиття – 36,76 дБ, високий коефіцієнт посилення 7,71 дБ та ефективність 81,59 %. Використання графену як провідного матеріалу покращує електричні та теплові характеристики, що дозволяє антені TSHP відповідати суворим вимогам високошвидкісних мереж Інтернету речей. Ця робота забезпечує міцну основу для розробки ефективних терагерцових антен, розширюючи можливості систем Інтернету речей та зв'язку наступного покоління 5G.

Ключові слова: IoT, ТГц-діапазон, Шестикутна форма патча, CST, Трислотовий.