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Original Article

Design and Performance Optimization of A Compact Microstrip Patch Terahertz Antenna for High-Gain Wireless Communication Applications

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Abstract - *An Emerging Terahertz (THz) communication technology is a promising technology for advanced wireless communication with incredibly fast data speeds. However, due to high-rate losses, impedance matching, and miniaturization of the antenna, it is a challenge to develop an effective antenna for the terahertz frequency range. Therefore, it is important to develop compact THz antennas for reliable use of terahertz communication as well as sensing applications. This study aims to design a planar type of microstrip THz antenna and evaluate its performance at 0.80 THz. The antenna is composed of a patch, ground plane, microstrip feed, and dielectric substrate. It ensures impedance matching as well as effective electromagnetic radiation. The study includes electromagnetic simulations to investigate various important parameters. The results obtained from the simulations have shown that the proposed antenna has a minimum reflection coefficient (−29.79 dB) and VSWR (1.06) at 0.80 THz of resonant frequency. In addition, it has a bandwidth of about 0.13 THz, with an efficiency of radiation of 89% and a maximum gain of 11.5 dBi. These outcomes show that the proposed compact THz antenna performs well, offering an efficient solution for terahertz communication, as well as advanced applications in imaging and sensing.*

Keywords - *Terahertz Antennas, Wireless Communication, Microstrip Patch Antennas, Advanced Communication, Electromagnetic Radiation, Parasitic Patch.*

1. Introduction

In modern electromagnetic technology, Terahertz technology has emerged as a potential option, facilitating ultra-high-speed systems in wireless communication and high-resolution imaging and sensing systems. The terahertz band is defined with a wide range of 0.1-10 THz [1] and represents a largely unused spectrum that has the potential to support high data transmission speeds that are well beyond what is currently achievable by existing wireless communication systems that use microwaves and millimeter waves. Terahertz antennas have therefore become a crucial element in the advancement of future systems for communication that will form the basis of sixth-generation (6G) communication systems and other applications in biomedical and security systems [2].

Several types of antenna configurations have been studied for use in the terahertz frequency range [3], among which are slot antennas, dielectric resonator antenna, microstrip patch antennas, and antenna arrays. Among these, the microstrip patch antenna [4] is preferred for use in the terahertz frequency range owing to its compact size, cost-effectiveness, and ease of integration with electronic circuits. The slot antenna [5] is also preferred for use in conjunction with other antennas for bandwidth enhancement. Similarly, antenna arrays are preferred for use in the terahertz frequency range for achieving higher gain and better directivity. Recently, advanced technologies involving metamaterials, graphene, and photonic crystals have also been studied for use in the terahertz frequency range for achieving better performance.

Despite the advancements in technology, there are challenges in the design of high-performance terahertz antennas. These challenges include high propagation losses, impedance mismatch, limitations in fabricating the structure at a micro-scale, and trade-offs in achieving bandwidth and complexity. For example, existing antennas with high gain are complicated structures, while simple antennas with single-element structures, which are compact, may have limitations in bandwidth and efficiency. Thus, there is a rising requirement for a solution that can deliver high performance with simplicity in structure. This study is aimed at solving the problem of designing a High-gain compact terahertz antenna with efficacy and a large bandwidth, without increasing the complexity of the structure. This research study is aimed at optimizing the structure of the antenna and the feeding mechanisms for better performance. The importance of the research is based on the potential of solving the challenges in the implementation of terahertz technology.

The major goal and objective of the investigation are to develop a compact microstrip terahertz antenna with a frequency of operation of 0.80 THz and evaluate its improved performance characteristics. The study's scope involves the analytical design, the performance optimization, and the performance comparison of the antenna with existing antenna models. The novelty of the proposed study is the improvement in the antenna's performance with precise optimization of the structure. The study's contribution is the development of the design methodology and the effect of the structure's parameters on the characteristics in terms of performance. The study's findings contribute to the development of efficient terahertz antenna designs for potential research.

2. Literature Review

Terahertz technology has gained significant attention in recent times because of the potential it holds in ultra-high-speed wireless communication [6], precise image recognition [7], and advanced sensing technologies [8]. The large and untapped terahertz frequency band is very promising for data transmission rates, and thus is a potential option for the advancement of wireless communication technologies. Though the design of efficient terahertz antennas is a key challenge in this technology. High propagation loss, impedance matching, and the limitations of the fabrication process at very high frequencies make the design of efficient terahertz antennas a challenging task [9].

In recent times, many antenna designs, including arrays of antennas, slot antennas, microstrip patch antennas, and dielectric resonator antennas, have been proposed. These antennas have their own strengths in gain, size, and bandwidth. Advanced technologies like metamaterials, graphene, and photonic crystals have also been proposed to improve the efficiency of the antennas. However, the major challenge in the design of terahertz antennas is the need to achieve a trade-off between size, gain, and bandwidth.

2.1. Recent Advancements in Research on Antennas

Recently, research on terahertz antennas has emphasized the radiation performance, frequency tunability, and integration capability of the antenna for high-speed communication, sensing, and biomedical applications. A frequency-tunable microstrip patch antenna using a liquid crystalline polymer substrate was discussed in [10], which can be useful for flexible medical device applications. For multi-channel communication and signal tracking, multibeam antenna configurations [11] with quasi-optical isolators [12] and reflector feed networks were introduced in several studies.

Significant advancements in directional radiation performance and beam control of the antenna were realized with new configurations, as discussed in [13], where a quasi-Yagi Uda antenna with graphene reflectors on silicon dioxide substrates was introduced. For improved aperture-fed patch antennas, polycarbonate and silicon substrates were investigated. Furthermore, improved electromagnetic modeling techniques using oxide layers on silicon substrates were discussed for anisotropic effects in the terahertz frequency ranges [14].

Moreover, integration with various semiconductor technologies has also gained importance in the design and development of THz antennas. The CMOS-compatible folded dipole design and its development, including annular ring array antennas, have shown improved gain characteristics while reducing surface losses [15]. Polarization properties have also been improved in circularly polarized conical horn antennas that use dielectric gratings and compact waveguide feeds. Similarly, improved reflection properties and high radiation characteristics have been shown in graphene-fed dual-polarized patch antennas [16].

Cost-effective antennas have also been explored in various types of antennas, such as dielectric resonator antennas that use high-resistivity silicon substrates and reduce dielectric losses while maintaining gain characteristics at acceptable levels [17]. However, in spite of various technological advancements in antenna design and development, integration with photonic crystal structures and compact patch-type terahertz antennas is still limited. Microstrip antennas [4] have been presented as a reliable option due to simplicity in structure and compatibility with modern technologies.

2.2. Design Challenges

Although considerable advancements have been recorded, there are still considerable challenges in the THz antenna design, particularly in a trade-off between gain, bandwidth, efficiency, and structural complexity [18]. For high-gain antenna design, arrays are often necessary, which are more difficult to manufacture compared to compact single-element designs that often have low bandwidths and moderate efficiency [19].

There are also considerable losses at THz frequencies due to an increase in conductor losses as well as dielectric losses. Moreover, there is considerable loss due to the propagation of surface waves, which affects efficiency and bandwidth utilization in antenna designs. Furthermore, it has been observed that antenna designs at THz frequencies are particularly susceptible to manufacturing tolerances [9, 18], where small variations in dimensions can significantly affect antenna performance in terms of impedance matching as well as resonance characteristics.

2.3. Research Gap

Although much research has been conducted in this field, the challenge of finding a balanced increase in gain, bandwidth, and radiation efficiency in a compact and simple structure for terahertz antennas is still a major challenge. Most studies have been conducted using complex array geometries, sophisticated materials, or multilayer technologies. Moreover, there is a lack of focus in the design and analysis of individual element microstrip antennas for geometric optimization to exhibit stable electromagnetic properties in terahertz bands.

Hence, the study proposes an optimized design for a microstrip terahertz antenna with improved impedance matching, radiation efficiency, and bandwidth using precise dimensional control and feeding structure optimization. The designed antenna is able to accomplish a significant gain, bandwidth, and radiation effectiveness. The research outcome is applicable for the implementation of emerging technologies in the field of sixth-generation wireless technologies, terahertz imaging for security and medical diagnostics, spectroscopy-based material analysis, and nano-scale biomedical sensing technologies.

3. Methodology

In the study, a proposed methodology is developed for designing and evaluating a high-performance THz (Terahertz) microstrip antenna suitable for future wireless and sensing applications. The framework is based on a systematic antenna engineering process that encompasses theoretical modelling, computational design, electromagnetic simulation, and performance evaluation.

The operating requirements for the proposed antenna are specified based on the specifications of the terahertz system. A planar microstrip antenna configuration is developed based on existing electromagnetic design theory for microstrip antennas. Mathematical equations are used to calculate the geometrical parameters for the design of the antenna configuration.

The model of the proposed THz antenna configuration is based on a full-wave electromagnetic simulation environment. Optimization is performed to improve the antenna's performance further. It is then assessed based on existing performance parameters, and its suitability for terahertz applications is examined.

3.1. Proposed Terahertz Antenna Design

The THz antenna design is a planar microstrip-type antenna operating in the terahertz band. It is composed of four major parts: ground plane, radiating patch, microstrip mechanism, and dielectric substrate. To increase the gain and bandwidth performance, the proposed antenna design is extended to incorporate a stacked configuration of parasitic patches placed above the driven radiating patch. The parasitic patches are separated from the radiating patch by a low-permittivity spacer layer. This facilitates electromagnetic coupling between the layers. The stacked configuration of the proposed design enables better performance in terms of radiation characteristics compared to single-layer microstrip antennas.

The radiating patch of the antenna produces the electromagnetic waves. The dielectric substrate is the part of the antenna used to provide support, and it affects the propagation of the electromagnetic waves. To augment the radiation efficiency, the ground plane reduces the unwanted electromagnetic coupling. The microstrip mechanism provides the necessary continuity of the impedance and excites the patch. The antenna is expected to function at a 0.8 THz resonant frequency within the terahertz band (0.1 - 10 THz). This range of electromagnetic waves is used in high-resolution sensing and high-capacity communication applications.

3.1.1. Design And Simulation Techniques

The process of designing the antenna involves the use of advanced technologies like microstrip antenna synthesis, modelling of the electromagnetic field, numerical parametric optimization, simulation verification, and performance evaluation using important parameters of the antenna. The use of these technologies helps in the accurate analysis of the behaviour of the electromagnetic field, thus making the process efficient.

For the simulation and analysis, the study makes use of special tools, such as ANSYS HFSS (High Frequency Structure Simulator) for simulating the high-frequency properties, and Python for the visualization of the results, with the main tool used being ANSYS HFSS, which makes use of the efficient Finite Element Method (FEM) for the simulation in the terahertz frequency range.

Figure 1 indicates the antenna structure for the proposed terahertz microstrip antenna. As demonstrated, the terahertz microstrip antenna comprises a radiating patch coupled to the microstrip feed line placed on a dielectric substrate. The substrate is then placed above a ground plane. In addition to conventional design techniques, a stacked Design of parasitic patches is also utilized for improving the performance of the proposed design.

The electromagnetic coupling between the radiating patches and the stacked Patches of parasites enables multiple resonance modes to occur. This helps to achieve better impedance bandwidth and improve efficiency for the proposed design. This design is widely utilized for designing antennas operating at higher frequency bands. This structure is efficient in exciting electromagnetic waves, thus enabling radiation within the desired terahertz frequency band.

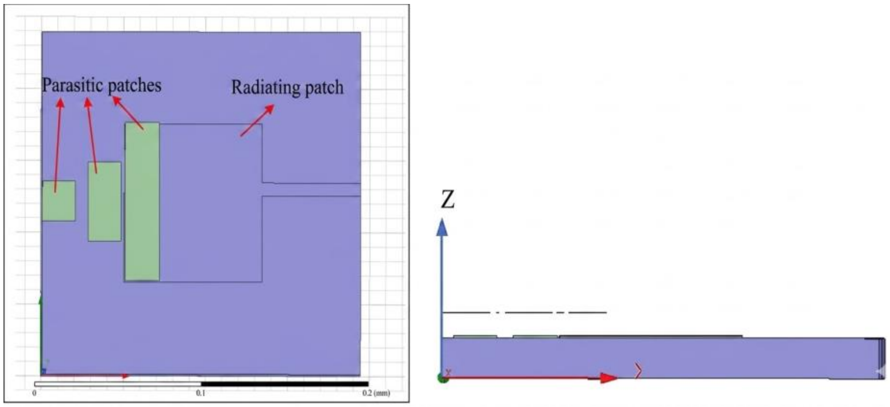

Fig. 1 Antenna Structure-Conceptual diagram

3.1.2. Antenna Design Specifications

The specifications of antenna design are initiated by specifying the antenna performance specifications, which affect the structure of the antenna. These specifications include frequency range, bandwidth, gain, efficiency, impedance, and other application-dependent specifications. They provide the basic framework for the antenna's structure and affect the selection of the device's material as well as structure. In the stacked antenna configuration, additional design specifications have been taken into account. These specifications include the parasitic patch size, which includes the length and width of the parasitic patch, the elevation of the spacer layer, and the interlayer spacing between the patches. These specifications have a critical role in controlling the coupling strength of the antenna.

3.1.3. Material Selection of Substrate

The dielectric material is a vital aspect for an antenna, especially when the frequency is as high as terahertz. To minimize the attenuation of the signal, it is important to select a material having minimal dielectric loss. The relative permittivity, dielectric loss, and thickness of the substrate material are also important. For a terahertz antenna, the most commonly used substrates are silicon, Polyimide, and Polytetrafluoroethylene (PTFE). For this antenna, Polyimide is selected as a dielectric material.

3.1.4. Mathematical Modeling of Antenna Dimensions

The microstrip patch antenna design is controlled by precise mathematical formulations based on electromagnetic theories. These mathematical equations relate their physical dimensions to the required resonating characteristics. These equations allow precise estimations of these dimensions for appropriate impedance matching and efficiency.

Patch Width: The width of the patch of antenna for improved bandwidth and efficiency of radiation is estimated as follows:

$$W = \frac{c}{2f_r}\sqrt{\frac{2}{\varepsilon_r+1}} \tag{1}$$

Where the width W of the patch antenna has a direct impact on the radiation conductance. The velocity of light propagation c in an open area is approximately 3×10^8 m/s. The resonating frequency f_r determines the antenna's operational frequency, including ε_r as a relative dielectric constant.

The dielectric constant: This leads to the fringing effects present at patch edges, and the antenna is not considered a perfect dielectric material. This is compensated using the effective dielectric constant, ε_{eff}, which is given by

$$\varepsilon_{eff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left(1+\frac{12h}{W}\right)^{-\frac{1}{2}} \tag{2}$$

Here, the ε_{eff} is a combination of the substrate material and air. Further, it indicates the material of the substrate dielectric value ε_r and the thickness h, which affects the patch antenna's performance. In addition, width W is critical in determining the impact created by the fringing effects.

Patch Length: To ensure that targeted resonance is achieved, the effective patch length is determined considering the effects of the fringing field.

$$L = \frac{c}{2f_r\sqrt{\varepsilon_{eff}}} - 2\Delta L \tag{3}$$

Here, L and ΔL are the actual length and length extension of the patch antenna because of the effects of fringing. Furthermore, it indicates the velocity of light c and resonant frequency f_r, affecting the propagation of waves.

In the stacked antenna configuration, the parasitic patches do not have a direct connection to the feed line. Instead, the electromagnetic coupling between the driven and areas occurs. The size of the parasitic patches is chosen in a way that it is slightly different from the driven patch, which provides nearby resonating frequencies. The electromagnetic coupling between the driven and parasitic patches provides multiple resonating frequencies, which in turn increases the bandwidth of the antenna.

After performing iterative design optimization and parametric analysis, it is observed that the study has obtained the optimized antenna design parameters for efficient terahertz operation. Table 1 represents the proposed design parameters for designing an Antenna THz.

Table 1. Design parameters of proposed THz antenna

Parameter	Symbol	Value	Unit	Description
Operating Frequency	f_r	0.8	THz	Target resonant frequency of the antenna
Light's speed	c	$(3 \text{ X } 10^8)$	m/s	Electromagnetic wave speed in free space
Substrate Material	-	Polyimide	-	Dielectric material used as a substrate
Dielectric Constant	ε_r	3.5	-	Relative permittivity of the substrate
Tangent Loss	$\tan \delta$	0.0027	-	Dielectric loss of the surface
Substrate Thickness	h	20	µm	Thickness of the dielectric layer
Patch Width	W	110	µm	Width of the radiant patch
Patch Length	L	84	µm	Length of the radiating patch
Parasitic Patch Width	W_p	110	µm	Width of parasitic patch
Parasitic Patch Length	L_p	21	µm	Length of parasitic patch
Spacer Height	h_s	12.5	µm	Air/foam gap between patches
Ground Plane Length	L_g	194	µm	Ground plane's length
Ground Plane Width	W_g	238	µm	Width of the ground plane
Feed Line Width	W_f	9	µm	Width of the microstrip feed line
Feed Line Length	L_f	60	µm	Length of the microstrip feed
Conductor Material	-	Gold	-	Conductive layer for the patch and ground
Conductivity	σ	$(4.1 \text{ X } 10^7)$	S/m	Electrical conductivity of gold

3.1.5. Development of Antenna Geometry

Based on the calculated values, a Three-Dimensional Antenna (3D) model is developed using an electromagnetic simulation environment. The developed antenna geometry is composed of a radiating patch, ground plane, and substrate, as well as a microstrip feed line. 3D modeling is a precise method for representing the behavior of electromagnetic wave propagation, in addition to field distributions and coupling effects.

3.1.6. Electromagnetic Simulation

The antenna, as designed, is subjected to electromagnetic simulation. This is usually carried out by the ANSYS HFSS. The simulation process involves the generation of an adaptive mesh, the setting of boundary conditions, the configuration of the frequency sweep, and the definition of the port excitations. In the simulation, the antenna is created as a multilayer structure. The structure includes the driven patch, the spacer layer, and the parasitic patch.

The radiation boundaries and air regions are also created in the simulation environment. The FEM is employed in the simulation. This is a numerical technique used in the simulation of Maxwell's equations. The results of the simulation include the radiation pattern, surface currents, electric field intensity, gain, return loss, and radiation effectiveness of the antenna. Table 2 shows the values of simulation parameters.

Table 2. Parameters in simulation setup

Parameter	Value
Simulation Software	ANSYS HFSS
Solver Type	FEM
Frequency Range	0.4 THz – 1.2 THz
Boundary Condition	Radiating
Port Type	Port (Feed Line)
Mesh Type	Adaptive Mesh Refinement

3.1.7. Parametric Optimization

To improve the suggested THz antenna's efficiency, a parametric optimization is carried out. This is done by varying the critical antenna's characteristics. These specifications are the size of the patch, the position, and how wide the feed line is. The optimization aims to enhance the loss of return, both the radiation efficiency and the gain. The final antenna design is arrived at through the optimization of the parameters. Apart from the conventional parameters, optimization is extended to include the height of the spacers, parasitic patch dimensions, and interlayer spacing. The parameters are systematically varied to attain optimal impedance matching, maximum gain, and bandwidth.

3.1.8. Simulation Analysis

The execution of the designed antenna is analyzed by studying the results obtained from the simulations in a graphical format to ensure that it meets the design requirements. Some of the important graphs include the reflection coefficient curve, VSWR curve, gain curve, and two-dimensional and three-dimensional radiation patterns. Besides this, surface current and electric field distributions are also studied to comprehend electromagnetic fields' actions within the antenna structure. These plots offer a strong understanding of the antenna's radiation qualities and confirm its functional efficiency.

3.1.9. Performance Evaluation Metrics

The efficiency and suitability of the proposed antenna design are determined by using various electromagnetic parameters that measure its operational efficiency.

Reflection Coefficient: For efficient antenna operation, the reflection coefficient must meet the condition S_{11}<-10 dB. The S_{11} reflection coefficient indicates the quantity of power sent back through the input port of the antenna. S_{11} below -10 dB specifies that most power is radiated instead of reflected, thus ensuring efficient operation and proper impedance matching.

Voltage Standing Wave Ratio (VSWR): It ascertains the quality of impedance matching and is given by:

$$VSWR = \frac{1+|\Gamma|}{1-|\Gamma|} \tag{4}$$

Here, $VSWR$ shows how much the antennas are mismatched, and the transmission line. The value represented by the parameter Γ is the reflection coefficient in linear form. When the $VSWR$ is close to unity, this means that the level of reflection is minimal and the impedance matching is optimal. However, higher values indicate power loss.

Antenna Gain: The directionality of the antenna is represented by the gain as given below.

$$G = \eta D \tag{5}$$

where the antenna gain G indicates the antenna's capacity of directing the radiated power in a specific direction. The radiation efficiency η accounts for losses within the antenna structure, while directivity D measures radiation concentrated in a particular direction. The higher the gain, the stronger the signal strength and the improved communication quality.

Bandwidth: The range of operational frequencies of an antenna is given by the bandwidth as

$$BW = f_h - f_l \tag{6}$$

Where f_h and f_l signify the upper and lower operational limits of an antenna. A greater bandwidth allows an antenna to support high-speed communication systems. Overall, the methodology proposed in the study provides a clear framework for designing and evaluating a terahertz antenna. The methodology includes important steps for defining the specification, selecting the substrate, analytical modeling, simulating the electromagnetic, and optimizing the parameters. The results show that the antenna can be effectively designed for reliable performance, meeting the criteria for the next generation of terahertz communication.

4. Result

The designed THz antenna is simulated through electromagnetic simulation to examine its performance in the THz frequency range. During the simulation, various antenna parameters, including the bandwidth, gain, standing wave ratio, voltage, reflection coefficient, radiation efficiency, and radiation pattern, are considered. These parameters affect the terahertz antenna's performance, especially in high-frequency communication as well as sensing applications. The addition of stacked parasitic elements enhances the aperture area, thus allowing multi-resonance, which in turn enhances bandwidth and gain. The design is thus suitable for terahertz applications, which require high data rates. Based on the simulation results, it is found that the terahertz antenna design shows better performance features, like impedance matching, radiation pattern, and radiation efficiency, especially in the terahertz frequency range.

Therefore, the evaluation shows that it is suitable for applications like high-frequency communication, including terahertz communication.

4.1. Performance of THz Antenna

4.1.1. Reflection Coefficient Analysis

The coefficient of reflection (S_{11}) indicates the quantity of power that is reflected at the input port. For efficient antenna performance, the reflection coefficient needs to be low for maximum power transmission. The proposed antenna shows a reflection coefficient in the frequency band of 0.4 THz to 1.2 THz.

Table 3 shows the performance of the reflection coefficient, where the THz antenna indicates a good resonance at a frequency of 0.80 THz with a −29.79 dB of reflection coefficient. The reflection coefficient should always be less than −10 dB for efficient antenna performance, showing excellent impedance matching with the feed line. This proves that the proposed antenna efficiently transmits the electromagnetic signal from the transmission line to free space radiation.

Table 3. Reflection coefficient performance of THz antenna

Parameter	Value
Resonant Frequency	0.80 THz
Minimum S_{11}	−29.79 dB
Acceptable Limit	< −10 dB
Impedance Matching	Excellent

Figure 2 illustrates the characteristics of impedance matching for the proposed terahertz microstrip antenna. As revealed, there is a strong resonance peak at 0.80 THz, where the reflection coefficient is approximately -29.79 dB. This shows that there is excellent matching of impedance between the terahertz microstrip antenna's feeding structure, thus enabling competent transfer of power with negligible signal reflections. The resonance obtained in the proposed antenna is deep at the operating frequency, showing efficient minimization of reflection for efficient transmission.

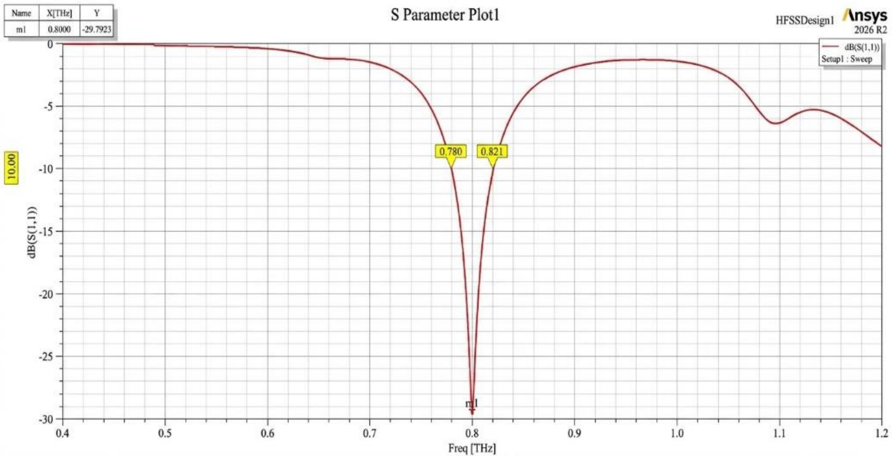

Fig. 2 S_{11} vs Frequency

4.1.2. Voltage Standing Wave Ratio (VSWR)

The VSWR offers more information regarding impedance matching. From Table 4, the VSWR has a value close to 1. This is an indication of the transmission line's good matching and antenna. The proposed antenna has been able to attain a VSWR of 1.06 at the 0.80 THz resonant frequency. The VSWR falls well within the acceptable limits for antenna systems. The low VSWR is an indication that little power is reflected to the source. This enhances transmission efficiency and allows the antenna to operate well. Figure 3 shows the impedance matching characteristics of the terahertz microstrip antenna.

As revealed, there is a strong resonance peak at 0.80 THz, where the VSWR is approximately 1.06, thus indicating that there is excellent matching of impedance of the terahertz microstrip antenna and its feeding structure. It shows that the terahertz microstrip antenna operates efficiently with minimal mismatch losses.

Table 4. VSWR performance of THz antenna

Parameter	Value
Resonant Frequency	0.80 THz
VSWR	1.06
Acceptable Range	< 2

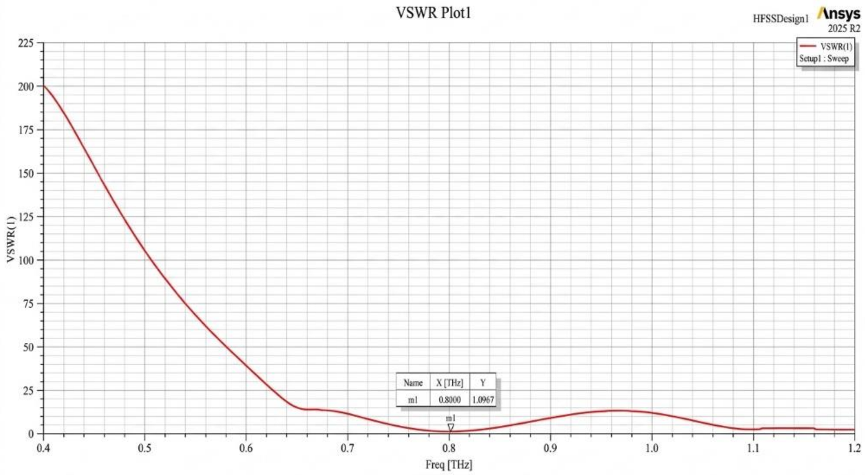

Fig. 3 VSWR vs Frequency

4.1.3. Bandwidth Performance

Bandwidth is another important parameter for terahertz communication system antennas, as it defines the operating frequency range for the antenna. From Table 5, it is clear that the anticipated antenna operates within a bandwidth of 0.13 THz, covering a frequency range of 0.78 THz to 0.82 THz.

Wide bandwidth is also seen in the simulation results for the proposed antenna. This shows that the antenna is able to support high-speed data transmission. Wide bandwidth is critical for future terahertz wireless networks due to the need for extremely high transmission speeds.

Table 5. Bandwidth characteristics of THz antenna

Parameter	Value
Lower Frequency Limit	0.78 THz
Upper Frequency Limit	0.82 THz
Achieved Bandwidth	0.13 THz
Fractional Bandwidth	16.25%

4.1.4. Antenna Gain Analysis

Antenna gain is a measurement of its capability to direct or focus the emitted signal in a specified direction. The ability to increase the distance of the transmitted signal is also related to the gain. From Table 6, it is clear that the proposed antenna is able to reach a maximum gain of 11.5 dBi at the resonant frequency.

The gain is considered high for compact terahertz antennas. The high gain is attributed to the optimal design of the antenna as well as impedance matching. The high gain improves the signal transmission capability as well as the reliability of the terahertz wireless system.

Table 6. Gain analysis of THz antenna

Parameter	Value
Peak Gain	11.5 dBi
Frequency at Peak Gain	0.80 THz

Figure 4 represents the gain curve with variations of the antenna gain with the operating frequency. From the curve, it is evident that the antenna's maximum gain is around 11.5 dBi at 0.80 THz. This suggests that the antenna has the capability for efficient radiation and thus improved transmission performance.

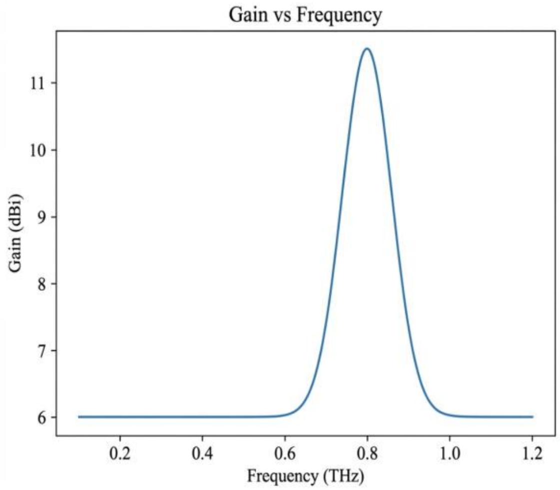

Fig. 4 Gain vs Frequency

4.1.5. Radiation Efficiency

Radiation efficiency is the capability of the antenna to convert the input power into radiated electromagnetic form. From Table 7, the Radiation Efficiency obtained by the proposed antenna is around 89% for the operating frequency of 0.80 THz.

The high radiation efficiency implies that the amount of power lost as a result of dielectric losses and/or conductor losses is quite low. This is important for the terahertz band because the energy lost may affect the quality of the communication.

Table 7. Radiation efficiency

Parameter	Value
Radiation Efficiency	89 %
Frequency	0.80 THz

The radiation efficiency curve in Figure 5 represents the efficiency with which the antenna radiates the input power. From the curve, it is evident that the antenna has an efficiency of around 89% at the resonating frequency. This suggests that the antenna does not lose much power due to dielectric and conductor losses.

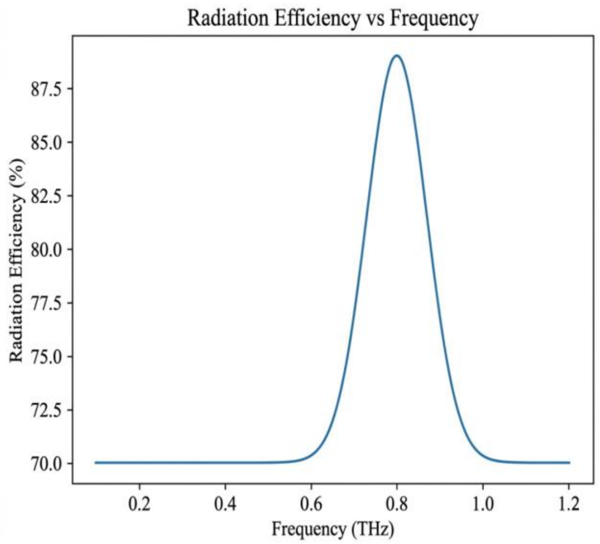

Fig. 5 Radiation efficiency vs Frequency

4.1.6. Radiation Pattern Analysis

The THz antenna design is investigated for the radiation pattern using 2D polar plots at 0.8 THz. Based on the results obtained, it can be observed that the proposed design has a broadside radiation pattern with the main beam oriented along 0°, which corresponds to the normal direction of the patch.

In the E-plane and H-plane, the radiation characteristics are mainly concentrated in the forward direction, indicating efficient radiation in the desired direction.

The back radiation at 180° is also minimized due to the presence of the ground plane. The radiation pattern also exhibits a single dominant main lobe with very small side lobes. This confirms the good conductivity and broadside radiation behaviour of the antenna. Similarly, smooth and stable gain distribution is maintained with minor fluctuations in the radiation pattern, as per the general design of antennas. Overall, it confirms effective forward radiation, reducing power loss in the backward direction, along with the antenna's capability for applications including high THz frequencies.

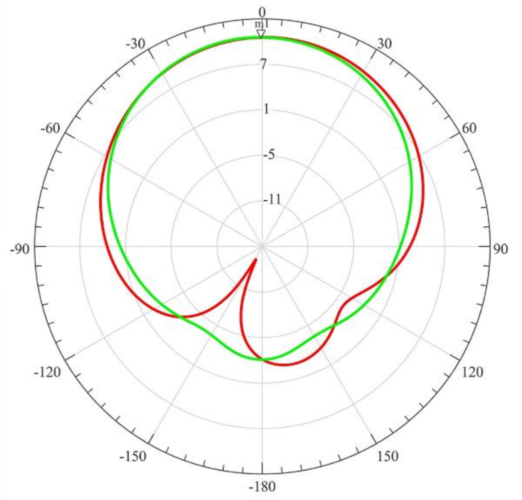

Fig. 6 Radiation patterns

4.1.7. Surface Current Distribution

The distribution indicates electromagnetic energy across the antenna structure. The simulation result indicates that the extreme density of current is distributed along the boundaries of the radiating feed line and the patch. This indicates that the radiating patch is effective in radiating electromagnetic waves at the operating frequency. The current distribution also indicates that the antenna structure is able to support strong resonance at the designed terahertz frequency.

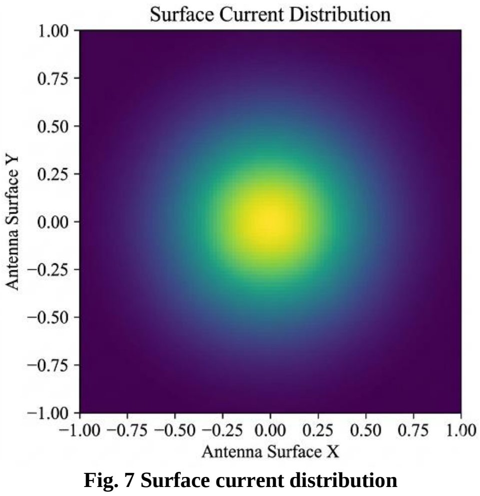

Fig. 7 Surface current distribution

The plot with the distribution of surface current in Figure 7 indicates the flow of current around the feed line and the radiating patch. It is observed that the highest density is concentrated around the patch edges and the feed area, which confirms that these areas are critical in electromagnetic radiation.

4.1.8. Electric Field Distribution

The distribution of the electric field for the antenna structure was also analyzed. This is for understanding the behaviour of the electromagnetic wave. The simulation results show that there is a high level of electric field intensity near the patch and the feed line. This level of electric field intensity decreases as the electromagnetic wave propagates into free space. This is an indication that the antenna is effectively radiating the electromagnetic wave.

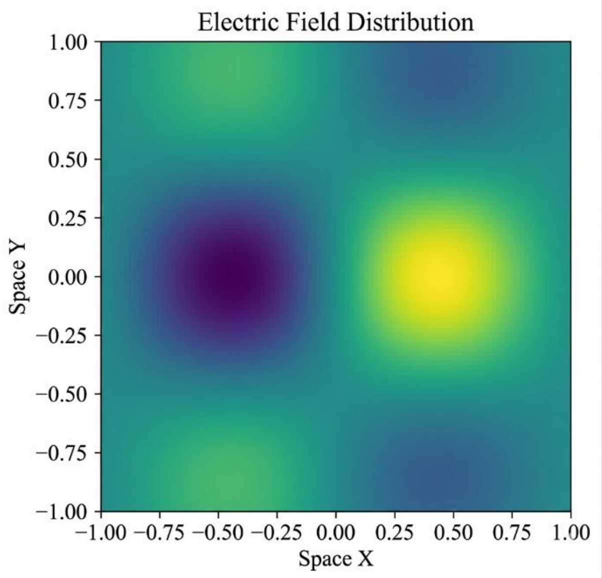

Fig. 8 Electric field distribution

Figure 8 shows the distribution of the electrical field, indicating the propagation of electromagnetic fields around the antenna structure. It is observed that high electric field intensity is concentrated around the radiating patch area and then decreases as electromagnetic waves propagate into free space.

4.1.9. Parametric Analysis

To further enhance the electromagnetic characteristics of the designed terahertz antenna, a parametric optimization technique was carried out. In this technique, various parameters were varied to obtain improved characteristics. As mentioned, various parameters were varied, such as patch length and width, feed line width and length, and substrate thickness. As shown in Table 8, with optimized parameters, the patch length is reduced to 84 µm from 95 µm, while the patch width is increased to 115 µm from 110 µm. Furthermore, the feed line width is reduced to 9 µm from 20 µm, while the feed line length is increased to 60 µm from 55 µm. Finally, the thickness of the substrate is increased to 20 µm from 18 µm, which is essential to enhance the terahertz antenna characteristics. In addition, while parasitic patch length is decreased to 80 µm from 110 µm, and for further parasitic patches, the length is successively decreased to half and quarter length, keeping a constant width of 21 µm and spacer height increased to 12.5 µm from 10 µm. Therefore, various parameters were optimized, which is essential to obtain improved terahertz antenna characteristics. In Figure 9, the parametric analysis graph indicates the impact of changing patch length on the reflection coefficient. It is observed that the minimum reflection coefficient is obtained when the patch length is around 92 µm, which confirms that antenna design is sensitive to patch length.

Table 8. Optimized parameters after simulation

Parameter	Symbol	Unit	Initial Value	Optimized Value
Patch Length	L	µm	95	84
Patch Width	W	µm	115	110
Feed Width	W_f	µm	20	9
Feed Length	L_f	µm	55	60
Substrate Thickness	h	µm	18	20
Parasitic Patch Length	L_p	µm	110	80
Parasitic Patch Width	W_p	µm	21	21
Spacer Height	h_s	µm	10	12.5

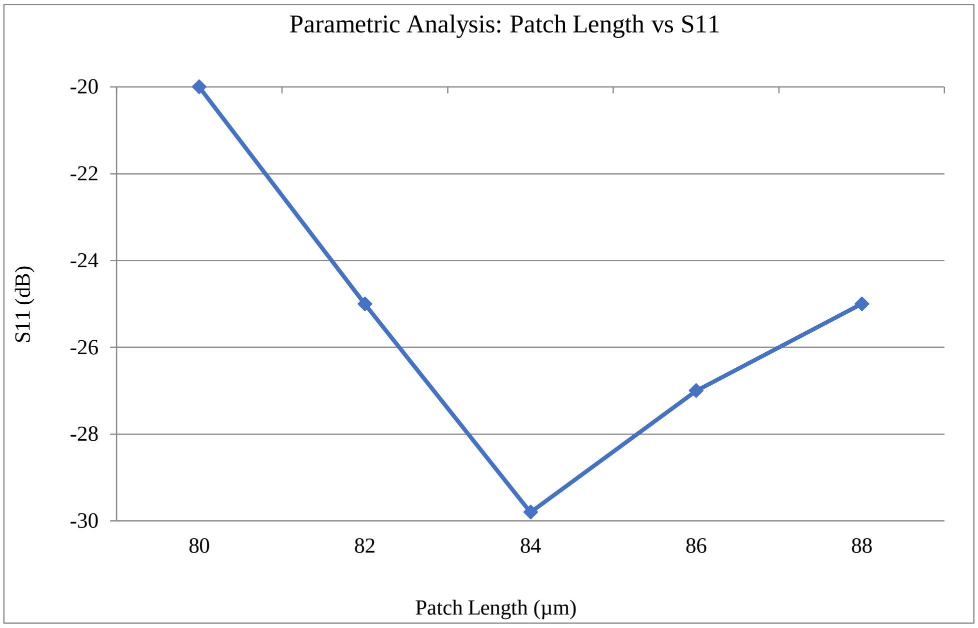

Fig. 9 Parametric analysis graph

5. Discussion

The proposed terahertz antenna design has been developed based on a microstrip configuration that is optimized for efficient operation in the terahertz regime. The proposed design includes a radiating patch that is compact in size and a low-loss dielectric material that ensures high-performance radiation characteristics and impedance matching properties. In this design, optimization techniques have been employed to optimize the design parameters and dimensions of the proposed terahertz antenna design. The proposed terahertz antenna design has been simulated and observed to operate efficiently at a resonant frequency of 0.80 THz, which is within the terahertz regime that supports high-performance wireless communication and sensing applications. Moreover, the proposed terahertz antenna design has achieved a reflection coefficient of -29.76 dB, which ensures high-performance impedance matching between the proposed antenna and the microstrip structure. In this design, a VSWR value of 1.06 has been observed, which ensures that mismatch losses are minimized and high-performance impedance matching is achieved between the proposed antenna and the microstrip structure. The performance result demonstrates the existence of several positive qualities associated with the proposed antenna. For instance, the antenna has a bandwidth of around 0.13 THz. The bandwidth ranges from 0.78 THz to 0.82 THz. The bandwidth is quite wide and thus useful for high data transmission rates. The bandwidth is important for the development of wireless terahertz networks in the future.

The gain analysis demonstrates the capability of the antenna to attain a maximum gain of around 11.5 dBi at the resonant frequency. This is quite high for terahertz band antennas. This demonstrates the capability of the antenna for directional radiation. This is evident by the stability of the radiation configuration in the E-plane and H-plane. In addition, the proposed antenna has the capability for high radiation efficiency. Specifically, the antenna has an efficiency of around 89%. This demonstrates that the projected antenna is effective in converting the input power into useful radiation. This is mainly due to the low-loss substrate and the structural design. The analysis of the surface current and electric field distribution will give a deeper understanding of the electromagnetic features of the antenna. The concentration of the current at the edges of the patch indicates the efficient radiation of the antenna, whereas the electric field distribution indicates the propagation of the radiated energy into free space. The proposed antenna design is found to have better gain and bandwidth in comparison with the previously reported terahertz antennas, mainly because of the optimized geometry and efficient radiation of the patch and the line.

5.1. Comparative Analysis

The effectiveness of the suggested terahertz antenna is compared with recent studies to evaluate the efficiency of the proposed antenna in terms of bandwidth, gain, and structural efficiency. Table 9 shows that the slot antenna in Youssef et al. [5] functions at a frequency of 0.118 THz with an increase of 7.36 dBi and a bandwidth of 0.004 THz. The photonic crystal patch antenna in Sridevi et al. [16] operates at a frequency of 0.625–0.645 THz with improved impedance matching characteristics and a gain of 8.92 dBi and a bandwidth of 0.038 THz. The total effectiveness of the antenna is moderate in comparison with the proposed antenna. Similarly, the Nataraj et al. [20] array antenna operates at a frequency of 0.6-1.6 THz with a high gain of 11 dBi and a wider bandwidth, but with increased size and structural complexity. However, the proposed THz antenna uses a frequency of 0.80 THz with a high gain of 11.5 dBi and a wider bandwidth of 0.13 THz with a compact size in microstrip configuration.

Figure 10 shows a comparison graph that compares the execution of the presented antenna with other terahertz antennas reported in various studies. From the results, it is evident that the presented design has a higher gain and bandwidth compared to various studies. Thus, the study demonstrates the effectiveness of the optimized antenna structure. The improved performance of the proposed study is mainly due to accurate geometric optimization and efficient design of the feed line, which optimizes impedance matching and reduces reflection loss. The use of a low-loss dielectric material and accurate dimensional tuning is believed to improve radiation efficiency and bandwidth.

Table 9. Comparative analysis of proposed and existing studies

Ref.	Frequency (THz)	Gain (dBi)	Bandwidth (THz)	Antenna Type
Youssef et al. [5]	0.118	7.36	0.004	Slot Antenna
Sridevi et al. [16]	0.625–0.645	8.92	0.038	Patch Antenna
Nataraj et al. [20]	0.6–1.6	11	1	Array Antenna
Proposed THz Antenna	0.80	11.5	0.13	Microstrip THz Antenna

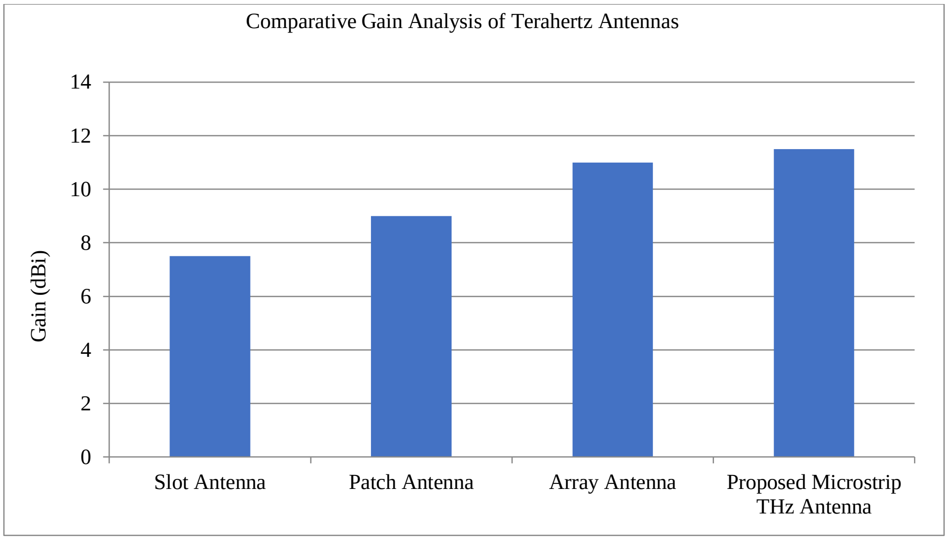

Fig. 10 Comparison with existing studies

In addition, the miniaturized microstrip design is believed to ensure consistent radiation performance with minimal energy loss.

All these design techniques have enabled the proposed study to show improved performance compared to various existing single-element antennas in terahertz frequencies.

5.2. Applications

Terahertz antennas are important components in the development of several new technologies, owing to the capability of these antennas to operate at extremely high frequencies, thus facilitating wideband communication.

Terahertz Wireless Communication: Terahertz antennas are expected to be important components in the development of future sixth-generation wireless communication systems, owing to the capability of these systems to facilitate the transmission of data at extremely high rates.

Terahertz Imaging Systems: Terahertz imaging systems are important components in the development of security systems, as terahertz waves are capable of penetrating non-conductive materials, thus enabling the progress of non-invasive imaging schemes.

Biomedical Sensing: Terahertz antennas are important mechanisms in the development of disease detection systems, as terahertz waves are capable of interacting with different biological materials in unique ways.

Spectroscopy and Material Characterization: Terahertz antennas are important elements in the development of spectroscopy systems, which are used in the characterization of molecular structures and chemical composition, thus facilitating the development of several important applications in the pharmaceutical, environmental, and chemical sectors.

Wireless Nano-Networks: Terahertz antennas are important components in the development of nano- Interaction in wireless systems, which are used in the growth of communication systems in wireless networks in biomedical monitoring and sensing systems.

Space Research Earth Exploration and Service Satellite (passive): As per 5.565 of the National Frequency Allocation Plan-2025 by the Government of India, this frequency range is to be used in passive Research Service for Space and Earth Exploration Satellite in the coming years.

5.3. Practical Implications

The proposed terahertz antenna design has potential benefits for the development of new high-frequency technologies with a reduced size, an extensive bandwidth of 0.13 THz, and a high gain of 11.5 dBi. The antenna has a high level of radiation efficiency (89%) and is energy-efficient in miniaturized and battery-powered devices. The proposed antenna has good impedance matching properties, making it efficient in the transmission of signals. The radiation properties make the proposed antenna applicable in 6G communication technologies.

6. Conclusion

The study is intended for the layout and performance assessment of a compact microstrip terahertz antenna, which is intended for communicating at high frequencies and sensing. Based on the design, the anticipated terahertz Antenna is designed to function at a resonant frequency of 0.80 THz using an optimized planar structure, where a radiating patch, dielectric substrate, ground plane, and microstrip feed line were used.

In addition, stacked parasitic elements enhance the aperture area, which allows multi-resonance, enhancing bandwidth and gain. During the design, analytical modeling and electromagnetic simulation were carried out to ensure improved impedance matching characteristics.

According to the simulation results, it is evident that the terahertz antenna can achieve a minimum reflection coefficient of -29.79 dB, peak gain of 11.5 dBi, a large bandwidth of 0.13 THz, VSWR of 1.06, a range of frequencies of 0.78 THz to 0.82 THz, a high data rate, a high radiation efficiency of about 89%, strong radiation characteristics, and minimal energy loss.

The study gives valuable insights into the effect of geometric optimization techniques on terahertz antenna design. The proposed design adds a compact, efficient, and high-gain antenna design that surpasses various existing designs in this area.

The novelty in this study is that it optimizes both the antenna and its feeding structure to obtain a high-efficiency and wideband design that may be applicable in various 6G communication systems, terahertz imaging systems, and terahertz sensors. However, the proposed design is based on simulated results that lack experimental results and fabrication, which may vary from simulated results in some cases. In future work, it is recommended that this design be implemented in a real-world scenario and experiments be conducted to validate the proposed design.

Further study in this area may be conducted by using exotic materials such as graphene and metamaterials to obtain a more efficient and miniaturized design. In addition, this study may be extended to biomedical applications such as non-invasive tissue imaging and disease detection using terahertz antennas.

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