A novel slotted antenna design for future Terahertz applications

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ABSTRACT

A slotted patch antenna operating at 118 GHz is proposed to address challenges in the terahertz (THz) frequency band for wireless communication systems. The antenna design, utilizing a Rogers RO3003 substrate, which has a dielectric constant of $\varepsilon r = 3$ and tan $\delta = 0.001$, strategically incorporates slots to enhance key performance parameters. Copper is employed for the ground and radiating patch, and a microstrip feeding method powers the antenna. High frequency structure simulator (HFSS) software is used for design and simulation, revealing resonance at 0.118 THz with a reflection coefficient of -42.41 dB and an impedance bandwidth of 4.42 GHz (115.84–120.26 GHz). At the operating frequency, the antenna exhibits a gain of 7.36 dB, maximum directivity of 7.38 dB, the voltage standing wave ratio (VSWR) of 1.01, and 99.75% radiation efficiency, all within a compact size of 1.5×1.3×0.1 mm³. The suggested antenna outperforms recent counterparts, making it suitable for applications like security screening and wireless communication systems (5G). Future efforts will target bandwidth expansion, gain enhancement, and further size reduction to enhance overall performance.

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1. INTRODUCTION

Generally, the terahertz frequency band spans from 0.1 to 10 THz and has a wavelength ranging from 0.03 to 3 mm. It is found between the millimeter and infrared wave bands on the electromagnetic spectrum [1]. Recently, it has attracted much interest in various fields such as imaging, spectroscopy [2], 6G technology, radar, radio astronomy [3], airport security screening, explosive detection [4], and material analysis [5], because of its larger bandwidth, nonionizing properties, sensitivity to weak interactions, high data rate, high chemical selectivity, and high resolution in wireless communication [6]. The necessity for high gain antennas at THz frequencies is critical to counteract high path loss, and high atmospheric absorption at these frequencies, which will have a negative impact on the wireless link's budget [7]. Consequently, the challenge at hand is the requirement for an innovative antenna design that solves the particular difficulties presented by the THz frequency spectrum. The goal of this design is to overcome the constraints imposed by traditional antennas, maximize performance parameters such as gain and bandwidth, improve radiation efficiency, and allow for smooth interaction with THz systems. Traditional antennas are frequently created to function at a certain frequency or within a constrained frequency range. This restricts their capacity to communicate over a larger range of frequencies. Furthermore, conventional antennas often have a set emission pattern that is difficult to modify or manage [8]. In some orientations, this may result in undesirable interference or signal loss. Traditional antennas can also be susceptible to adjacent objects and other electromagnetic sources, which can interfere with signals and reduce the effectiveness of the antennas. Due to these constraints, novel slotted antenna designs have been created with the goal of overcoming these restrictions and enhancing antenna performance across a variety of applications.

Currently, research on terahertz antennas faces several limitations. The terahertz antenna is much smaller than other types of antennas, such as microwave antennas, since it operates in the high-frequency range. This size reduction often leads to higher energy loss and lower manufacturing precision in terahertz antennas [9]. Therefore, enhancing the terahertz antenna's performance poses a significant challenge. Thus, to increase the patch antenna's radiation properties, different methods can be utilized, such as reducing the substrate's permittivity, employing metamaterials, increasing the substrate's thickness, using extra dielectric layers to the substrate, or adding slots into the patch. Although using metamaterial structures increases antenna gain, the geometry becomes complicated and demands very precise construction [10]. In practice, adding slots into the patch design can significantly improve radiation while maintaining a modest antenna size. Furthermore, it is less difficult to develop and manufacture than other solutions. As a result, this research seeks to enhance the performance of a slotted patch antenna in the terahertz frequency [11].

Some ways to design a THz antenna have been developed. Several publications on wireless communication in the THz frequency region have been published, including [7], where the authors presented a THz microstrip antenna for on body wireless body area network (WBAN) applications with a reflection coefficient of -52.4 dB, a gain of 11.9 dB, and a resonance frequency of 230 GHz. The drawback is that the recommended antenna is large, has a limited gain, and operates at a low frequency. Similarly, the authors in [12] reported a new compact circularly polarized (CP) horn antenna. The manufactured CP horn antenna offers a 20% impedance bandwidth between 270 GHz and 330 GHz and an S11 ≤ -15 dB at 300 GHz for the next generation of wireless communications 6G. However, at 300 GHz, Wu *et al.* [13] demonstrated a CP lens antenna fed by a typical linearly polarized pyramidal horn. According to the experimental results, the 3-D printed THz circularly polarized lens can generate right-hand CP (RHCP) radiation with a 1 dB gain bandwidth of more than 13.3% and a 3-dB axial-ratio (AR) bandwidth of more than 18.8%. A new photonic bandgap substrate antenna with a resonance frequency of 198 GHz, an S11 of -68.5 dB, and a maximum gain of 3.4 dBi is designed for cancer detection. The design demonstrates good feedline matching with a voltage standing wave ratio (VSWR) value of 1.0007 [14]. A 420 GHz on-chip antenna (OCA) with an excellent gain is created utilizing ordinary 55 nm complementary metal–oxide–semiconductor (CMOS) technology to satisfy the demands of THz imaging and communication. An analytical methodology for calculating radiation efficiency is offered, as well as a thorough design approach. Ansoft high frequency structure simulator high frequency structure simulator (HFSS) is used to simulate the suggested antenna. The suggested antenna has a radiation efficiency of 76.27%, and a gain of 4.9 dBi. On-chip antennas (OCA) perform well and have a wide variety of applications in terahertz imaging and communication [15]. One basic arrangement is employed in [16] to obtain ultrawide-band and highly directive properties that indicate a considerable enhancement in graphene based slotted bowtie antennas. The simulated results indicate that the efficiency of this bowtie is 71% with 18.19 dB directivity, and 17.52 dB realized gain at 11.1 THz, and the directivity is reduced by over 13 dB at 11.1 THz when compared to a bowtie antenna that resonates at 7.1 THz. The fractional impedance bandwidth of the proposed antenna was 40.595%, 14.425%, and 13.21% at 7.1 THz, 11.1 THz, and 13.1 THz, respectively. In fact, high-performance antennas are necessary for THz wireless communication systems. Considering the research challenge, we suggest a patch antenna design that includes numerous slots in the radiation element (patch) to address this demand. The added slots significantly influence how well the antenna radiates. By changing the size and position of these slots, the radiation properties, including the return loss, gain, and bandwidth, have been enhanced. When compared to earlier research that provided antennas for similar frequency bands, our antenna performs better, and this approach is simple. The main contributions of this work are as follows: a compact slotted terahertz antenna operating at 118 GHz has been designed with various slots in the patch. Different parameters such as the gain, directivity, and efficiency of the proposed antenna have been calculated to analyze its performance.

We organized the remainder of this work as follows: section 2 details the antenna's design technique. Section 3 discusses the simulated results with a general comparison with the most current research cited in the literature. Finally, we have summarized the content of the article.

2. METHOD OF ANTENNA DESIGN

In this section, a microstrip antenna with slots is designed for the THz band frequencies. Figure 1(a) illustrates the design of the suggested antenna element. The antenna shown has three different layers: The ground plane is in the bottom layer with 0.035 mm-thick copper with a conductivity of 5.8×10^{7} s/m as shown in Figure 1(b), a 0.1 mm-thick RO3003 substrate ($\tan\delta = 0.001$ and $\varepsilon r = 3$), and the top layer is the radiating element, which is formed from a rectangular patch (copper) as shown in Figure 1(c). As a first step, the antenna dimensions are computed using the substrate's properties, as well as the resonance frequency (fr=118 GHz). Equations (1) and (2) facilitated the computation of the size of the patch (Wp and Lp). In this design, the antenna is excited using a microstrip feeding method with a central feed of width wf and length lf; the antenna has a total volume of $W \times L \times hs = 1.5 \times 1.3 \times 0.1$ mm^3, with six slots engraved in the patch and in the ground plane. By judiciously placing slots within the antenna structure, the recommended design aims to enhance key performance characteristics. The suggested antenna is excited by a 50 Ω microstrip line with a width of wf. The principal benefits of using this microstrip line to build microwave circuits are the simplicity with which passive and active components may be surface mounted. In addition, the findings obtained from the transmission line model are applied in the design process of a patch antenna, aiming to achieve resonance at a frequency of 118 GHz. The detailed dimensions of the antenna element are indicated in Table 1.

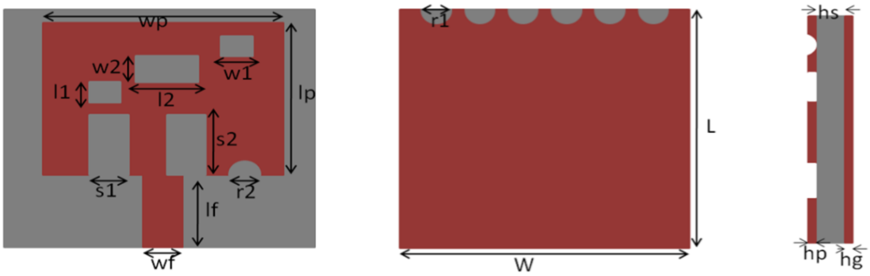

Figure 1. Suggested antenna design, (a) upper view, (b) bottom view, and (c) side view

Table 1. Detailed dimensions of the suggested antenna (unit: mm)

Variables	Value (mm)	Variables	Value (mm)
w	1.5	hg=hp	0.035
l	1.3	r1=r2	0.05
wp	0.9	hs	0.1
lp	0.7	S2	0.23
w1=l1	0.1	S1	0.13
w2	0.07	l2	0.245
wf	0.25	lf	0.3

The patch's length and width are determined by (1) and (2) respectively [17]:

$$Lp = \frac{c}{2fr\sqrt{\epsilon e}} - 2\Delta L \quad (1)$$

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

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

$$\epsilon_e = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\frac{1}{\sqrt{1+12\frac{h}{w}}} \quad (4)$$

where ΔL and ϵe denote the fringing extension length and effective permittivity, respectively, as expressed in (3) and (4).

This section discusses the development of the suggested antenna design. The design procedures for the proposed antenna is illustrated in Figure 2. In comparison to existing antenna structure design approaches, the antenna structure described in our work is very creative. We started with an initial structure Ant I in Figure 2(a), which is a basic rectangular patch consisting of a 50 Ω feedline with a -19.74 dB return loss. In this case, the basic antenna is created at a single resonant frequency of 118.4 GHz using a typical microstrip patch radiator with two slots embedded in it; however, S11 is not sufficient. Then, another pair of rectangular and circular slots are created at the radiating element concerning the first iteration, as shown in

Ant II in Figure 2(b). The rectangular patch is now reduced in the third case Ant III in Figure 2(c) to create one slot in the center of the second rectangular patch. This reduces its S11 value to below -10 dB, and it is better than Ant I at 118.7 GHz with a bandwidth of 4.07 GHz as demonstrated in Figure 3. This results in an operation at 118 GHz to obtain better characteristics for the suggested antenna. Therefore, incorporating slots results in a frequency displacement of 118 GHz, and improves the antenna's performance. The simulation results of all design processes are represented in Figure 3 by using the Ansoft HFSS simulation, and their respective frequency and bandwidth performances are examined in Table 2.

Ant I (a) **Ant II** (b) **Ant III** (c)

Figure 2. Various steps involved in antenna design (a) Ant I, (b) Ant II and (c) Ant III

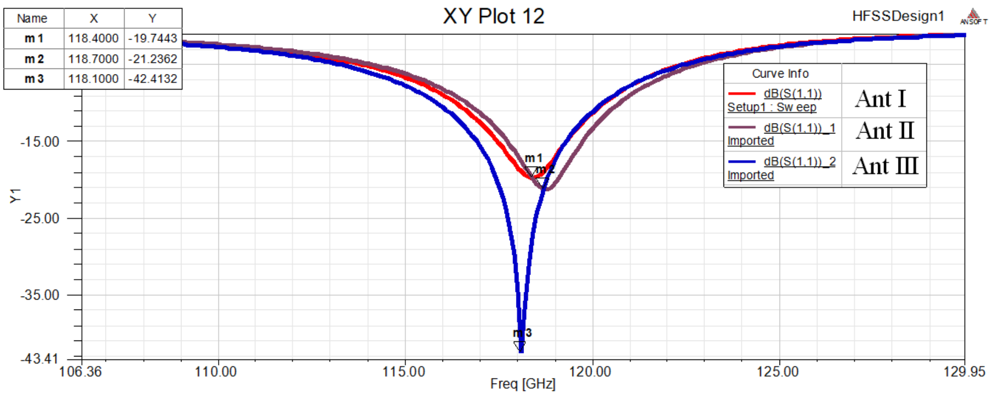

Figure 3. S11 comparison of various iterated antennas

Table 2. Frequency and bandwidth comparison of several steps

Antenna	Frequency (GHz)	Lower frequency (GHz)	Higher frequency (GHz)	BW (GHz)	S11 (dB)
Ant I	118.4	116.35	120.30	3.95	-19.7443
Ant II	118.7	116.64	120.71	4.07	-21.23
Ant III	118	115.84	120.26	4.42	-42.41

3. SIMULATION RESULTS ANALYSIS

To simulate the designed structure, we used Ansoft HFSS. The antenna's characteristics are assessed in terms of S11, which is among the parameters used to evaluate the antenna feed system's quality; VSWR, which is used to determine how efficiently the antenna transmits power; input impedance, efficiency, gain, and directivity. The antenna element is modelled by Ansoft HFSS, and Figure 4 demonstrates the S11 of the suggested antenna. The results show that S11 is more than -10 dB over the frequency bands of 115.84–120.26 GHz, and the reflection coefficient reaches -42.41 dB at a resonance frequency of 118 GHz. These findings clearly show that we were able to produce a decent reflection coefficient focused on the appropriate frequency by selecting the precise width and position of the slots in the patch. These findings motivate scientists and antenna specialists to use it.

To analyze the adaptation of the antenna, which generally symbolizes the transmission of electric power between the source and the load, two major elements were simulated: the VSWR, and the input impedance. Figure 5 shows the VSWR of the suggested antenna; the VSWR should ideally be one, signifying that the antenna obtains 100% of its power and implies zero reflection from the antenna impedance [18], but in practice, it is possible to have a VSWR of 2. The slotted antenna suggested in this simulation has a VSWR of 1.01(<2). It is clear that the suggested antenna has excellent impedance matching characteristics.

Figure 6 displays the variation in the suggested antenna's input impedance (Zin) characteristic, which determines the power transfer efficiency between the incoming wave and the antenna. At 118 GHz, the Zin of the suggested antenna is 49.54 in the real part and -0.59 in the imaginary part. The obtained values of the input impedance are Zin = (49.54 -0.59 j). The Zin value must be 50 Ω in the real part and 0 Ω in the imaginary part [19]. This shows that the optimized antenna is well adapted. Figure 7 demonstrates the radiation efficiency of the recommended antenna. The antenna's total efficiency can be determined by calculating the product of the gain and the directivity, which provides the capability to assess the overall effectiveness of the antenna. As a result of the source and load's excellent impedance matching, the suggested antenna offers an improved radiation efficiency of 99.75% at 118 GHz, as depicted in Figure 7. Additionally, as shown in Figure 8, the suggested antenna has a gain of 7.36 dB and a directivity of 7.38 dB at 118 GHz.

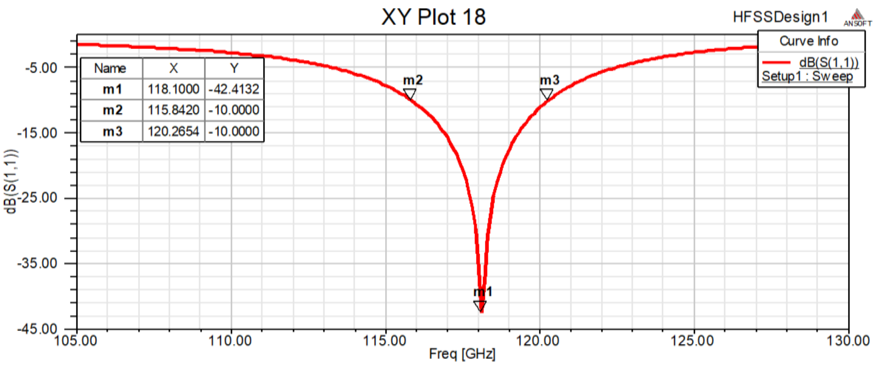

Figure 4. The suggested antenna reflection coefficient simulation results

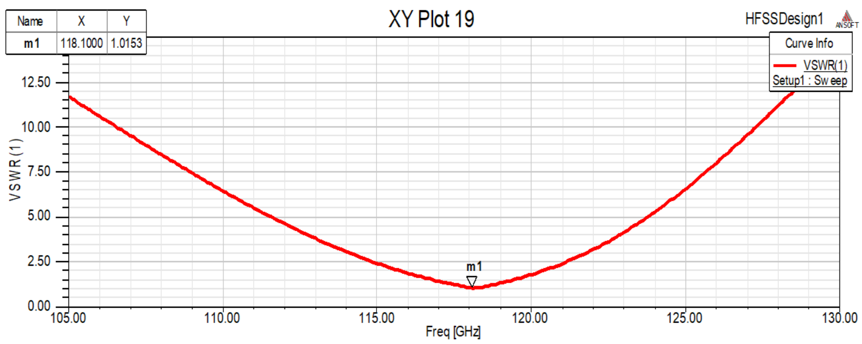

Figure 5. VSWR of the suggested antenna

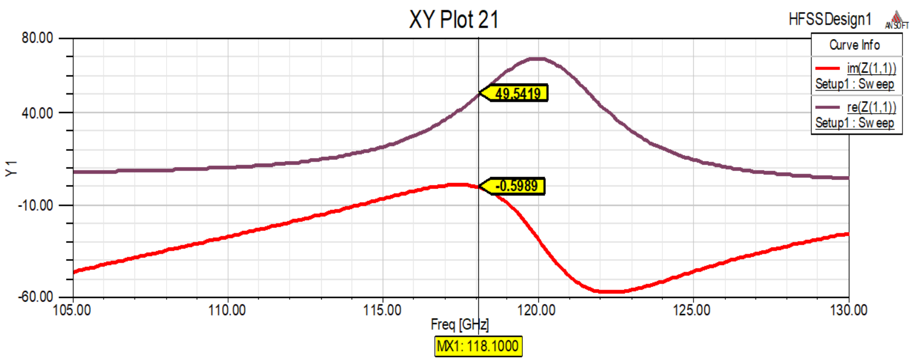

Figure 6. The suggested antenna's input impedance characteristics

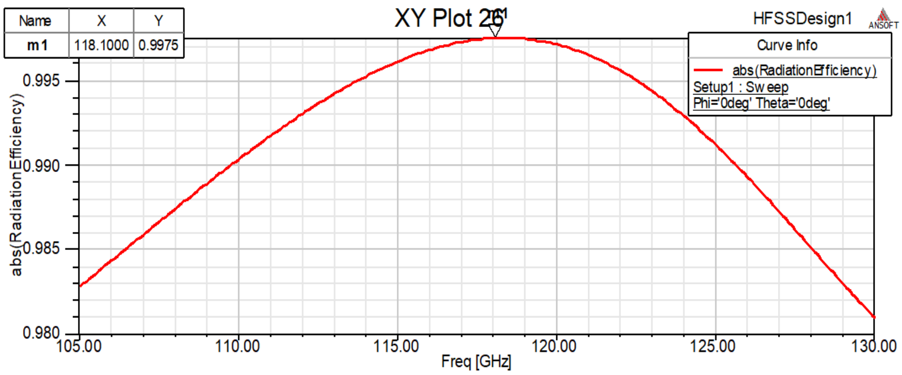

Figure 7. Radiation efficiency performance

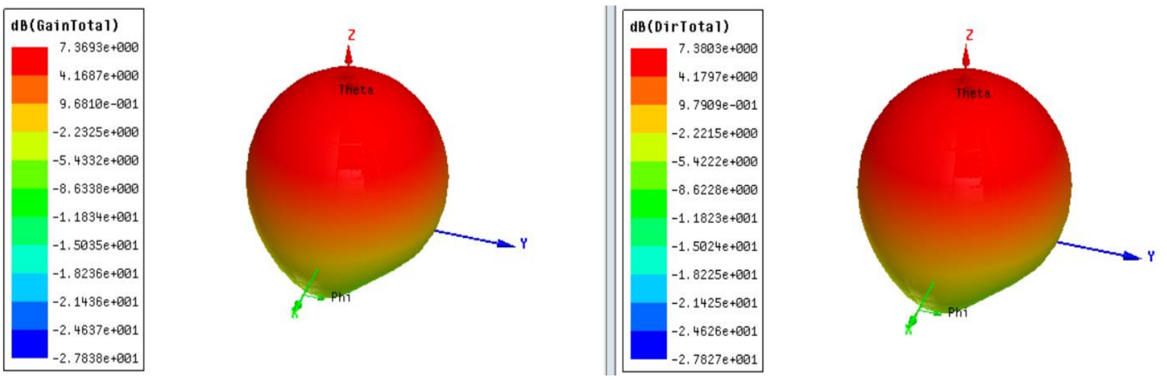

Figure 8. Total gain and directivity of the optimized antenna at 118 GHz

Figure 9 depicts the surface current distributions of the recommended antenna at the resonating frequency (118 GHz). The dispersed surface currents are substantially concentrated near the edge of the suggested patch structure, as shown in Figure 9. A large surface current concentration is also seen on the edges of the slots. This demonstrates that the antenna structure's carved slots begin to participate in the resonance and contain a sizeable portion of the field. Moreover, the surface current distribution is higher and more noticeable at higher resonant frequencies, indicating that it influences the suggested antenna design for improving characteristics at higher resonance. In conclusion, it is clear that the proposed slots control all operational frequencies.

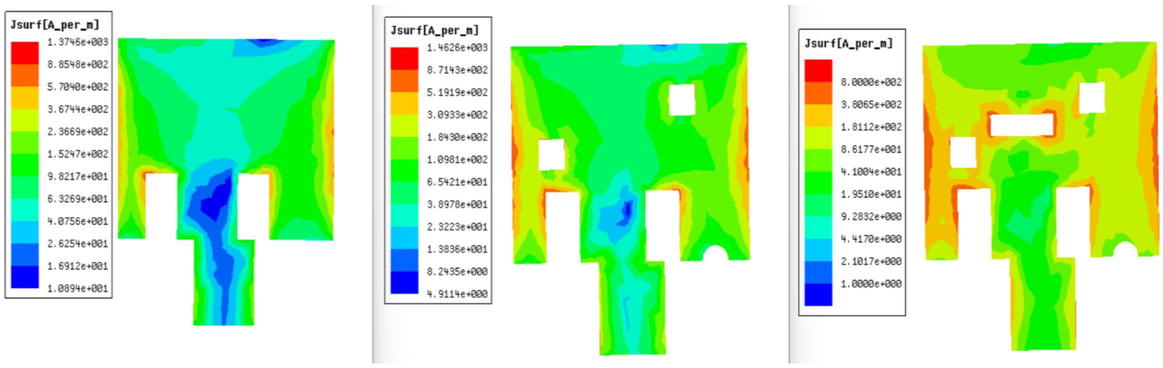

Figure 9. Surface current distribution of various steps involved in antenna design at 118 GHz

Moreover, to verify the accuracy of the simulation results, we conducted an additional simulation using CST software. Figure 10 illustrates the simulated S11 of the suggested antenna obtained through HFSS and CST software. There is good agreement between the two graphs. The small difference is due to each solver's various calculating methodologies. HFSS is based on the finite element method, while CST is based on the finite integration technique. Table 3 compares the performance of the suggested antenna with the software mentioned before. Thus, the simulation results from both tools are nearly similar.

Finally, the performance of the suggested terahertz antenna is compared to that of several other previously reported THz antennas, which are listed in Table 4. Several critical characteristics are provided, including resonance frequency, gain, bandwidth, directivity, and efficiency. The essential output parameter is the antenna gain, and the recommended antenna has a maximum gain of 7.36 dB, which is good in comparison to the 4.9 dBi of [15], 3.8 dB of [18], 6.88 dB gain of [20], 5.24 dB of [21], 5.6 dB of [22], 7.286 dB of [23], 5.09 dB of [24], 5.5 dB of [25], and 5.72 dB of [26]. Furthermore, Table 4 indicates that our proposed antenna delivers better efficiency compared to other antennas. In addition, as demonstrated in Table 4, this antenna has a better S11 than the antenna [20] and a larger bandwidth than the antenna [27]. Antenna [23] has a very high bandwidth in comparison to other antennas, but its characteristics, such as gain, are low in comparison to the suggested antenna. This table demonstrates that the antenna described here is advantageous depending on the needs of the targeted applications.

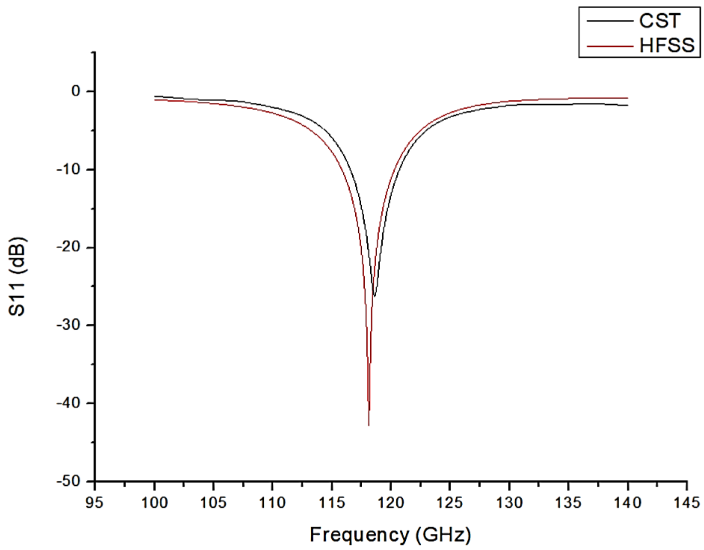

Figure 10. S11 of the suggested antenna using HFSS and CST software

Table 3. A comparison of simulation results using the suggested antenna's HFSS and CST

Simulator	HFSS	CST
Fr (GHz)	118	118.63
S11(dB)	-42.41	-26.157
Bandwidth (GHz)	4.42	4.13 GHz
VSWR	1.01	1.1054
E_f	99.75%	67%
Gain	7.36 dB	5.071 dBi
Directivity	7.38 dB	6.735 dBi

Table 4. A comparison of existing THz antennas and suggested THz antennas

Ref.	Frequency (THz)	Return loss (dB)	BW(GHz)	VSWR	Gin (dB)	D (dB)	Efficiency (%)
[15]	0.42	-	44	-	4.9 dBi	-	76.27
[18]	960	-15.70	310	1.3	3.8	-	-
[20]	0.69	-34.9	24	1.04	6.88	7.01	-
[21]	0.703	-50.94	26.4	1.00	5.24	6.81	-
[22]	0.312	-50	22.6	-	5.6	-	-
[23]	7	-75.21	386	1.0003	7.286	7.408	97.21
[24]	0.75	-	50	-	5.09	-	86.58
[25]	6.35	-	-	-	5.5	-	-
[26]	1.65	-	118	-	5.72	-	77.5
[27]	0.3	-35	2	-	-	11.71	70.8
This work	0.118	-42.41	4.42	1.01	7.36	7.38	99.75

4. CONCLUSION

In this article, a slotted terahertz antenna at 118 GHz is designed using Ansoft HFSS. The objective of the slots is to increase the performance of the antenna. According to the simulation findings, the directivity and the gain of the suggested terahertz antenna are 7.38 dB and 7.36 dB, respectively, at 0.118 THz, with 99.75% radiation efficiency and a VSWR of 1.01. The minimal reflection coefficient of the suggested antenna is less than -42.41 dB at the resonant frequency. A comparison of the suggested THz antenna with previous work is included at the end of this article. It is apparent that the suggested antenna offers numerous advantages. The suggested approach for creating a terahertz antenna appears simple. As a consequence, the recommended antenna is a potential candidate for use in imaging systems such as passive millimeter-wave imaging. This type of imaging is useful in applications such as security screening, where it can detect hidden weapons or explosives. In addition, this antenna can be used in wireless communication systems such as 5G.

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