A compact triband patch antenna design at terahertz frequencies

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ABSTRACT

The rapid evolution of terahertz (THz) technology has fueled an increasing demand for efficient, compact, and adaptable antennas that can function for a number of frequency bands in the THz spectral regime. This research outlines the analyses and design process of a multiband antenna for THz applications. Initially, an antenna with a single frequency band is created without any slot, with its lower resonant mode functions at a singular frequency of 171 GHz. To achieve multiband functionality, various rectangular slots can be added into the microstrip antenna's radiating element. The suggested structure is constructed on a polyimide substrate, while its radiating elements are crafted from copper, with a compact size of 1.4×1.1×0.14 mm. It can achieve a reflection coefficient of −30.38 dB, −33.37 dB, and −19.33 dB at 123 GHz, 168 GHz, and 182 GHz, respectively. Furthermore, the antenna yields favorable gains at the respective frequencies, measuring 3.97 dB, 4.34 dB, and 5.66 dB for 0.123, 0.168, and 0.182 THz respectively. Additionally, the antenna demonstrates high efficiencies of 81.5%, 85%, and 91.2%, respectively. Hence, the suggested THz antenna will be useful for surveillance radar (123 GHz), medical imaging (168 GHz), and radio astronomy (182 GHz) applications.

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1. INTRODUCTION

Over the recent times, there has been a noticeable increase in the need for developing compact devices that can transmit and receive data at the utmost speeds while also conserving energy. The terahertz (THz) band occupies a vital but largely unexplored domain in the realm of wireless communication technologies [1], [2]. This frequency range typically encompasses frequencies spanning from 0.1 THz to 10000 GHz (Wavelength ranging from 3 mm to 30 µm), which aligns with the infrared range in the shorter wavelengths and transitions into the millimeter wave region in the longer wavelength spectrum [3], [4]. The advantages of the THz band encompass attributes such as exceptional spatial resolution, rapid high-speed communication, low power consumption, ultra-wideband capabilities, and efficient high-data-rate transmission [5], [6]. Due to its distinctive characteristics, the THz band holds promise for different applications in fields such as biomedical applications [7], imaging [8], communication [9], and spectroscopy [10]. However, the THz band encounters emerging concerns, including significant signal attenuation and path loss attributed to water and molecular absorption within the atmosphere [11]. The antenna stands as a pivotal component in the THz band, and among the different THz antennas available, microstrip antennas are highly regarded for their suitability in THz applications [12]. They are favored due to their cost-effectiveness, lightweight nature, compatible with integrated circuit technology, and ease of manufacture and design. Nevertheless, it's important to acknowledge that conventional patch antennas operating at frequencies face certain challenges, including issues with low gain, subpar radiation performance, and limited bandwidth [13]. Over the past few years, numerous microstrip antenna variants have developed, encompassing stacked, slotted T-type configurations, as well as both single-band and multi-band designs [14]. To ensure the efficient utilization of available spectrum, communication systems demand antennas that combine compact size with the ability of working over several frequency bands. These multiband antennas are engineered to function effectively over many frequency ranges, with different parts of the antenna designed to be responsive to distinct bands [15].

Attaining multiband resonance in antenna operating within the THz spectrum has presented a multifaceted challenge, leading researchers to explore a variety of methods to achieve this capability. Common techniques include the utilization of metamaterials [16], frequency-selective surfaces (FSS) [17], fractal antenna [18], and the incorporation of slots. The best strategy to use will rely on the particular requirements of the application because each of these approaches has a different set of benefits and drawbacks. For this paper, the utilization of a slotting technique has been adopted, incorporating slots into the patch structure to achieve multiband frequencies. This approach offers the distinct advantage of providing versatile resonance characteristics across the entire THz spectrum while preserving the compactness and integration potential necessary for modern THz applications. The primary objective of employing the slotted technique in this paper is to attain multiple operating frequencies across different bands.

Numerous THz multiband antennas have been suggested in the literature [15], [18]-[21]. The antenna [18] has a total area of 700×900 mm^2 and has three resonant frequencies, 1.04, 0.984, and 0.948 THz, with a 9 dB realized gain at the 0.948 THz resonating frequency. The outcome and performance suggest that the suggested antenna will work well with monolithic microwave integrated circuit (MMIC) and small wireless devices. Vijayalakshmi *et al.* [19] presents a tri-band antenna array designed multiple input/multiple output (MIMO) for THz communications. The antenna provides an impressive performance with a 10 dB return loss bandwidth of 60, 43, and 38 GHz, centered at frequencies of 4.5, 3.2, and 2.3 THz, respectively. Additionally, the antenna realizes gains greater than 5 dBi for each of these working frequencies. Krishna *et al.* [15], a self-similar two parasitic components are inserted close to the patch to give multiple resonances. A rogers RT material is used to incorporate a multi-band THz antenna that is biased on a very thin sheet of graphene that serves as a radiating element and has a thickness of 0.5 m. With radiation efficiencies of 93.73%, 83.87%, 94.14%, 87.25%, 88.8%, and 90.16% at corresponding resonant frequencies, this antenna operates at 7.96, 7.45, 6.64, 6.28, 5.86 and 3.58 THz. Nissiyah and Madhan [20], the straightforward graphene-based patch antenna's performance is improved by allowing it to function at higher frequency ranges in order to achieve quad and triple band resonances. The antenna is made to work on the triple band (2.01, 2.74, 4.52) and the quad band (1.73, 2.6, 4.01, 4.72). To investigate the resonance properties and radiation patterns, the chemical potential of the surface plasmons is changed from 2 to 0 eV. At 4.41 THz, the triple band operation achieves a directivity of 3.66 dBi and gain of 1.22 dB. At 4.72, 4.01, 2.6, and 1.73 THz, quad band operation is also accomplished, with a directivity of 7.17 dBi and gain of 1.61 dB. Shalini and Madhan [21], the slot has been adjusted in order to allow the antenna to work at two distinct frequencies: 4.83 and 1.96 THz, each with a bandwidth of 100 and 80 GHz, respectively. Additionally, the antenna delivers a sizable gain of 4.3 and 4.75 dB across the operational bands. Furthermore, by creating defects in the ground plane, the antenna is able to operate in three bands at 5.55, 4.83, and 1.96 THz. The inclusion of a slot inside the radiator stands out as a powerful and effective way to introduce a number of modes into the antenna, facilitating its multi-band functioning and concurrently improving the antenna's impedance qualities. Our method seeks to address the difficulties related to THz frequency antenna design. Thus, a new tri band slotted antenna for THz applications is analyzed and designed in this research. To boost the recommended antenna's performance, enhancements were implemented through the incorporation of a combination of rectangular and semicircular slots onto the patch. In the study, many physical characteristics of the suggested antenna are analyzed.

The following list of major contributions and performance metrics is provided in the manuscript: i) a compact tri band of a THz antenna; ii) high-efficiency multiband THz antenna, and it exhibits conventional performance characteristics compared to previously reported THz patch antennas in literature; iii) the slotted antenna structure is very straightforward, making it easy to fabricate and suitable for THz systems; iv) the recommended antenna sustains a radiation efficiency exceeding 80% across the resonating frequency range; and v) the presented multiband antenna functions with mean gains of 3.97 dB, 4.34 dB, and 5.66 dB across its operating frequency bands.

2. THEORY AND DESIGN APPROACH

This work suggests a tri-band microstrip antenna design for THz applications with an overall substrate area of 1×1.5×0.14 mm^3, as depicted in Figure 1. The antenna's radiating components are printed on top of a polyimide substrate with a loss tangent of 0.008 and a relative permittivity of 3.5. Various rectangular and semicircular slots varying in length (L), but with the same width (w) and same radius (r) are printed in the radiating element (patch) as shown in Figure 1(a). Utilizing the finite element method based ansys high frequency structure simulator, the design and simulation processes were carried out. With a central feed of width Wf and length Lf, the antenna is stimulated in this configuration by a microstrip transmission line technique. The antenna's bottom view is observed in Figure 1(b). The conducting patch is the primary component of a microstrip antenna that changes return loss, surface current distribution, band-width, impedance matching, and radiation pattern to modify antenna performance. In the current research, the radiating patch's performance was enhanced through the implementation of slotting techniques. This study's uniqueness is attained through the implementation of patch modifications aimed at enhancing the current distributions on the antenna's surface. For more details in the design approach see reference [22].

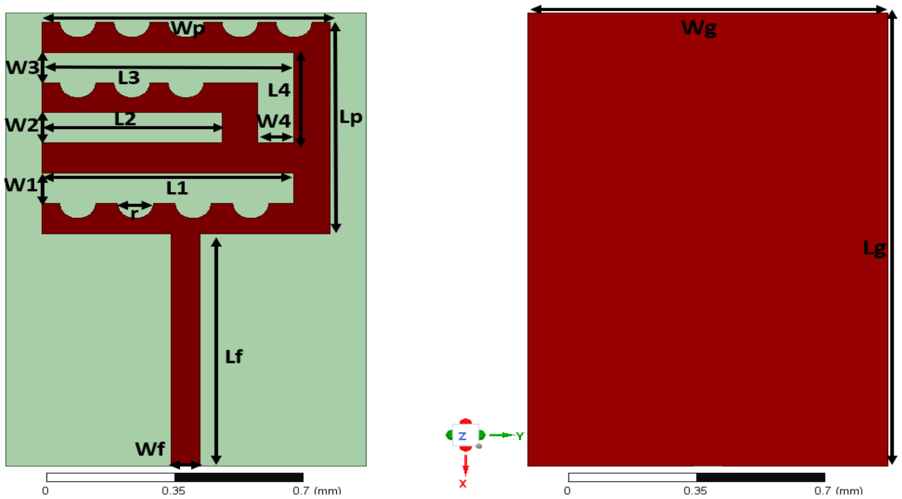


Figure 1. Tri band antenna design in HFSS; (a) the top view and (b) the rear view

The equations available in the literature simplify the calculation of radiating element dimensions, as in [23]. The width (Wp) of the microstrip antenna is expressed in (1) for efficient radiation. Accounting for the fringing effect, where electromagnetic waves partially travel through the dielectric material and partially through the air, an effective dielectric constant (ε_{reff}) is introduced in (2). Due to these fringing effects, the electrical length exceeds the physical dimensions, and (ΔL) the extended electrical length of the patch can be calculated utilizing (3). Where in (4) is employed to calculate the patch's length (LP), and (5) is used to calculate the wavelength. In these equations, C represents the speed of light in a vacuum, fr is the resonant frequency, and ε_e represents the dielectric constant. The width wf is found using (6) and (7). By using these equations, the parameters of the suggested antenna are summarized in Table 1.

$$\mathrm{Wp} = \frac{\mathrm{c}}{2\mathrm{f_r}}\sqrt{\frac{2}{\epsilon\mathrm{r}+1}} \quad (1)$$

$$\epsilon_{\mathrm{reff}} = \frac{-1+\varepsilon_{\mathrm{r}}}{2} \times \frac{1}{\sqrt{\frac{\mathrm{h}}{\mathrm{w}}\times 12+1}} + \frac{1+\varepsilon_{\mathrm{r}}}{2} \quad (2)$$

$$\Delta\mathrm{L} = \frac{(0.3+\epsilon\mathrm{e})}{(\varepsilon\mathrm{e}-0.258)} \times \frac{(\frac{\mathrm{w}}{\mathrm{h}}+0.262)}{(0.813+\frac{\mathrm{w}}{\mathrm{h}})} \times h \times 0.412 \quad (3)$$

$$Lp = -2\Delta L + \frac{c}{fr\times 2\times\sqrt{\epsilon e}} \quad (4)$$

$$\lambda = \frac{c}{f_r} \tag{5}$$

$$\frac{wf}{h} = \begin{cases} 8e^{A} \times \frac{1}{e^{2A}-2}\ ;if\ 2 \geq \frac{w}{h} \\ \frac{\varepsilon_r-1}{2\varepsilon_r}\left[\ln(B-1) - \frac{0.61}{\varepsilon_r} + 0.39\right] + 2 \times \frac{1}{\pi}\left\{B - 1 - \ln(-1+2B)\right\}; if\ 2 \leq \frac{w}{h} \end{cases} \tag{6}$$

$$A = \left(0.23 + 0.11 \times \frac{1}{\varepsilon_r}\right) \times \frac{\varepsilon_r-1}{\varepsilon_r+1} + \sqrt{\frac{\varepsilon_r+1}{2}} \times 2\pi \times \frac{Z_0}{Z_f} \tag{7}$$

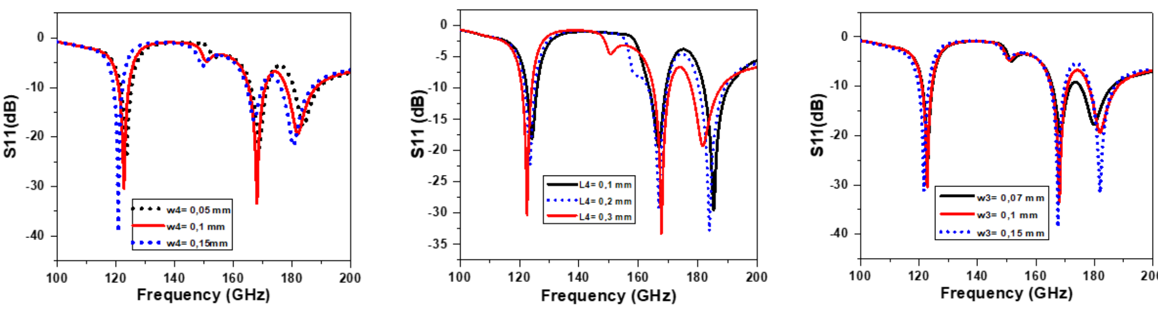
Z_f is the wave impedance in free space, while Z_0 is the characteristic impedance.

Table 1. The size specifications of the recommended antenna (mm)

Dimensions	Value	Dimensions	Value	Dimensions	Value
Lg	1.5	Wg	1	r	0.05
Lp	0.7	wp	0.8	L4	0.3
Lf	0.67	wf	0.08	L3	0.5
L1	0.4	w1	0.1	w3	0.10
L2	0.7	w2	0.10	w4	0.1

3. RESULTS AND DISCUSSION

A study was conducted to understand and illustrate the influence of the parameters of the tri band antenna. This study used a parameter-centric technique, systematically varying one parameter at a time while maintaining the others intact, to identify the ideal antenna size and performance. In Figure 2, the return loss in the lower, middle, and higher frequency bands may be varied by varying the values of w4, L4, and w3. Figure 2(a) exhibits the effect of changing the value of w4 from 0.05 to 0.15 mm. It can be noticed that the increase in the value of w4 shifts the resonant frequencies from 123 to 120.8 GHz, 169 GHz to 167 GHz, and 184 GHz to 180.5 GHz in the lower, center, and higher frequency bands, with a rise in S11. Figure 2(b) also shows that the lower band shifted from 124 GHz to 123 GHz when the values of the L4 increased from 0.1 to 0.3 mm, while the middle band remained almost unchanged. The highest band decreased from 185 GHz to 182 GHz, with an increase in return loss in the lower and middle bands as shown in Figure 2(b). Changing the value of w3 from 0.15 mm to 0.07 mm results in the upper frequency band shifting from 179 GHz to 181 GHz, while the middle band still unchangeable, and the lower band shifts from 123 to 121 GHz with an increase of S11 as presented in Figure 2(c). Thus, the suggested antenna's best dimensions are w4= 0.10 mm, L4= 0.3 mm, and w3= 0.10 mm.



(a) (b) (c)

Figure 2. Parametric study of the antenna fluctuation in; (a) 'w4', (b) 'L4', and (c) 'w3'

The recommended antenna design's procedure is shown in this section. The suggested antenna starts with a rectangular patch as displayed in Figure 3 (Ant I) with a - 10 dB bandwidth of 5.6 GHz (S11 = -15.20 dB) but in this instance, the antenna is working only at 171 GHz frequency as appears in Figure 3. Then, to shift the frequency towards the multiband, different rectangular slots are introduced onto the patch of initial rectangular patch, as depicted in Figure 3 (Ant II). The S11 response of the second step (Ant II) reveals a tri-band with resonance at 124 GHz, 171 GHz (the fundamental frequency), and 185 GHz frequencies with a reflection coefficient of -15.57 dB (3.04 GHz), -35.85 dB (5.9 GHz), and -20.92 dB (11.98 GHz) respectively as shown in Figure 3. Finally, in the third case (Ant III), various semicircular slots are added on the radiating element as presented in Figure 3 (suggested antenna). When the semicircular slots are used (Ant III), there is a change in the lower frequency from 124 to 123 GHz although, with excellent return loss (S11= -30.38 dB) at the same time, while the middle frequency shifted from 171 GHz to 168 GHz (S11= -33.37 dB), with a bandwidth of 5.6 GHz. Similarly, the upper frequency is changed from 185 GHz to 182 GHz (S11= -19.33 dB) as depicted in Figure 3. Thus, it can be noted that the recommended antenna is a viable option for multiband THz applications.

Additionally, a simulation of the standing wave ratio (SWR) will be employed to describe and evaluate the suggested antenna. Since the SWR value controls how well the antenna adapts, if the voltage standing wave ratio (VSWR) value is less than 2 dB, the antenna will be perfectly adapted [22]. As presented in Figure 4(a), the recommended antenna has an SWR of 1.07 dB, 1.06 dB, and 1.2 dB for the lower, middle, and higher frequency bands, respectively. Figure 4(b) displays a graph depicting the efficiency values at: 123 GHz, 168 GHz, and 182 GHz. At a frequency of 123 GHz, the efficiency is approximately 81.6%. At 168 GHz, the efficiency reaches 86.06%. Finally, at 182 GHz, the efficiency peaks at 91.17%. This figure illustrates how antenna efficiency varies with frequency, showcasing a gradual increase in efficiency as the frequency rises. The recommended antenna's radiation pattern is illustrated in Figure 5. Figure 5(a) to (f) depict the 3D and 2D antenna radiation pattern in H-plane and E-plane of the suggested THz antenna. A maximum gain of 4.34 dB at 168 GHz, 5.66 dB at 182 GHz, and 3.97 dB at 123 GHz is what the simulation results show for the recommended antenna.

The surface current distribution over the radiating patch is apparent in Figure 6 to help explain the multiband behavior of the recommended antenna employing different slots in the patch. In Figures 6(a) to (c) the resonating frequencies exhibit the highest current density within the transmission line and semicircular section.

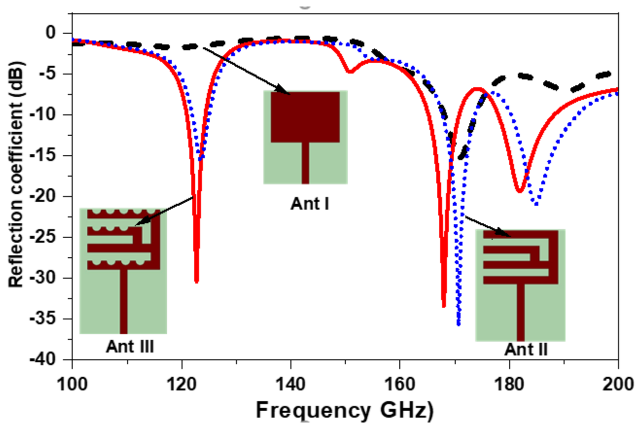


Figure 3. Comparison of S11 simulation results for the recommended antenna design processes

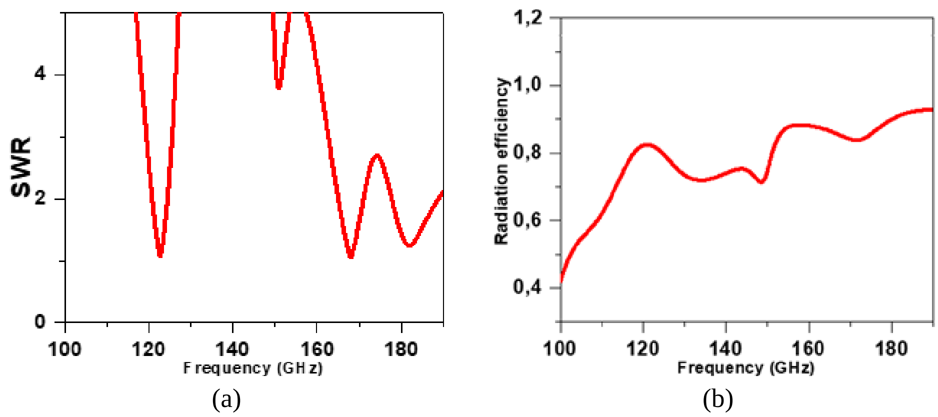


Figure 4. SWR and radiation efficiency of the recommended antenna: (a) SWR and (b) radiation efficiency

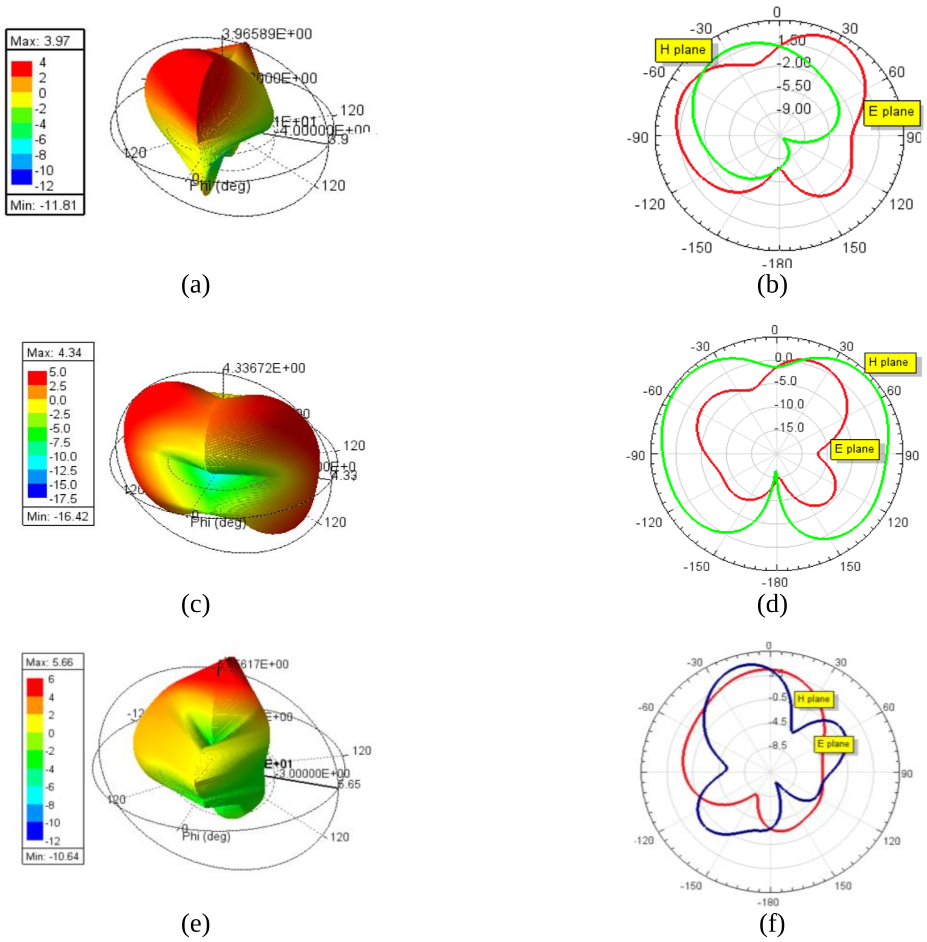


Figure 5. Simulated far-fields radiation pattern in 3D and 2D at; (a) 123 GHz, (b) 123 GHz, (c) 168 GHz, (d) 168 GHz, and (e) 182 GHz, and (f) 182 GHz

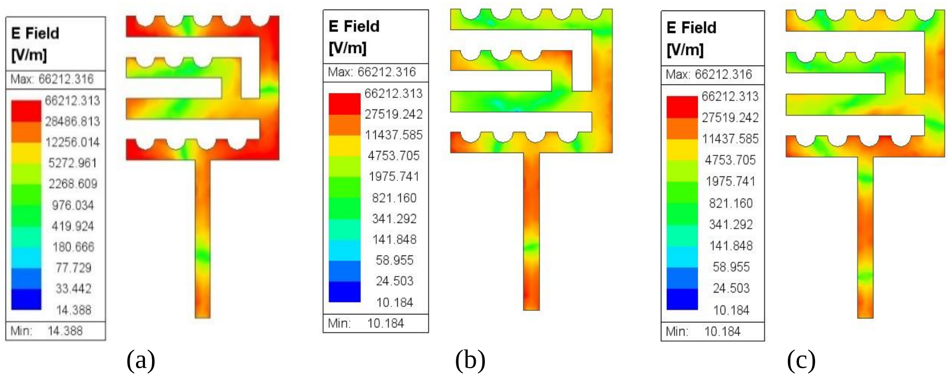


Figure 6. Surface current distribution of suggested antenna at; (a) 123 GHz, (b) 168 GHz, and (c) 182 GHz

Table 2 offers a comparative analysis between the recommended antenna and other antennas documented in the existing literature. Notably, the recommended antenna stands out by offering a tri-band response within the THz spectrum. It's crucial to emphasize that while enhancing the performance of a single-band antenna can be relatively straightforward, achieving such improvements in a multi-band antenna is a notably challenging task, and this accomplishment is a significant achievement highlighted in the research work being reported. The antenna presented in [20], [24], [25] operates at the multi-band frequency but has poor gain and a smaller S11 compared to our antenna. The antennas mentioned in [26], [27] have some good performance, but they operate at a single band. Additionally, it should be highlighted that the application of the suggested method offers a simpler solution when contrasted with other strategies involving graphene or alterations in substrate height. When considering the comparison table, it becomes evident that the suggested technique outperforms existing methods documented in the literature. This advantage is especially notable when it comes to applying the technique to design a dual-band antenna, where other approaches may pose challenges or complexities. finally, compared to the other antennas, the suggested antenna performs far better.

Table 2. Comparison of the suggested and previously documented designs

	Frequency band (THz)	Gain (dB)	Radiation efficiency (%)	Technique	S11 (dB)
[24]	2.48; 3.35	2.7 dBi 6.2	87.3 53.47	Varying substrate height	-17 -22
[25]	2.17 2.59	4.01 5.03	64.12 60.8	Graphene	-28 -35
[20]	1.81; 2.64; 4.41	1; 1.03; 1.22	-	Graphene	-17.51; -22.08; -10.56
[26]	1	2.45 dBi	44	Single	-24
[27]	0.72	-	-	Single	-59.97
This work	123; 168; 182	3.97; 4.34; 5.66	81.5; 85; 91.2	Slotted	-30.38; -33.37; -19.33

4. CONCLUSION

In the present research, a tri-band antenna with varied slots in the radiating element (patch) is employed for THz applications. The suggested antenna exhibits resonance at 123 GHz, 168 GHz, and 182 GHz with return losses of -30.38 dB, -33.37 dB, and -19.33 dB, respectively. SWR<2 is attained in all frequency ranges. At lower, medium, and higher band frequencies, the antenna, with 81.5%, 85%, and 91.2% radiation efficiency, respectively, produces a considerable gain of 3.97 dB, 4.34 dB, and 5.66 dB. The gain, bandwidth, reflection coefficient, and radiation efficiency of this antenna were much higher than those of comparable antennas. Thus, this antenna can serve as an effective solution for surveillance radar, medical imaging, and radio astronomy applications. In order to further improve data transmission capacity and system reliability in these frequency ranges, this research also sets the path for future improvements in integrating MIMO systems.

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AUTHOR CONTRIBUTIONS STATEMENT

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY

Data will be made available on request.

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