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Design and analysis the performance of triangular patch antenna for THz applications

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Abstract Modern technology advancement requires a more extensive data rate to convey information more rapidly than ever. Improved bandwidth can satisfy the need for high-speed transmission demand. In order to achieve significantly increased bandwidth for a high data rate communication, the antenna design at the THz band is essential. The microstrip patch antenna is one of the most prominent antennas for THz band applications such future 5G communication systems and advanced wireless communication system. This paper proposed a triangular patch antenna for THz applications where FR4 is used at the substrate as an insulator and Graphene at the patch as a conductor. Moreover, we improve the performance of the proposed antenna by modifying the shape of the patch and ground (GND) layer. We modify the patch shape by cutting the corner edge of the triangular patch. Moreover, the GND layer is modified with horizontally partial ground. The size of the proposed antenna is set to 160×120 µm^2. We analyze the performance of the proposed antenna using CST simulation software. Based on the simulation results, the proposed antenna with a modified patch and GND shape shows wide bandwidth of 1.27 THz and minimal return loss of -33.22 dB at a resonant frequency of 2.28 THz. Additionally, the gain and efficiency of the suggested antenna show good improvement. Therefore, the proposed triangular patch antenna with a modified patch and GND shape is expected to be suitable for high-speed THz applications.

Keywords: Triangular shape patch, THz band, CST simulator, partial ground, modifed patch.

1. Introduction

In the present scenario, the demand for wireless communication systems and their services must proliferate in response to consumer needs (Song et al 2011). The main shortcomings of the current wireless communication system are inadequate bandwidth, ineffective spectrum utilization, interference, and low data rates (Malviya and Gupta 2021; Pant et al 2021). To meet the criteria of consumer speed demand, the THz band is becoming a crucial factor with high bandwidth to transmit information at a high data rate with low interference. The frequency range from 0.1-10 THz has been allocated for the THz applications (Yadav et al 2021), such as in advanced wireless communication system and future 5G communication system; in the medical application for the detection of infected tissues (Rabbani and Ghafouri-Shiraz 2016), medical imaging for non-invasive diagnostics (Orlova et al 1998; Taylor et al 2009), Room temperature detection, or microbolometers (Lee et al 2006), because of its non-ionizing nature. It was confirmed (Woodward et al 2002) that THz radiation is almost harmless to human tissue because of its non-ionizing nature.

Researchers developed different types of antennas (Shaddad et al 2021) for THz application, such as wideband horn antenna, leaky-wave antenna, Yagi-Uda antenna, bow-tie antenna, log-periodic antenna, MEMS antenna, for transmitting and receiving at wide bandwidth, and high data rates. However, despite the advantage of the THz band, most of the THz antennas undergo high loss, complex structural design, and low fabrication due to the small size of THz antennas. Also, the quality and efficiency of the overall communication system are directly correlated with antenna performance (He et al 2020). A microstrip patch antenna (MSA) with a simple structure, wide bandwidth, and high gain is needed to overcome previous problems. Moreover, MSA is inexpensive and features easy fabrication, less weight, and compactness.

Author (Khulbe et al 2016) proposed a T-shaped patch antenna was proposed for the THz band. After that, the author proposed an RMSPA antenna (Nag et al 2016) with sea foam as a substrate material and obtained a gain of 5.95 dB, bandwidth of 130 GHz, and a return loss of -27 dB. In (Azam et al 2017), the rectangular and circular patch-based antenna was proposed for the THz application. Then authors (Khan et al 2019) proposed a graphene-based circular patch antenna with a novel substrate to enhance gain and bandwidth for THz applications. Based on the concept of multilayer substrate (Sharma et al 2009), the author (Khan et al 2020) proposed graphene-based patch antenna with different substrate types for

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further enhance the THz band antenna performance. Our earlier research (Alam et al 2020) employed graphene as a conducting material that achieved enormous bandwidth and good efficiency but failed to increase gain and reduce return loss.

In this paper, we have proposed a triangle-shaped patch antenna with a modified patch shape and partial ground method where graphene is used at the patch and ground layer as a conductive material, and FR4 is used as an insulator at the substrate. This paper designed the antenna to operate at THz frequency bands. This article assesses the suggested antenna's characteristics, including return loss, antenna gain, and efficiency. The proposed antenna is expected to provide low return loss, high bandwidth, and enhanced gain in the THz band. The following list summarizes the main characteristics of the suggested antenna:

- The designed antenna is small and can operate in the THz frequency band.
- The gain of the antenna is comparatively high.
- The suggested antenna has an extensive bandwidth to enable increased data speeds.
- Overall, the suggested antenna has the potential for optical communication, 5G mobile communication, and wireless communication.

The remainder of the paper is organized as follows. The design process for simulating the triangle patch antenna is described in the following section. The modeling environment and model of the suggested antenna are described in Section 3. The performance assessment of the recommended antenna based on simulation results is covered in Section 4. Finally, Section 5 concludes the work.

2. Antenna Design Consideration

This paper aims to design a compact triangular shape patch antenna for THz applications. This Section describes the design methodology of the proposed antenna.

2.1. Structure of the proposed antenna

We should consider the following steps for the efficient design of the microstrip patch antenna:

- Step 1- Select the patch shape: Several researchers proposed different patches for design, analysis, and enhanced antenna performance. Previously rectangular, circular (Azam et al 2017), elliptical (Alam et al 2020), T-shaped (Khulbe et al 2016), and many other patch shapes were proposed to operate the antenna in a specific frequency band. Those antennas were designed for different applications, such as medical imaging and diagnosis, security screening, high speed communication system and many more. As the present era demands high data rates and wide bandwidth, we need to design an antenna at the THz band to solve the high-speed data transmission problems. Therefore, this paper proposed a triangular-shaped patch antenna for THz applications.
- Step 2- Set the operating frequency: The dimension of the microstrip antenna is determined by the resonant frequency. Therefore, it is crucial to ascertain the appropriate resonance frequency of an antenna. The proposed antenna is designed for THz application in the frequency range from 1 to 4 THz. Hence, for the operation and investigation antenna performance, the operating frequency (f_c) is set to 2.28 THz.
- Step 3- Patch and subtrace material selection: Patch and subtrace materials are essential for antenna design. Antenna performance intensely depends on material selection. We need to choose the proper patch and substrate the material to operate the antenna at a specific frequency band. In this paper, we use graphene at the patch and GND layer as a conductive material and FR-4 as an insulator at the substrate. Graphene has been used in the design of the proposed antenna for breathtaking and promising properties such as exceptional electrical conductivity that allows efficient current distribution and radiation of electromagnetic conductivity. Graphene is a single layer of carbon atoms, making it incredibly thin and lightweight to reduce metallic losses in these sectors. Some incredible features such as dynamic tuning, miniaturization, optical transparency (Geim and Novoselov 2007), and mechanical flexibility can be achieved by using graphene in antennas (Lin et al 2008). It has 200 times faster electrical conductivity than silicon and a significantly high thermal conductivity of 5300 W/m/kIt has remarkable properties like transparency and flexibility and holds the status of the most robust material (Lin et al 2008) making it work at the THz frequency band. Due to the extraordinary electronic, mechanical, and optical properties of graphene (Niu et al 2012), it is used at the patch and GND layer to operate the proposed antenna at the THz band.
- Step 4- Patch and substrate dimension: The following equations were used to numerically determine the patch antenna's dimensions, which were then utilized to design the antennas.

The following equation is used to determine the length and width of triangle patch (Swami et al 2015).

$$l = \frac{2c}{3f_c\sqrt{\varepsilon_r}} \tag{1}$$

$$w = \sqrt{a^2 - \left(\frac{a}{2}\right)^2} \tag{2}$$

Where,
f_c= Operating frequency,
c= velocity of light in free space,
l= length of the triangular patch
w= width of the triangular patch
ε_r= relative dielectric constant

Since the dielectric constants of the air and substrate differ, an effective dielectric constant (ε_{eff}), which is determined using the provided equation, must be taken into account (Balanis 2005).

$$\varepsilon_{eff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left[1+\frac{12h}{w}\right]^{-1/2} \tag{3}$$

Where,

h= thickness of the substrate

Electrically, fringing causes the antenna's size to rise by a factor of Δl. The following quation is used to determine the increased length

$$\Delta l = 0.412h\frac{(\varepsilon_{eff}+0.3)\left(\frac{w}{l}+0.264\right)}{(\varepsilon_{eff}-0.258)\left(\frac{w}{l}+0.8\right)} \tag{4}$$

The thickness of the substrate (h) has an impact on the control of the bandwidth and surface waves (Singh and Tripathi 2011). Increasing the height of the dielectric substrate (h) causes an increase in surface wave power, spurious feed radiation, a decrease in radiation efficiency, and an increase in antenna size and bandwidth. It also impacts inductive impedance.

- Step 5- Determine proper feeding technique: Feed is an important component in antenna design used to excite the antenna patch. However, proximity coupling, aperture coupling, and microstrip line feed are the most popular feeding technique used in antenna design. Our proposed antenna design implemented the microstrip line feed technique because of its simplicity in modeling and easy match by adjusting the inset location.
- Step 6- Select feed position for impedance matching: The feed line is connected to the patch for excitation. The connected point on the patch is known as the feed position. The feed line connected point on the patch is responsible for impedance matching at the transmitting or receiving port of the antenna. Proper impedance matching ensures performance enhancement of the antenna with wide bandwidth, low return loss, and enhanced gain. The proper feed point is determined by an iterative testing procedure for 50 Ω impedance matching where the antenna is designed on YZ plane.
- Step 7- Imply performance enhancement technique: For performance enhancement of the proposed antenna, we modified the patch shape by cutting the corner edge of the triangle patch. The front side of the triangle-shaped patch is modified by cutting with 6 µm where the cutting area of the upper and lower backside corner of the patch are 14×4 μm^2 and 16×2 μm^2, respectively.

2.2. Antenna Performance Assessment Matrics

This section described the evaluation metrics to assess the antenna performance.

- Return loss: The return loss is an essential parameter for analyzing the performance of an antenna. It measures the power that is reflected from the antenna’s input port. The ratio of the reflected power to the incident power of an antenna is known as return loss and is denoted in decibels (dB).
- Gain: Antenna gain is an important parameter for evaluating the performance of any antenna. Gain measures the radiated power in each direction.
- Efficiency: Antenna efficiency is another essential parameter for evaluating the performance of any antenna that measures the radiated energy in the air.
- Radiation pattern: An antenna's radiation pattern indicates the power in various directions. Due to the radiating function of the antenna, it is a crucial factor in determining how well an antenna performs. It is a crucial factor that controls how much energy the antenna radiates into space and denotes the direction in which the power is transmitted.

3. Antenna Design Procedure at THz Band

3.1. Simulation environment

There are various simulation softwares available for the design and analysis of antenna performance, such as COMSOL, MATLAB, IE3D, MWO, SONNET, FEKO, ADS, HP MDS, CST MS, and HFSS etc (Odeyemi et al 2011; Patir 2015). To design and simulate the suggested antenna, we employ the computer simulation technology microwave studio (CST-MWS) as a conducting simulator in this research due to its extensive collection of solvers and capabilities. CST-MWS is a well-known and commonly used program for calculating return loss, gain, bandwidth, efficiency, and radiation patterns. Since only the good-performance antenna is fabricated, this simulator reduces fabrication costs. These are the following crucial steps in creating and solving a proper CST-MWS simulation:

- Create model/geometry
- Assign boundaries
- Impedance Matching
- Set the feedline height and width
- Assign excitations
- Solve
- Post-process the results

3.2. Proposed antenna design

In the previous section, we described that graphene is used as the conducting material at the patch and GND layer to observe the change and improvement of the proposed antenna.

Figure 1 shows the triangle patch antenna with the horizontally partial ground and modified patch shape, where Figure 1(a) shows the front view and Figure 1(b) shows the back view of the triangle shape antenna. It is evident from Figure 1(a) that the shape of the patch is modified through corner cutting. Moreover, Figure 1(b) shows the horizontally partial GND layer. As the frequency range of this paper is in the THz regime, the antenna size has been reduced tremendously. The overall area of the proposed antenna is set to 160×120 µm^2. The thickness of the substrate is 6 µm. The antenna consists of triangular-shaped patches with an area of 80×120 µm^2; the patch and ground layer thickness is 1.5 µm. The distance between the feed line and the patch is 30 µm. The width of the feed line is 3 µm, and it was chosen to provide a line impedance of almost 50 Ω. The other parameters of the proposed antenna are listed in Table 1.

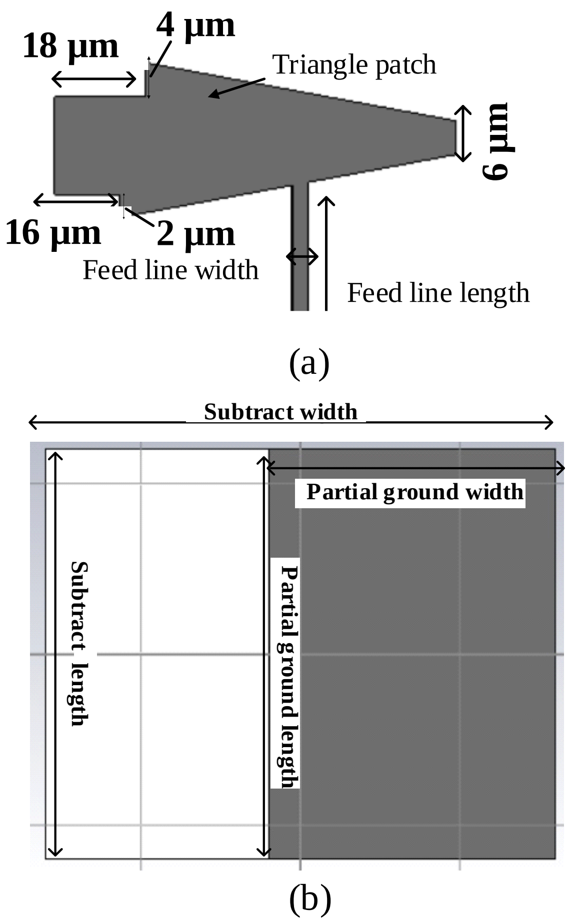

Figure 1 Triangular patch antenna (a) front view (b) back view.

Table 1 Antenna parameter.

Parameters	Value (μm)
Length of the substrate	160
Width of the substrate	120
Length of the patch	80
Width of the patch	120
Thickness of the substrate	6
The thickness of the ground plane and patch	1.5
Length of partial ground plane	80
Width of partial ground plane	120
Length of the feed line	30
Width of feed line	3
Width of the frontside corner cutting of the patch	6
Upper side corner cutting area of the patch	18×4 (μm^2)
Lower side corner cutting area of the patch	16×2 (μm^2)

4. Results and Discussion

We used a high-performance EM solver CST-MWS as described in Section 3.1, to design and simulation of the triangle patch antenna shown in Figure 1. We investigate the proposed antenna performance by computing S_{11}, gain, efficiency, and radiation pattern from the simulator.

4.1. Return loss (S_{11}) and bandwidth

The return loss is an essential parameter for analyzing the performance of an antenna. It always has a negative value and only considers the value over -10 dB. A lower return loss indicates less power reflected from the antenna. Figure 2 shows the spectra of the return loss where the x-axis indicates the frequency in the THz range and the y-axis indicates the value of return loss in dB. For the investigation, we measured one of the single-ended *S*-parameter, S_{11}, which indicates the reflection characteristics at the input port of the antenna.

It is evident from this figure that the minimum return loss for the proposed antenna is -33.22 dB at the resonant frequency of 2.28 THz. In this case, we only consider the frequency with a return loss of less than -10 dB. It is also observed from this figure that the bandwidth of the proposed antenna is 1.27 THz (1.71 THz – 2.98 THz) which is expected to support high data transfer for THz applications. This confirmed the bandwidth improvement of the antenna with low return loss by implementing a horizontal partial ground plane technique with a modified patch shape. Hence, the proposed antenna with high bandwidth is suitable for THz applications such as advanced wireless applications and future 5G mobile communication system.

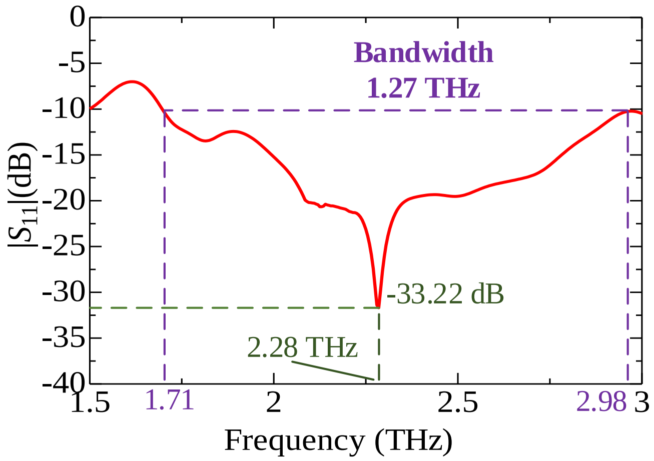

Figure 2 Spectra of return loss with respect to frequency.

4.2. Antenna gain, efficiency and radiation pattern

Antenna gain, efficiency and radiation pattern are important parameters for evaluating the performance of any antenna. Gain affects antenna performance by indicating the direction of the radiation power. One of the essential design goals is to construct an antenna with high gain as it radiates maximum power in a specific direction. In contrast, a low-gain antenna radiates power in all directions. On the other hand, a high-efficiency antenna indicates proper impedance matching and results in low losses at the input port. Finally, radiation pattern is a crucial factor that governs how much energy the antenna radiates into space and denotes the direction of the radiated power.

Figure 3, Figure 4 show the spectra for antenna gain and efficiency, respectively. It is observed from Figure 3 that the maximum gain obtained for the antenna is 7.72 dB at a frequency of 2.68 THz, which provides a broader range, good signal quality, and radiation in a specific direction. Similarly, we obtain the maximum antenna efficiency of 95.22 % for the proposed antenna at 1.76 THz frequency. On the other hand, Figure 5 shows the radiation patterns for a triangle antenna in 1D view. The radiation pattern indicates omnidirectional radiation, with the reference patch antenna having a maximum power of 6.88 dB, indicating a significant advantage in THz band communication systems.

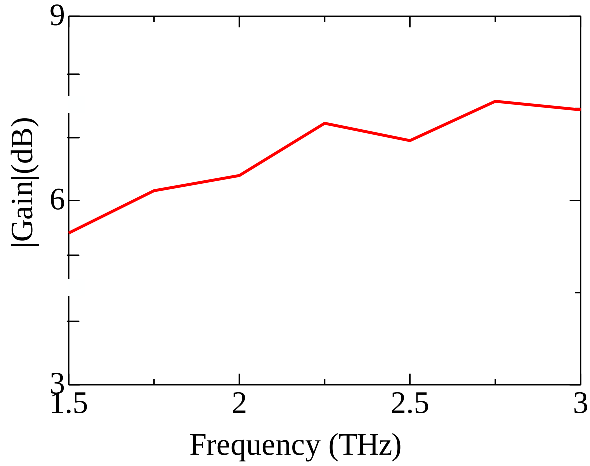

Figure 3 Spectra of gain Vs frequency.

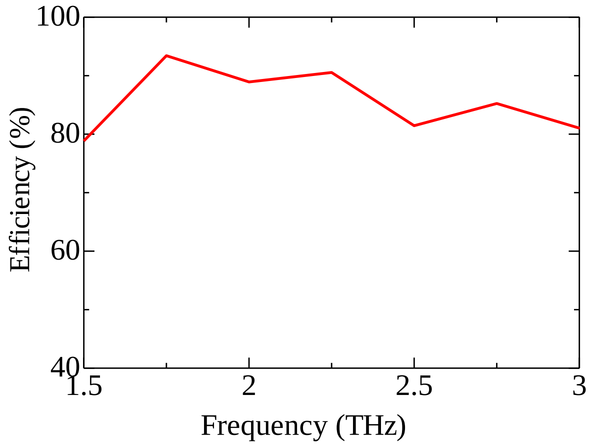

Figure 4 Efficiency of the proposed antenna.

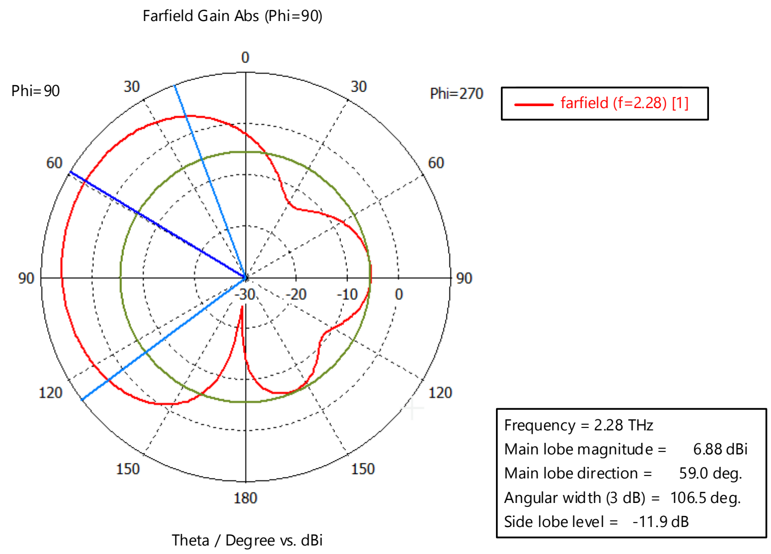

Figure 5 Radiation pattern of the proposed antenna.

4.3. Comparative Analysis

Table 2 compares our suggested antenna and a few existing antennas. This table shows that, compared to other existing antennas, the size of our suggested antenna is petite. It is also observed from this table that the suggested antenna shows reduced return loss and wide bandwidth compared to other antennas that make it operate at higher data rate to fulfill the requirement of high-speed communication system such as 5G communication system. The antenna suggested by khulbe et al (Khulbe et al 2016) showed better gain than the proposed antenna but fails to compact the antenna size and minimize return loss. Similarly, in (Alam et al 2020), the author enhanced efficiency but fails to compact the antenna size, minimize return loss and enhanced antenna gain. All the previous work had some limitations. Some methods enhance gain but fail to enhance other properties of the antenna. Therefore, the compactness, low return loss, maximum gain, and higher bandwidth of our suggested antenna make it more compact and effective than other antennas. Hence, the proposed triangle path antenna could be a better option for THz applications such as 5G communication system and advanced wireless communication system.

Table 2 Comparative analysis.

Ref.	Size (μm^2)	S11 (dB)	Bandwidth (THz)	Peak Gain (dB)	Efficiency (%)
(Sing et al 2015)	950×950	-15.70	1.20	3.80	N/A
(Khulbe et al 2016)	600×600	-19.00	0.10	8.82	54.9
(Sahdman et al 2019)	170×170	-22.36	0.21	4.71	N/A
(Alam et al 2020)	170×170	-18.00	0.93	4.45	98.41
Proposed	160×120	-33.22	1.27	7.72	95.32

5. Conclusions

Designing a microstrip patch antenna with a high data rate and wide bandwidth is one of the significant challenges for researchers in the THz range. In this paper, a triangle patch antenna with horizontally partial ground and modified patch shape is successfully designed and investigated to mitigate the requirement of high data rate transmission. The simulation result obtained from CST simulator, parades 1.27 THz bandwidth with a return loss of -33.22 dB at resonant frequency of 2.28 THz. Due to the wide bandwidth of 1.27 THz, the proposed antenna is able to support very high dana rate that is the main feature of upcoming 5G communication system. Moreover, the proposed antenna exhibits 7.72 dB of gain and 95.32% efficiency. As a result, the concept of the partial ground method and corner cutting of the patch confirmed satisfactory antenna performance for THz applications, and we validated it through simulation results. Therefore, the suggested antenna is appropriate for wireless communication and upcoming 5G mobile communication in the THz frequency spectrum. In future, We want to enhance the performance of the proposed antenna by applying different performance enhancement method for energy harvesting.

Ethical considerations

Not applicable

Conflict of Interest

The authors declare no conflicts of interest.

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