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Design of Ultra-Wide Band Tapper Rectangular Patch Monopole Antenna for Terahertz Applications

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Abstract

In this paper, an ultra-wideband terahertz monopole antenna is proposed to address the limitations of lower bandwidth and low gain in previously designed antennas at THz frequencies. The antenna is composed of three parts: a pentagonal patch, a modified ground plane that provides impedance matching (2.5-12) THz, and an FR-4 material substrate. The complete proposed antenna has been simulated using electromagnetic software and a computer simulation tool. Based on the simulation findings, the proposed antenna is the best option for Tera-Hertz applications. The antenna has an acceptable gain in the intended frequency spectrum band and operates between 2.4 and 12 THz. Computer simulation technology (CST 2020) software has been used to Analyze and simulate the proposed antenna. The simulation results show that the return losses of the frequency band (2.4-12) THz are less than -10 dB, and the gain has an appropriate value over the frequency band 2.4-12) THz. The radiation pattern of the antenna is omni-direction at the desired frequency band.

Keywords: Microstrip patch antenna; Monopole; Sixth generation; Tera-Hertz antenna; Ultra-Wide band antenna

1. Introduction

The terahertz (THz) frequency range, spanning from 0.1 to 10 THz, offers a broad spectrum that is well-suited for supporting the high data rates anticipated in future 6G wireless communication technologies. However, several technical challenges associated with this frequency band must be addressed to enable its effective use in next-generation networks [1]. As wireless communication systems demand higher data rates and face limitations in the available spectrum, the terahertz frequency range (0.1–10 THz) has become a focal point of research efforts [2].

Recent advances in data creation, sharing, and consumption have led to a significant increase in wireless data traffic. Due to this modification, high-speed wireless data transfer is now required everywhere, at all times [3]. It is expected that communications in terahertz technology will double every five years. With terahertz communication technology, data traffic problems can be minimized because it can send data at a very high-speed rate [4]. The THz frequency band is the part of the spectrum that occupies spectrum (0.1 -10) THz. The frequency ranges are less than those of far infrared and somewhat more than those of microwaves, which are part of the spectrum. THz advantage, used in biomedical, security, imaging, and spectroscopy, has increased dramatically in the past ten years [5].

Terahertz (THz) and sub-terahertz (S-THz) communications are increasingly being utilized due to the ever-growing demand for high bandwidth, higher data rates, and improved spectrum efficiency [6]. This has created a wealth of opportunities for the development of THz and S-THz antennas. It outlines the THz spectrum's application in wireless communication and its distinct radiation properties. Located in a vast domain of the electromagnetic spectrum between the microwave and infrared bands, the THz and S-THz band is typically characterized as a segment that spans from 0.1 THz to 10 THz. This band exhibits rich promise for applications in sensing, imaging, communication, and screening [7].

Death is one of the most prevalent health issues in today's world. Globally, extensive research has been conducted on the detection and treatment of cancer. Promising research demonstrating notable progress in treating THz radiation and cancer diagnostics has been conducted in recent years. However, this topic is relatively new and hasn't yet reached the end of the literature [8]. The sub-THz (0.1–0.3 THz) and Terahertz (0.1–10 THz) ranges are commonly used for short-range wireless communication. Compared to long-distance data transfer, the main drawback is the shorter transmission distance, but the data rate will be higher [9],[10]. A notable obstacle encountered at THz communication frequencies is the extremely high path loss imposed over longer distances. The primary benefit of THz frequencies is in their ability to reduce antenna size below micrometers (mm) [11],[12].

The implementation of communication devices operating in the THz band was made possible by the discovery of photonic and semiconductor devices that function in this frequency range [13]. These communication lines are essential for short-distance transmission of very high data rates [14]. The main drawback is the short transmission distance, although the data rate will be higher. The shorter wavelengths of Tera-hertz cause greater attenuation and free-space loss [15]-[17]. Antennas with greater gain and directivity can help overcome this problem.

Due to its low cost, simplicity of installation, and production, the microstrip patch antenna meets the specifications above. Several types of patch antennas are recommended for Terahertz applications in the literature. Numerous varieties of nanoantennas, most of which have complicated structures, have been studied in the literature. Countless additional applications, including brain cancer detection and medical imaging, are also considered [18]. Numerous antennas, including horn antennas, integrated waveguides, and surface log-periodic antennas, are being studied in the literature. Still, none of these structures can be used due to their three-dimensional structure, coupled with a compact structure [18], [19]. Due to its low cost and sub-millimeter size, microstrip antennas are suitable for integration with small devices. The substantial path loss that results in short-distance communication is the worry when using terahertz [9], [19]. To increase the channel capacity, a Mult Input-Multi-output technique was used [20]-[23].

By va6G, wireless communications will be incorporated into numerous applications in the future. It's anticipated that it will manage satellite communications as well as all Internet of Things services. For instance, wireless data rates are currently approaching the capacity of traditional communication networks at a rapid pace and have been increasing every 1.5 years. Within the next five to ten years, it is anticipated that this technology will make wireless Terabit-per-second (Tbps) links a reality. Above all, new spectral bands and advanced physical layer technologies will be needed to achieve these incredibly enormous data rates. The oversaturation of gigahertz (GHz) wireless communication channels and the growing demand for increased bandwidth are driving forces behind the exploitation of the underutilized terahertz (THz) band. Due to the THz band's larger bandwidth, future wireless devices will be able to achieve high data rates, such as one terabit per second.

The structure and gold deposition method required to create thin layers with a trace width of less than 100 nm. It also results in substantially lower conductivity values for gold than for the bulk material. Grain boundary scattering, surface scattering, and surface roughness are the causes of this lower conductivity. The radiation efficiency of antennas in the THz range and above is expected to be significantly reduced by these variables. Other materials, besides metals, should be considered for small-scale antenna loss management. Graphene is the most recent breakthrough in the boundary of science and technology.

Furthermore, due to its unique properties and advantages, the single atomic layer of graphene from Carbone dubbed the most fundamental and complicated material, has received more attention lately. Graphene is used in various sectors, including thermal, electrical, and mechanical sectors. Many graphene-based devices have been proposed for applications in the microwave, terahertz, and optical frequency ranges. These devices include filters, absorbers, polarizers, and antennas. This is because the applied electrical potential can be changed to regulate the surface conductivity of graphene. Moreover, graphene-based THz and photonic antennas were developed as a result of the gold deposition and manufacturing process.

This study focuses on the design and simulation of an ultra-wide band tapered rectangular patch monopole antenna optimized for terahertz applications. The antenna is engineered to provide wideband performance while maintaining compact size and high efficiency, making it suitable for integration into modern THz communication systems. The design employs advanced electromagnetic modeling techniques and parametric analysis to achieve the desired performance characteristics. The key objectives of this work include achieving a wide impedance bandwidth suitable for terahertz frequencies, ensuring stable radiation patterns and gain across the operating band, and maintaining structural simplicity for practical fabrication using photolithographic or nanofabrication techniques.

The proposed design contributes to the growing body of research aimed at advancing THz antenna technology, supporting the development of high-speed wireless networks, spectroscopy, imaging, and security screening systems.

2. Proposed Mono-pole Antenna Element

The UWB THz technology frequency spectrum uses a bandwidth of many THz, unlike commercial narrowband communication systems. The design of UWB antennas in the terahertz range is more challenging and presents numerous problems compared to commercial narrowband antennas. The microstrip patch antenna is illustrated in Fig 1. It consists of three parts: patch, substrate, and ground from a conducting material. A 50Ω transmission line feeds the patch of the antenna.

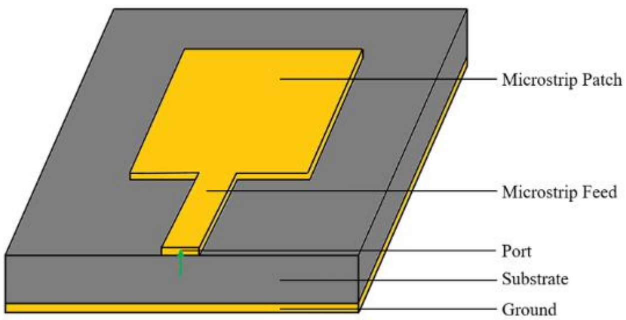


Figure. 1. Rectangular MPA

Equations (1) to (5) were used in the design procedure, and MATLAB software was used to calculate the antenna dimensions. CST-2020 program was used to simulate the antenna and analyze the results, such as the radiation pattern, return losses, and gain of the antenna [4]:

$$\mathbf{W_p} = \frac{\mathbf{c}}{\mathbf{2f_r}\sqrt{\frac{(\boldsymbol{\varepsilon}_\mathbf{r}+\mathbf{1})}{\mathbf{2}}}} \tag{1}$$

$$\boldsymbol{\varepsilon}_\mathbf{reff} = \frac{\boldsymbol{\varepsilon}_\mathbf{r}+\mathbf{1}}{\mathbf{2}} + \frac{\boldsymbol{\varepsilon}_\mathbf{r}-\mathbf{1}}{\mathbf{2}}\left[\mathbf{1}+\mathbf{12}\left(\frac{\mathbf{h}}{\mathbf{W}}\right)\right]^{\frac{-\mathbf{1}}{\mathbf{2}}} \tag{2}$$

$$\mathbf{\Delta L} = \mathbf{0.412h}\frac{(\boldsymbol{\varepsilon}_\mathbf{reff}+\mathbf{0.3})\left[\frac{\mathbf{W_p}}{\mathbf{h}}+\mathbf{0.264}\right]}{(\boldsymbol{\varepsilon}_\mathbf{reff}-\mathbf{0.258})\left[\frac{\mathbf{W_p}}{\mathbf{h}}+\mathbf{0.8}\right]} \tag{3}$$

$$\mathbf{L_{eff}} = \frac{\mathbf{c}}{\mathbf{4f_r}\sqrt{\boldsymbol{\varepsilon}_\mathbf{reff}}} \tag{4}$$

$$\mathbf{L_p} = \mathbf{L_{eff}} - \mathbf{2\Delta L} \tag{5}$$

In this context: *Wp* represents the width of the patch, *c* denotes the speed of light, *fr* is the resonant frequency, *εr* refers to the dielectric constant of the substrate, *εreff* is the effective dielectric constant, *h* indicates the substrate thickness, *W* is the substrate width, *Lp* stands for the patch length, and *Leff* corresponds to the effective patch length.

In this paper, the modified and optimized proposed monopole antenna consists of a pentagon-shaped radiating patch element made from copper material. It is deposited on FR-4 material substrate (Er = 4.4). The modified ground plane is on the same side as the radiating element. A 50 Ω transmission line was used to feed the antenna. The proposed antenna shape and its dimensions are shown in Fig. 2, and all dimensions are in micrometer**s.** The lower band edge is affected by the ground plane cut, and the design geometry, material properties, and the extent of the ground plane modification influence the overall impedance bandwidth. The first resonance frequency of the antenna can be found at one-quarter of a wavelength variation. The OA, shown in Fig. 2, is the distance from the end of the transmission line to the top of the patch.

$$f1 = \frac{75}{\sqrt{(\mathcal{E}_{eff}x\ OA)}} \tag{6}$$

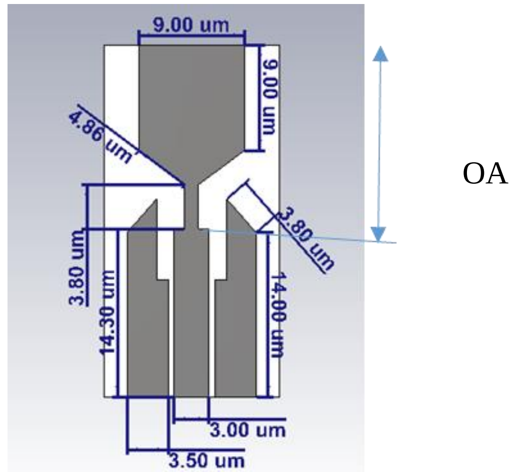


Figure 2. The proposed monopole antenna

3. Discussion and Results

The antenna's dispersion parameter, or return loss, is depicted in Fig. 3. The antenna has an ultra-wide bandwidth from (2.5 to 12) THz, at which the return losses are less than -10 dB. The antenna has many resonances frequency at 3, 5.5, and 8 THz

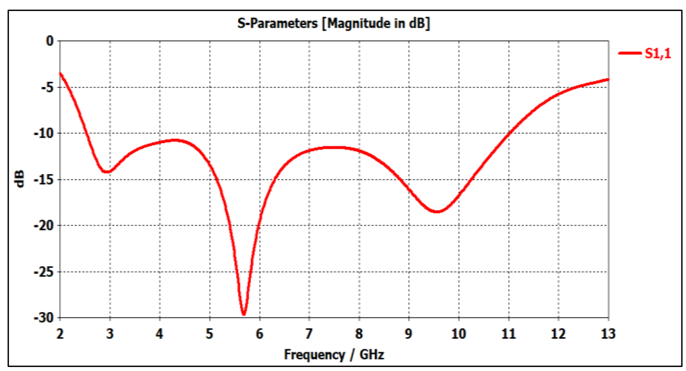


Figure 3. Return loss of the antenna

The voltage standing wave ratio is shown in Fig**.** 4. It is clear that the standing wave ratio is less than 2 at the operating frequency band (2.5-12) THz, and the minimum SWR occurs at 3 and 8 THz.

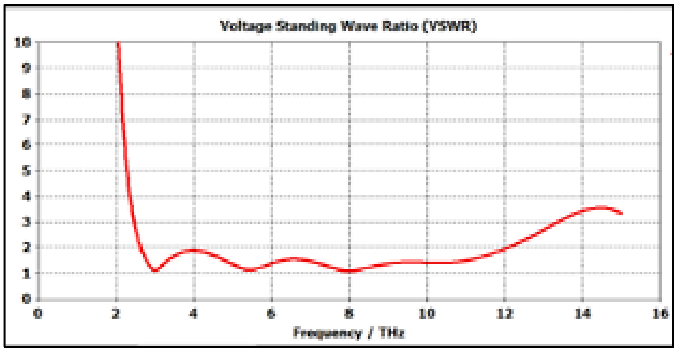


Figure 4. SWR of the antenna

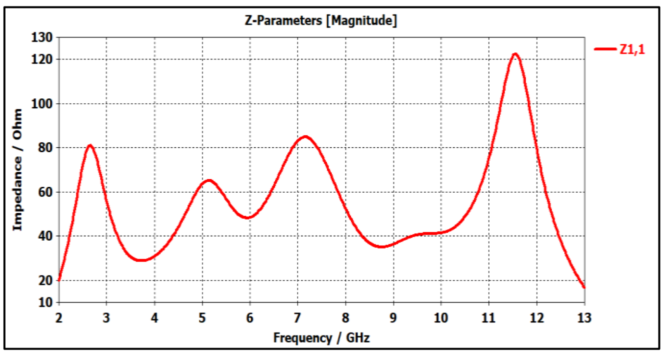


Figure .5. Impedance of the designed monopole antenna antenna

Fig. 5 shows the total Impedance of the antenna. It can be seen that the Impedance varies around 50 ohm around the designed frequency band. The proposed antenna gain is shown in Fig. 6; the antenna has a good gain (1-3) dB. The maximum gain occurs at a frequency of 10 THz, corresponding to approximately 3.5 dB.

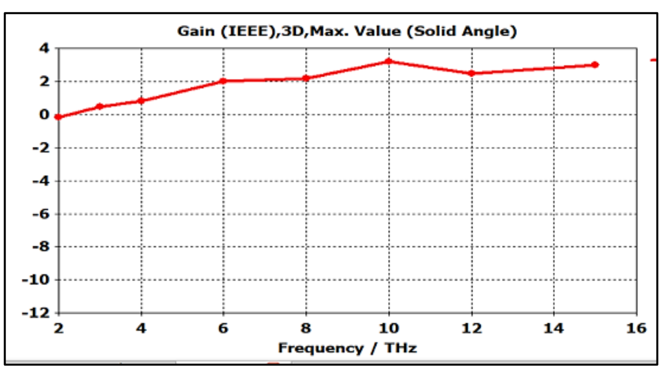
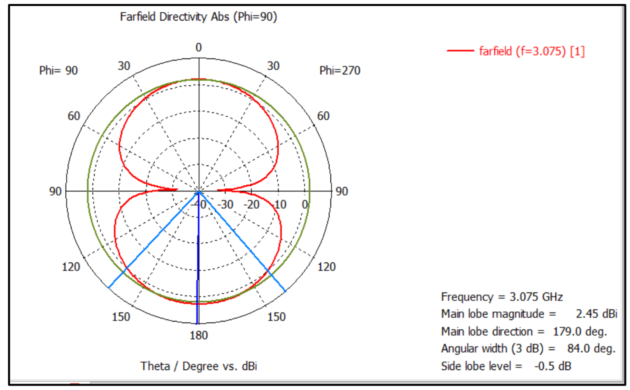
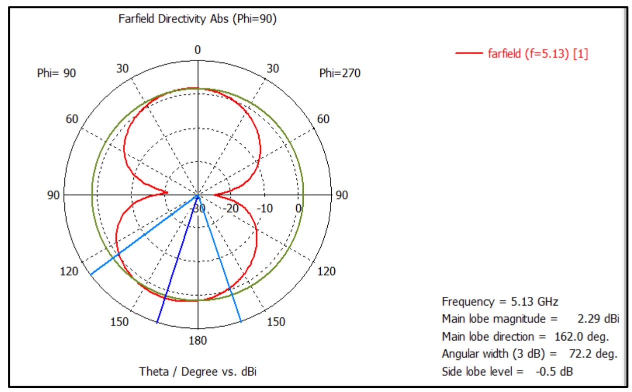


Figure 6. Gain of the antenna

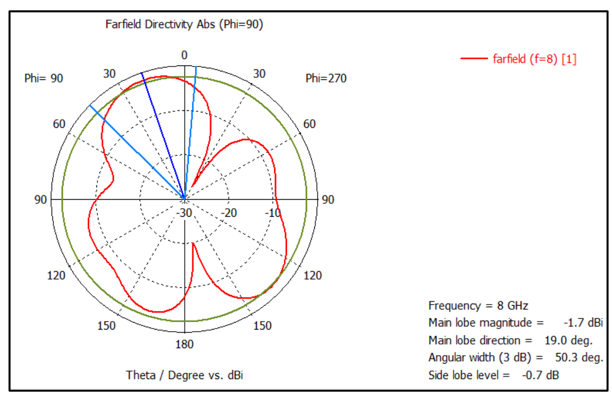
Fig. 7 illustrates the radiation pattern of the designed antenna at various frequencies: 1, 2, 3, 4, 6, 8, 10, 12, and 15 THz. The antenna demonstrates an omnidirectional radiation behavior across the intended frequency range. Additionally, Fig. 8 presents the radiation efficiency, showing that the antenna maintains a high level of performance, with efficiency values ranging from 62% to 88% throughout the operating band.



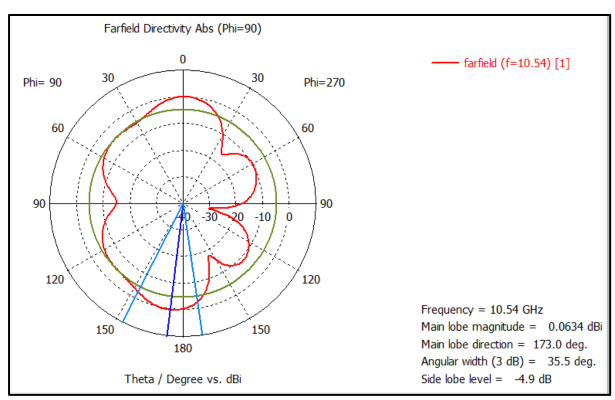
a (f=3.07THz)



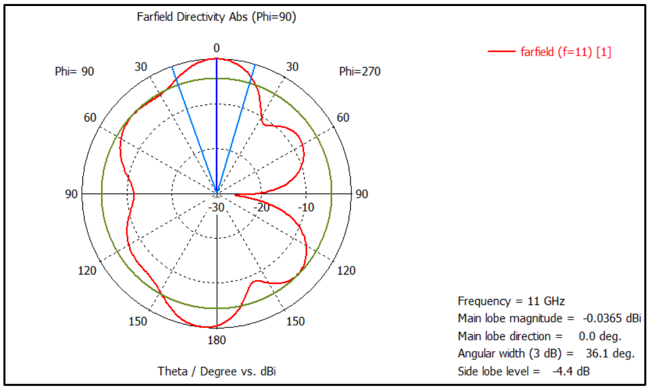
b (F=5.13THz)



c (F=8 THz)



d (f=10.54 THz)



e (f=11 THz)

Figure 7. Far-field of the antenna at frequencies (a) 3.07THz, (b) 5.13THz, (c) 8 THz, (d) 10.54 THz, (e) 11THz.

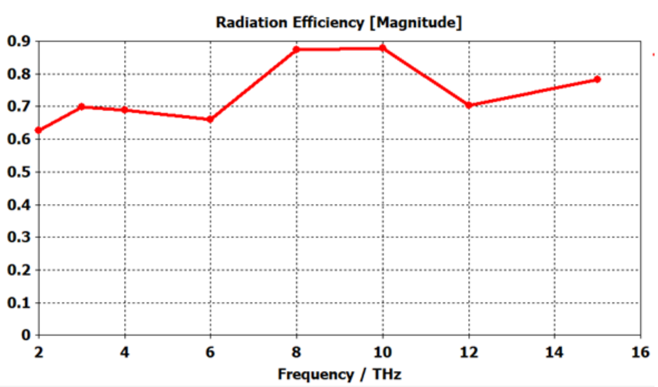


Figure 8. Radiation efficiency of the antenna

4. Conclusions

A compact planar monopole antenna featuring an innovative ground plane design is proposed for use in terahertz and biomedical applications. The antenna structure comprises three main components: an RF-4 substrate, a modified ground plane, and a copper pentagon-shaped radiating patch. The overall size of the antenna is 10 × 14 μm². It operates efficiently within the 2.5 to 12 THz frequency range, achieving a return loss below -10 dB across this band. The design was modeled and evaluated using CST Studio Suite 2020. The result showed that the antenna has acceptable gain and good return losses at the designed frequency band. These achievements make the proposed design a good candidate for THz and 6G applications.

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Author Contribution Statement

Hussein A. Abdulnabi proposed and developed the methodology.

Ahlam Alsudani verified the analytical methods and conducted an investigation.

Yasin Yousif Al-Aboosi performed the software.

Mariam Qutaiba Abdalrazak conducted the investigation and validation of the work.

Haider Ali Abdulnabi: reviewed and edited the work.

Mustafa Mahdi Ali: discussed the results and contributed to the final manuscript.

Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this article.

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