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High-performance THz Metallic Axial Mode Helix Antenna with Optimised Truncated Hollow Cone Ground Plane for 6G Wireless Communication System

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ABSTRACT

The Terahertz (THz) band antenna configuration operates in the 0.1–10 THz frequency range and offers a stable performance for future 6th Generation (6G) wireless communication systems. However, the available metallic axial mode helix antenna designs exhibit a peak directivity of lower than 18 dBi within 0.5–1 THz, making it inappropriate to be applied in wireless communication systems. Therefore, this study proposed a high-performance THz metallic five-turn axial mode helix antenna with an optimised truncated hollow cone ground plane for 6G wireless communication systems. Following the creation of the proposed antenna design using cost-effective copper (annealed), the truncated hollow cone ground plane of the THz axial mode helix antenna was optimised via simulation in a Computer Simulation Technology Microwave Studio (CST MWS) software and a verification of the proposed THz antenna design in Analysis System High-Frequency Structure Simulator (Ansys HFSS) software for a fair comparison. Based on the results, the proposed THz metallic axial mode helix antenna with optimised truncated hollow cone ground plane recorded an impedance bandwidth of 0.46 THz, Fractional Bandwidth (FBW) of 61.33% for $|S_{11}| \leq -10$ dB, and a maximum directivity and realised gain of 21.8 dBi and 21.5 dBi at 0.85 THz,

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respectively. Within the 0.5–1 THz, the proposed optimised THz antenna design achieved an outstanding performance, including an FBW of more than 50%, excellent directivity of higher than 15.8 dBi, radiation efficiency of greater than 87%, circular polarisation, and low-profile helix turns. In short, the proposed THz metallic axial mode helix antenna with optimised truncated hollow cone ground plane design is appropriate for various THz 6G wireless applications.

Keywords: 6G wireless communication system, axial mode, helix antenna, high-performance, metallic, terahertz

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INTRODUCTION

The Terahertz (THz) band antenna configuration has received overwhelming interest over its compatible application in 6th Generation (6G) wireless communication systems. The 0.1–10 THz range offers numerous advantages, such as non-ionic high-frequency range, excellent resolution, broad bandwidth (Singhal, 2019), more robust information security, and stable communication, making it a more favourable alternative for future wireless (6G) communication (P. K. Singh et al., 2021). Nevertheless, one of the main drawbacks of the THz frequency band is the high attenuation path loss and molecular absorption loss (P. K. Singh et al., 2021; Ullah et al., 2019; Xia & Jornet, 2019). In particular, frequencies over 1 THz are inappropriate for wireless communication due to the absorption wavelengths of humidity and other gases in the THz band (P. K. Singh et al., 2021). Thus, only the low THz frequency range (0.1–1 THz) is suitable for future wireless communication, given its fewer signal losses due to the effect of small fog and dust particles (P. K. Singh et al., 2021; Ullah et al., 2019). Additionally, several low attenuation windows appear below 1 THz, specifically around 0.3, 0.35, 0.41, 0.65, and 0.85 THz (P. K. Singh et al., 2021), w_1=0.38–0.44 THz, w_2=0.45–0.52 THz, w_3=0.62–0.72 THz, and w_4=0.77–0.92 THz (M. Singh et al., 2021). In view of this, broad bandwidth THz band antennas could be utilised for various THz band applications in future 6G wireless communication, such as medical diagnosis (0.42, 0.50, and 0.80 THz), homeland defence (0.6–0.8 THz), video-rate imaging (0.6 THz), explosive and weapon detection (0.41 THz), Terabits/sec links (0.2375, 0.350, and 0.840 THz), space communication, and energy conservation devices (Ghalamakri & Mokhtari, 2022).

The propagation path loss can be compensated by employing two key components, namely, the high-gain and directive THz band antenna (Aqlan et al., 2020; Fan et al., 2016; Faridani & Khatir, 2018; Kürner, 2018; Pillai et al., 2022; Wu et al., 2019; Xia & Jornet, 2019). However, using metallic materials (Hajiyat et al., 2021b) to design Ultra-Wideband (UWB) THz band antennas with high directional gain (Chen et al., 2020) is extremely difficult due to the impact of antenna size on gain and bandwidth (Harrington, 1960; Huang & Boyle, 2008). Besides, the decreased skin depth and conductivity of the copper metal at the THz band minimises the radiation efficiency of the antenna elements in the THz band (Dash & Patnaik, 2018; Jamshed et al., 2020).

Antennas on-chip based on meta-materials and meta-surfaces are interesting techniques to achieve high-performance THz antennas without altering their physical size (Alibakhshikenari et al., 2022). Various studies have demonstrated the advantages of these techniques in terms of smaller size, low profile, wider bandwidth, and better radiation properties (Alibakhshikenari et al., 2022; Alibakhshikenari et al., 2021). However, these studies only reported fractional bandwidth of lower than 50%.

Interestingly, Chetioui et al. (2022) and most research by Acharya et al. (2015), Boudkhil et al. (2018), Guo et al. (2014) and Guo et al. (2016) operated THz band helix antenna above 1 THz frequency. Although they provide wideband or UWB bandwidth for THz 6G communication, such approaches are unsuitable for wireless communication systems due to their frequency of over 1 THz. On the contrary, very few studies on THz band axial mode helix antennas have reported such applications below 1 THz (Boudkhil et al., 2019; Hajiyat et al., 2021a; Hajiyat et al., 2021c). Moreover, the study by Hajiyat et al. (2021c) achieved a peak directivity of 13.4 dBi. Thus, the result implies that further investigation is required to design a THz axial mode helix antenna with greater peak directivity than 18 dBi to compensate for the propagation path loss in the THz range, ultimately achieving effective UWB 6G wireless communication systems.

To the best of the author's knowledge, a high-performance metallic axial mode helix antenna with a peak directivity of higher than 18 dBi has not been reported in 6G wireless communication systems at a frequency range of 0.5–1 THz. Therefore, this study proposed a high-performance THz metallic axial mode helix antenna with an optimised truncated hollow cone ground plane for the UWB 6G wireless communication system. The truncated hollow cone ground plane parameters of the proposed metallic axial mode helix antenna were optimised. Subsequently, the simulation results were computed using the Computer Simulation Technology Microwave Studio (CST MWS) software. The performance of the proposed antenna design was then verified via an Analysis System High-Frequency Structure Simulator (Ansys HFSS). Finally, both findings were compared and revealed a strong association. The computed results notably outperform similar research in terms of directivity for frequencies between 0.5 and 1 THz.

METHODS

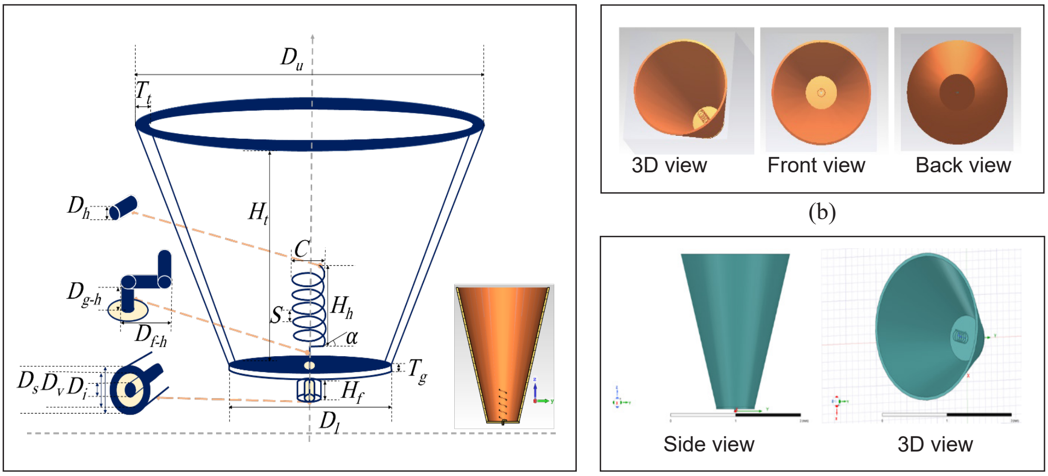
Design of the Proposed Axial Mode Helix Antenna with Optimised Truncated Hollow Cone Ground Plane

This study investigated the performance of an optimised three-dimensional (3D) copper ground structure added to the THz axial mode helix antenna. Figure 1(a) shows the proposed optimised THz antenna design schematic diagram. Copper (annealed) was applied in the design due to its widespread use in antenna manufacturing and past literature studies on copper antennas at THz frequencies. The ground plane of the proposed THz metallic axial mode helix antenna was reshaped, designed, and optimised to reach exceptionally high directional gain performance. Notably, this study introduced a truncated hollow cone ground plane (3D-shaped), which differs from that of the circular ground plane (2D-shaped) in Hajiyat et al. (2021c). Regardless, the same number of helix turns was used in this study to maintain a low profile of helix turns.

The proposed optimised THz antenna design was fed with a 50-Ω copper (annealed) coaxial cable (vacuum as an insulator), where the inner conductor diameter of the coaxial feed is equivalent to the diameter of the helix wire to simplify the antenna geometry for enhanced and reproducible antenna design at THz frequency. The values of the optimised truncated hollow cone ground plane parameters for the proposed axial mode helix antenna are shown in Table 1.

Figure 1(b) presents the proposed five-turn axial mode helix antenna geometry with an optimised truncated hollow cone ground plane fed with the 50-Ω coaxial waveguide port in the Computer Simulation Technology Microwave Studio (CST MWS) software based on the Finite Integration Technique (FIT) (SIMULIA, 2019). A waveguide port was used in the feeding line due to extremely low reflection levels at high frequencies. For analysis purposes, a time-domain solver with a hexahedral mesh type of -50 dB accuracy and open (add space) boundary conditions for all directions were utilised for the simulation setting.

Experimental measurements of THz band antennas are hampered by unresolved issues in THz band antenna manufacturing technology, equipment availability, and expensive



(a) (b) (c)

Figure 1. The proposed metallic axial mode helix antenna with optimised truncated hollow cone ground plane: (a) Schematic diagram; (b) 3D view, front view, and back view in the CST MWS software with air surrounding, respectively; and (c) Side view and 3D view in the Ansys HFSS Software plane
Note. Design drawn not to scale

facilities (Akyildiz et al., 2020; Hajiyat et al., 2021b). Therefore, further software comparisons were used in this work to validate the proposed optimised THz antenna design. The proposed antenna design and optimisation were performed using the CST MWS software, while Analysis System High-Frequency Structure Simulator (Ansys HFSS) software version 2021 R1, which is based on the Finite Element Method (FEM) (Ansys Inc, 2021), was used for antenna design validation and comparison. Figure 1(c) shows the proposed optimised THz antenna design in the Ansys HFSS software.

Table 1
Design parameters for the proposed metallic axial mode helix antenna with optimised truncated hollow cone ground plane

Parameter	Value (mm)
Helix antenna with truncated hollow cone ground plane	
Circumference of a turn (C)	0.40
Spacing between turns (S)	0.10
Height of the helix antenna (H_h)	0.50
Diameter of the helix wire (D_h)	0.0150
Distance between the feed wire and the helix antenna ($D_{f\text{-}h}$)	0.0790
Distance between the ground plane and the helix antenna ($D_{g\text{-}h}$)	0.0085
Upper diameter of the truncated hollow cone (D_u)	1.70
Ground lower diameter of the truncated hollow cone (D_l)	0.60
Height of the truncated hollow cone (H_t)	1.950
Ground thickness of the truncated hollow cone (T_g)	0.020
Thickness of the truncated hollow cone (shell thickness of loft) (T_t)	0.035
Coaxial waveguide port	
Inner conductor diameter of the coaxial feed (D_i)	0.015
Vacuum diameter of the coaxial feed (insulator) (D_v)	0.034
Outer conductor diameter of the coaxial feed (outer sheath) (D_s)	0.036
Height of the coaxial feed (H_f)	0.030
Parameter	Value
Helix turn number (N)	5
Helix angle (α)	14.03°

Optimisation of Truncated Hollow Cone Ground Plane Parameters

The geometrical dimensions of the truncated hollow cone ground plane were determined to maximise the antenna directivity while maintaining a high Fractional Bandwidth (FBW) in the selected frequency range. The upper diameter of the truncated hollow cone, the ground lower diameter of the truncated hollow cone, the height of the truncated hollow cone, and the thickness of the truncated hollow cone were assessed as independent variables. Other helix antenna dimensions were kept constant as control variables. Table 2 shows the data input in the CST MWS software.

Factors Affecting the Performance of the Metallic Axial Mode Helix Antenna

The following sections describe the effects of the truncated hollow cone ground plane parameters (height, upper diameter, ground lower diameter, and thickness) on the directivity and FBW performance of the proposed optimised THz antenna design.

Table 2
Investigated parameter range of truncated hollow cone ground plane optimisation

Variable	Parameter	Investigation range
Independent	H_t (unit)	0.218–2.5 (mm)
	D_u (unit)	0.5–1.8 (mm)
	D_l (unit)	0.5–0.9 (mm)
	T_t (unit)	0.01–0.07 (mm)
Control	C (unit)	0.40 (mm)
	S (unit)	0.10 (mm)
	H_h (unit)	0.50 (mm)
	D_h (unit)	0.0150 (mm)
	$D_{f\text{-}h}$ (unit)	0.0790 (mm)
	$D_{g\text{-}h}$ (unit)	0.0085 (mm)
	N	5
	α	14.03°

Effect of Varying Height

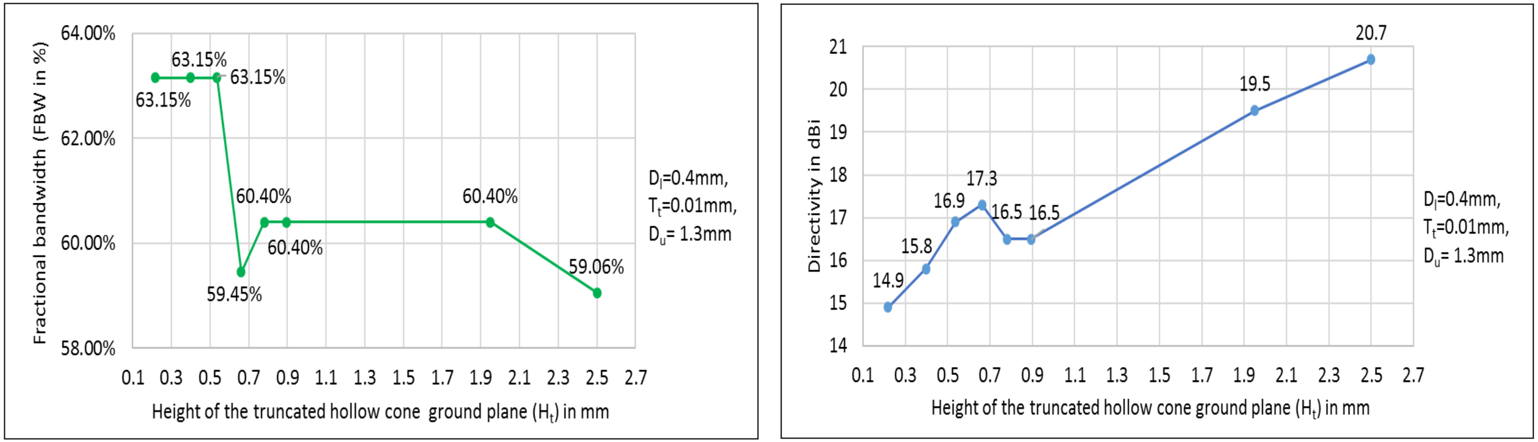
The effect of the height of the truncated hollow cone ground plane (H_t) of the proposed optimised THz antenna design was assessed at fixed D_u, D_l, and T_t values. The H_t was varied to determine the height effect on the directivity and FBW performance of the metallic axial mode helix antenna in the THz band. Figures 2 (a) and 2(b) show that the increased H_t led to an increase in the directivity performance of the axial mode helix antenna but decreased the FBW performance. Additionally, the directivity performance of the proposed optimised THz antenna design has achieved over 18 dBi when the H_t value was more than 1.95 mm. In short, the analysis suggests that the directivity and FBW performance of the proposed optimised THz antenna design are positively and negatively correlated with the $H_{t,}$ respectively.

Effect of Varying Upper Diameter

The effect of the upper diameter of the truncated hollow cone ground plane (D_u) of the proposed optimised THz antenna design was analysed at fixed H_t, D_l, and T_t values. As shown in Figures 3(a) and 3(b), the directivity performance of the metallic axial mode helix antenna enhanced as the D_u increased. The FBW performance also increased until the D_u value reached 0.8 mm, where the FBW performance decreased and maintained within a D_u range of 1.3–1.8 mm. Based on the analysis, the directivity performance of the metallic axial mode helix antenna is more positively correlated to the D_u compared to the FBW performance, with higher FBW recorded at specific D_u values.

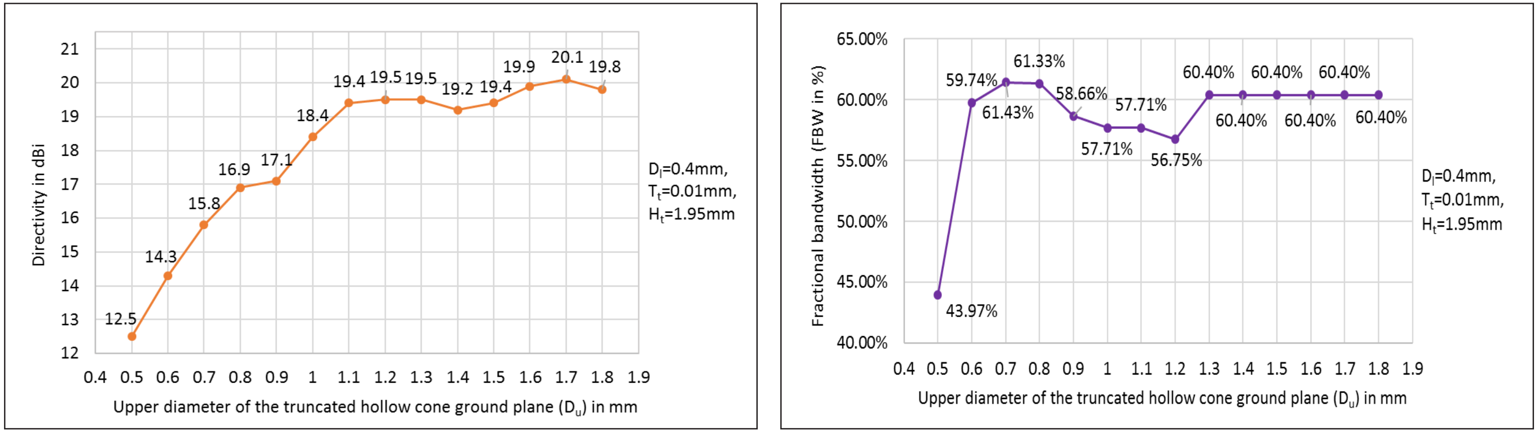
Effect of Varying Ground Lower Diameter

The effect of the ground lower diameter of the truncated hollow cone ground plane (D_l) of the proposed optimised THz antenna design was determined at fixed H_t, D_u, and T_t values. According to Figures 4(a) and 4(b), increasing the D_l decreased the directivity performance



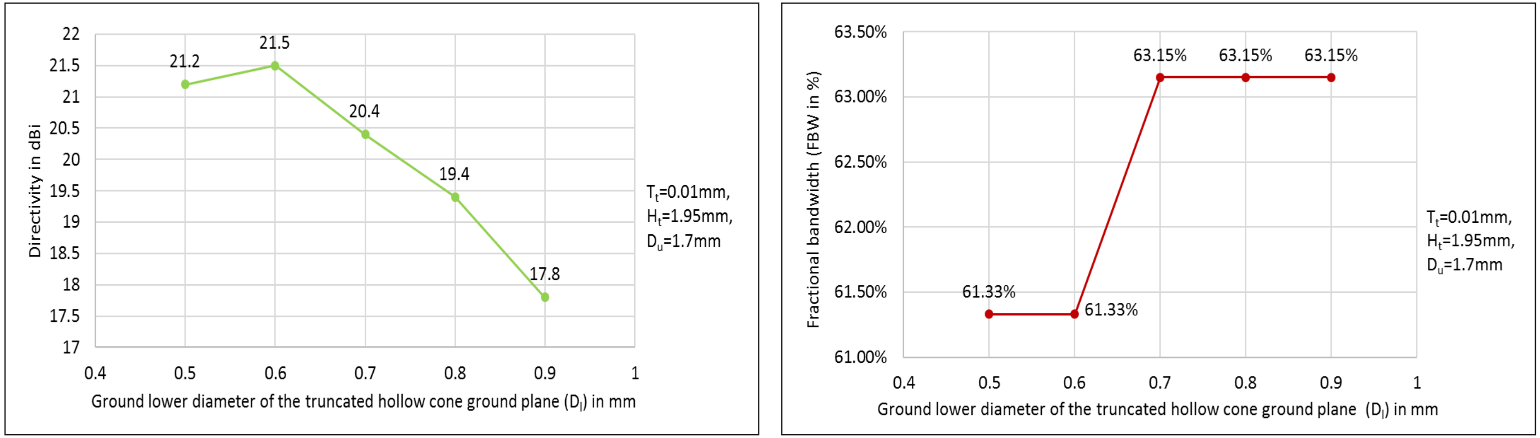
(a) (b)

Figure 2. The effect of varying H_t values on the performance of the metallic axial mode helix antenna in terms of: (a) directivity; and (b) FBW



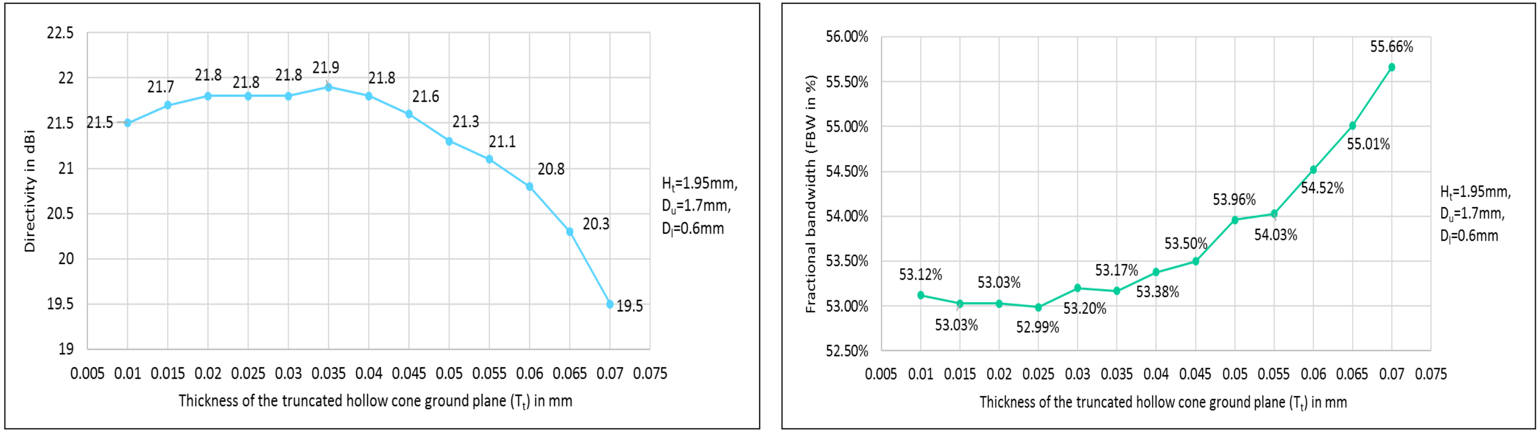
(a) (b)

Figure 3. The effect of varying D_u values on the performance of the metallic axial mode helix antenna in terms of: (a) directivity; and (b) FBW



(a) (b)

Figure 4. The effect of varying D_l values on the performance of the metallic axial mode helix antenna in terms of the (a) directivity and (b) FBW



(a) (b)

Figure 5. The effect of varying T_t values on the performance of the metallic axial mode helix antenna in terms of: (a) directivity; and (b) FBW

of the proposed optimised THz antenna design. However, the FBW performance was enhanced as the D_l increased and stabilised at a D_l range of 0.7–0.9 mm.

Effect of Varying Thickness

The effect of the loft (T_t) shell thickness of the truncated hollow cone ground plane of the proposed optimised THz antenna design was evaluated at fixed H_t, D_u, and D_l values. Figures 5(a) and 5(b) show that the increase in T_t reduced the directivity performance but increased the FBW performance of the metallic axial mode helix antenna. Thus, thickening the ground plane of the truncated hollow cone significantly improved the FBW performance of the proposed optimised THz antenna design compared to the directivity performance.

RESULTS AND DISCUSSION

Design Results of the CST MWS Software

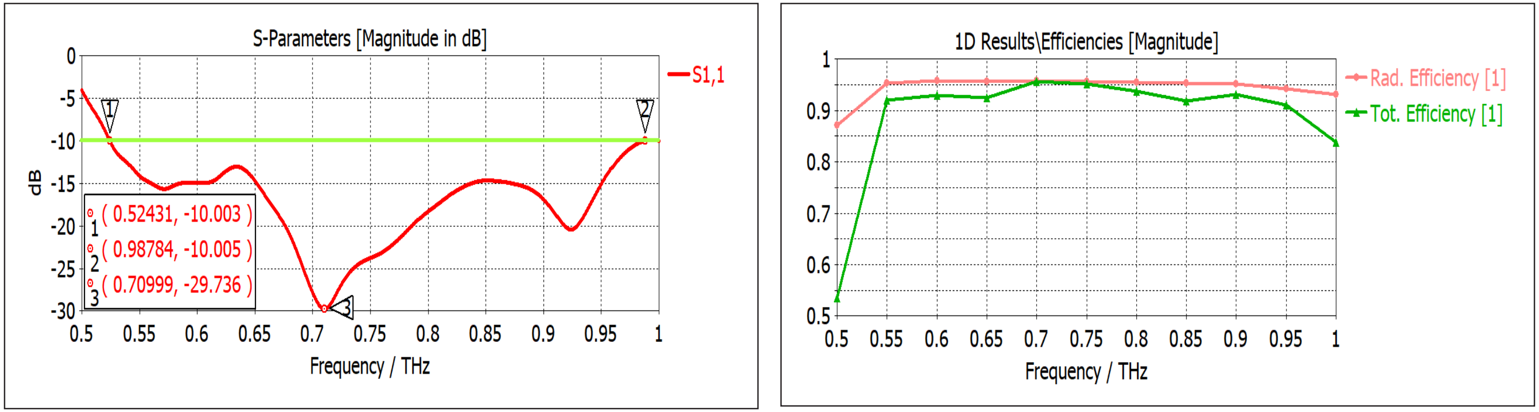
Figures 6(a) and 6(b) depict the performance of the proposed optimised THz antenna design using the CST MWS software in terms of the S_{11} parameter and total efficiency and radiation efficiency, respectively. Based on the results, the UWB bandwidth ($|S_{11}| \leq -10$ dB) operates between 0.52 to 0.98 THz with an FBW of 61.33%, impedance bandwidth (BW) of 0.46 THz, and a deeper return loss of -29.73 dB at 0.709 THz. In addition, the optimised metallic axial mode helix antenna exhibits two resonant frequencies at 0.710 THz and 0.924 THz, with a total efficiency of 0.53–0.95 and radiation efficiency of 0.87–0.95 within a frequency range of 0.5–1 THz.

Furthermore, the directivity and realised gain of the proposed optimised THz antenna design at 0.5–1 THz were 15.8–21.8 dBi and 15.1–21.5 dBi, respectively. Figure 7 shows that the proposed optimised THz antenna design recorded a maximum directivity of 21.8 dBi with a realised gain of 21.5 dBi at 0.85 THz.

Validation Results of the Ansys HFSS Software

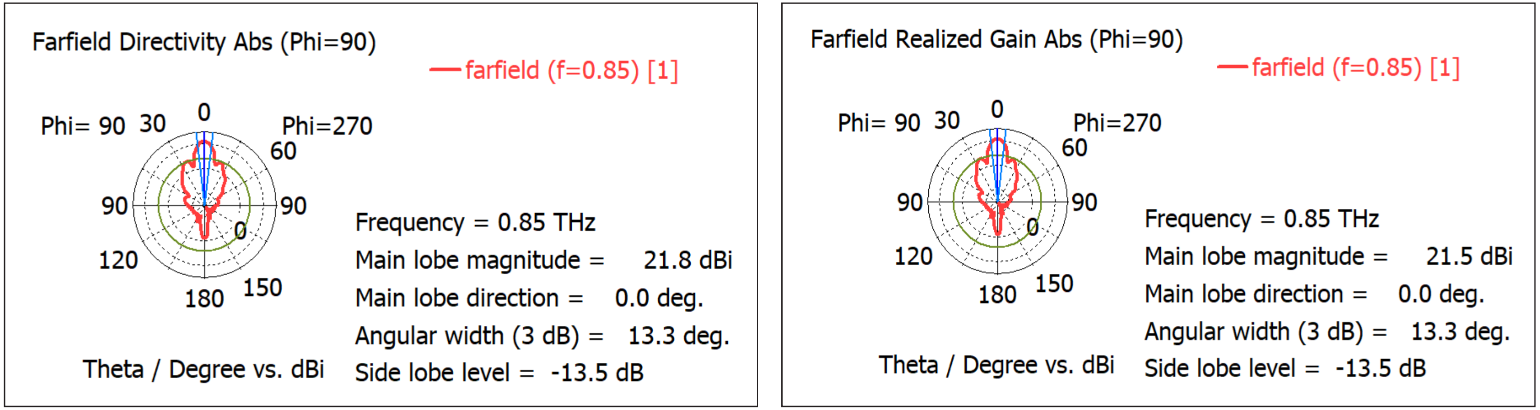
Figures 8(a) and 8(b) illustrate the performance of the proposed optimised THz antenna design using the Ansys HFSS Software in terms of the S_{11} parameter and radiation efficiency, respectively. The UWB bandwidth was attained within the 0.52–0.98 THz range, which also recorded an FBW ($|S_{11}| \leq -10$ dB) of 61.33%, impedance BW of 0.46 THz, and a minimum return loss of -31.45 dB at 0.71 THz. The optimised proposed THz antenna design also recorded three resonant frequencies at 0.57 THz, 0.71 THz, and 0.91 THz, with a radiation efficiency of 0.87–0.99 at a frequency range of 0.5–1 THz.

Moreover, the proposed optimised THz antenna design recorded a directivity of 15.87–21.8 dBi and a realised gain of 14.1–21.6 dBi within the 0.5–1 THz frequency range. Figure 9 shows a maximum directivity of 21.8 dBi with a realised gain of 21.6 dBi at 0.85 THz by the proposed optimised THz antenna design.



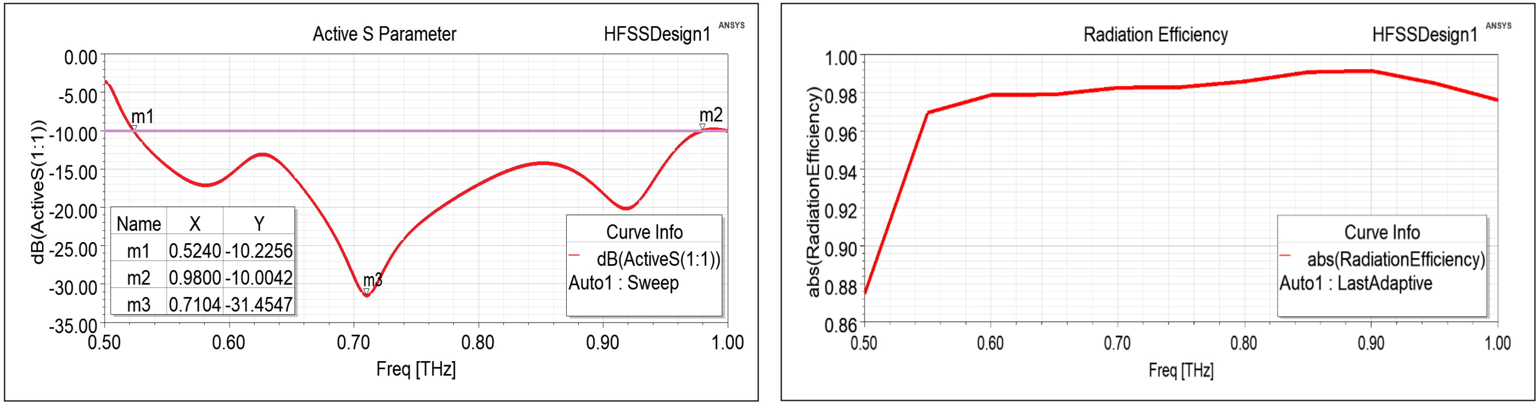
(a) (b)

Figure 6. The CST MWS performance analysis of the proposed metallic axial mode helix antenna with optimised truncated hollow cone ground plane in terms of: (a) S_{11} parameter; and (b) total efficiency and radiation efficiency



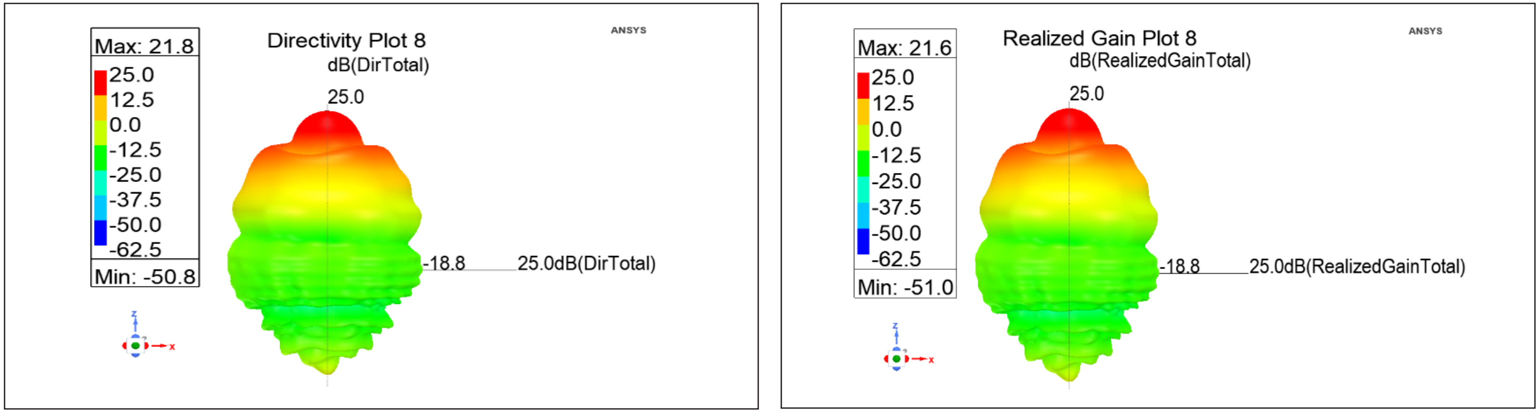
(a) (b)

Figure 7. The CST MWS farfield polar view of: (a) directivity; and (b) realised gain of the proposed metallic axial mode helix antenna with optimised truncated hollow cone ground plane at 0.85 THz



(a) (b)

Figure 8. The Ansys HFSS performance analysis of the proposed metallic axial mode helix antenna with optimised truncated hollow cone ground plane in terms of: (a) S_{11} parameter; and (b) radiation efficiency



(a) (b)

Figure 9. The Ansys HFSS farfield 3D polar view of: (a) directivity; and (b) realised gain of the proposed metallic axial mode helix antenna with optimised truncated hollow cone ground plane at 0.85 THz

Comparison Between CST MWS and Ansys HFSS Results

Figure 10 compares the directivity findings from the CST MWS and the S_{11} parameter (BW) from the Ansys HFSS software of the proposed optimised THz antenna design. With respect to the CST MWS, the average relative difference[1] of the S_{11} parameter and directivity between CST MWS and Ansys HFSS within the 0.5–1 THz range is 5.5% and 0.65%, respectively, signifying a good agreement between the two simulation results. The two simulators' different numerical approaches and mesh structure contributed to the varying outcomes. These variations also match those reported in past literature. Remarkably, both simulation results recorded an FBW of 61.33% within the 0.52–0.98 THz range and a peak directivity of 21.8 dBi at 0.85 THz, which is effective for UWB 6G communication systems.

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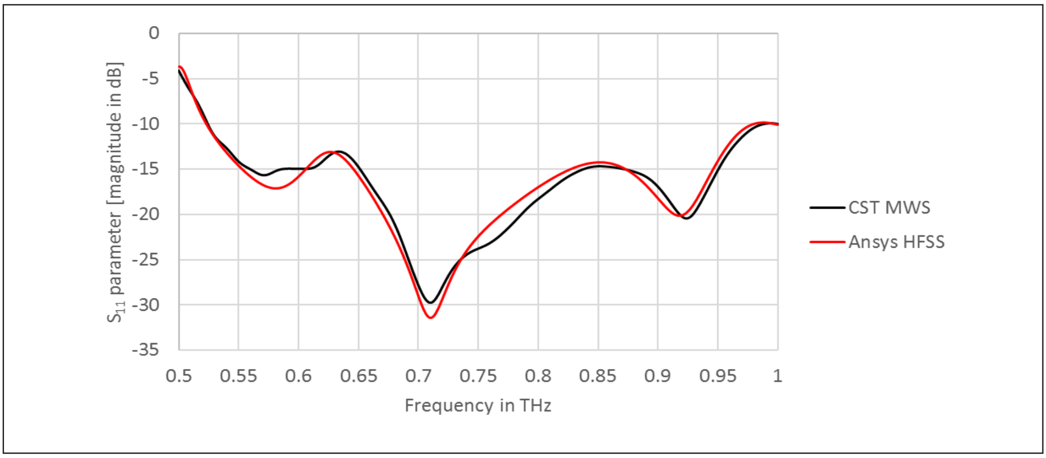
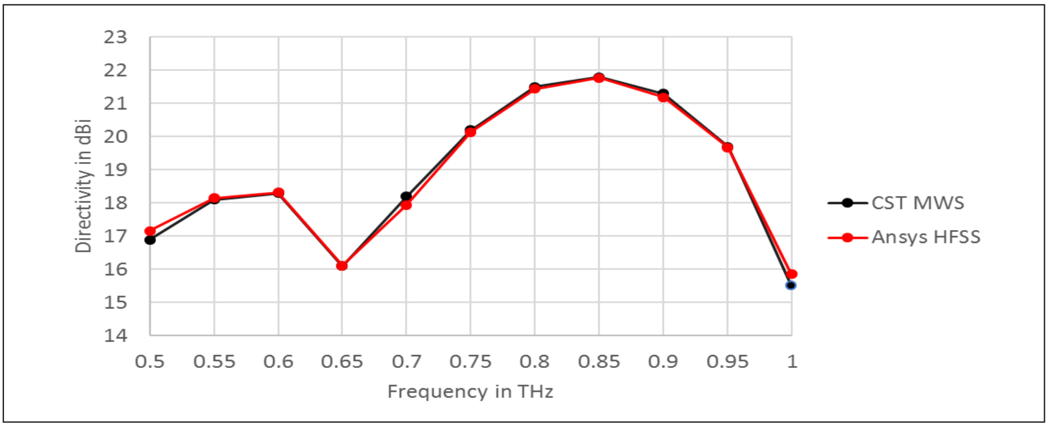
[1] Relative difference (%) = (Ansys HFSS value - CST MWS value / CST MWS value) × 100%



(a)



(b)

Figure 10. Comparison between the Ansys HFSS and CST MWS results of the proposed metallic axial mode helix antenna with optimised truncated hollow cone ground plane in terms of: (a) S_{11} parameter; and (b) directivity

Performance Comparison with Past Literature Studies

Table 3 displays the performance comparison of the proposed optimised THz antenna design in this study to that of currently available THz helix antennas operating at similar frequency ranges in terms of the FBW, directivity, radiation efficiency, physical dimensions, applied antenna design method, and antenna design complexity. It is worth mentioning that there are only a few axial mode helix antenna studies in the 0.5–1 THz frequency band. Comparatively, most existing THz axial mode helix antennas achieved a lower directivity with over 50% FBW (or less) compared to the proposed optimised THz antenna design in this study.

Additionally, the physical antenna dimensions applied in past studies are smaller than that of this study's proposed optimised THz antenna design due to their simple ground plane structure. In contrast, the proposed optimised THz antenna design recorded lower profile helix turns without the ground plane compared to the smallest THz helix antenna dimension (Boudkhil et al., 2019). Therefore, the results suggest that the optimised truncated hollow cone ground plane structure (3D copper) enhanced the helix antenna directivity with a slightly lower FBW in the THz band and large antenna size. Overall, the comparative analysis verified the excellent performance of the newly proposed metallic axial mode helix antenna in the 0.5–1 THz frequency range for potential application in 6G wireless communication systems.

Table 3
Performance comparison of the proposed THz axial mode helix antenna design with other THz axial mode helix antennas

References	Boudkhil et al., 2019	Hajiyat et al., 2021a	Hajiyat et al., 2021c	This work
Frequency range (THz)	0.8 - 1.05	0.52 - 1.03	0.52 - 1.057	0.52 - 0.98
BW % (FBW %)	25	51 (65.40)	53.70 (68.10)	46 (61.33)
Peak directivity, realised gain in dBi (frequency)	-	12.1, 11.8 (1 THz)	13.4, 13 (0.95 THz)	21.8, 21.5 (0.85 THz)
Radiation efficiency (%)	-	90 - 96.92	89.69 - 96.6	87.09 - 95.77
Physical dimensions in mm (width, length, height)	0.07981 × 0.080 × 0.18173	0.40 × 0.40 × 0.329	0.60 × 0.60 × 0.52	1.7 × 1.7 × 1.97 (D_u, D_u, $H_t + T_g$)
Applied antenna design method	10.74 turns of tapered helix antenna with coplanar waveguide	Three-turns of uniform helix antenna with circular ground plane	Five-turns of uniform helix antenna with large circular ground plane	Five-turns of uniform helix antenna with truncated hollow cone ground plane
Antenna design complexity	Higher number of helix turns with a simple ground plane	Low number of helix turns with a simple ground plane	High number of helix turns with a simple ground plane	High number of helix turns with a complex ground plane

CONCLUSION

A high-performance THz metallic axial mode helix antenna with an optimised truncated hollow cone ground plane for 6G wireless communication systems was proposed in this paper. The simulation results show that the optimised copper (annealed) axial mode helix antenna performed well in the 0.52–0.98 THz frequency band with an impedance BW of 0.46 THz and FBW of 61.33%. Additionally, the highest directivity and realised gain recorded were 21.8 dBi and 21.5 dBi at 0.85 THz, respectively. The comparative analysis between the CST MWS and Ansys HFSS showed good agreement, further validating the proposed antenna design. Moreover, the performance comparison of this study shows that the proposed optimised THz antenna design offered an outstanding directivity performance compared to other available THz axial mode helix antennas. In conclusion, the proposed axial mode helix antenna design offers a promising approach for THz 6G wireless applications, including directional UWB communication links, data centre networks, satellite communication, environmental pollution monitoring, augmented reality, and entertainment technology.

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