

MINIATURIZED TERAHERTZ ANTENNA DESIGN BASED
ON SYMMETRIC FRACTAL GEOMETRY FOR SENSING
AND IMAGING APPLICATIONS

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Abstract

Miniaturized terahertz (THz) antennas often face trade-offs between size, bandwidth, and performance, limiting their suitability for integrated high-frequency applications. To address these limitations, this paper proposes a compact microstrip antenna based on a fourth-iteration Sierpinski Carpet fractal applied to both the patch and ground plane. Designed on a polyamide substrate ($\epsilon_r = 4.3$, $\tan \delta = 0.004$) with a footprint of $8 \times 12 \times 1.6 \mu\text{m}^3$, the antenna demonstrates multiband operation at 6.59, 12.49, and 14.42 THz. Simulations using Ansys High Frequency Structure Simulator (HFSS) v15 show return losses ranging from -15.62 dB to -22.61 dB, bandwidths up to 1050 GHz, VSWR below 1.5, and peak gains of 1.99 to 7.25 dBi. The use of symmetric fractal geometries enables enhanced bandwidth and gain in a compact form, making the design suitable for THz sensing, imaging, and on-chip communication.

Key words: fractal antenna, multiband applications, Sierpinski antenna, Sierpinski carpet, terahertz antenna

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1. Introduction. The terahertz (THz) frequency band, spanning approximately from 0.1 to 10 THz, is rapidly gaining prominence due to its unique potential in enabling ultra-fast wireless communication, high-resolution imaging, non-invasive sensing, and advanced medical diagnostics.

Its intrinsic advantages, including large available bandwidth and high data rates, make it a compelling candidate for next-generation communication systems such as 6G. However, the realization of efficient and compact THz antennas presents a formidable challenge due to physical constraints associated with miniaturization, material limitations, and trade-offs between bandwidth, gain, and isolation. Numerous researchers have explored novel antenna designs to address these challenges. KUMAR et al. [1] introduced a compact THz MIMO antenna incorporating a defected ground structure (DGS) to enhance bandwidth. In further studies, AMRAOUI and colleagues developed a dual-band FSS-based metasurface antenna [2], a multiband graphene-loaded photonic crystal design [3], and a high-isolation THz MIMO array [4]. Efforts to miniaturize antennas have also been observed. ABOLADE [5] proposed a multiband miniaturized antenna suitable for wireless body area networks, and KRISHNA et al. [6] implemented a micro-scaled wideband patch antenna using graphene. XIONG et al. [7] proposed a decoupled 2D phased-array antenna with wide-angle scanning capabilities, and LI et al. [8] applied photonic bandgap techniques to achieve high gain and tri-band operation. NASIR et al. [9] introduced a dual-band THz antenna with high gain for 6G use.

Despite these advancements, many existing designs face persistent limitations in achieving a compact footprint while simultaneously delivering wideband, high-gain, and multiband operation. Traditional approaches often fail to fully optimize both the radiating patch and ground structure, limiting performance for on-chip or wearable THz applications. To address these gaps, the present study proposes a novel miniaturized microstrip antenna utilizing a fourth-iteration Sierpinski Carpet fractal, symmetrically applied to both the patch and ground plane. The design leverages the geometric self-similarity of fractals to achieve multiband operation at 6.59, 12.49, and 14.42 THz, with return losses between -15.62 dB and -22.61 dB, and improved gain performance, making it a strong candidate for high-performance, integrated THz systems. The remainder of this paper is structured as follows: Section II details the antenna geometry and materials, Section III presents simulation results and performance evaluation using HFSS v15, and discusses the comparative analysis with recent literature, Lastly Section IV concludes with key findings and future research directions.

2. Antenna design. The proposed terahertz (THz) antenna is designed on a polyamide substrate, selected for its mechanical flexibility and low dielectric loss at high frequencies. The substrate has a relative permittivity (ϵ_r) of 4.3, a loss tangent of 0.004, and a thickness of $1.6 \mu\text{m}$. The antenna is fed by a microstrip line with a width of $0.5 \mu\text{m}$ and a length of $6 \mu\text{m}$, providing appropriate impedance matching and efficient power transfer to the radiating element. The overall layout

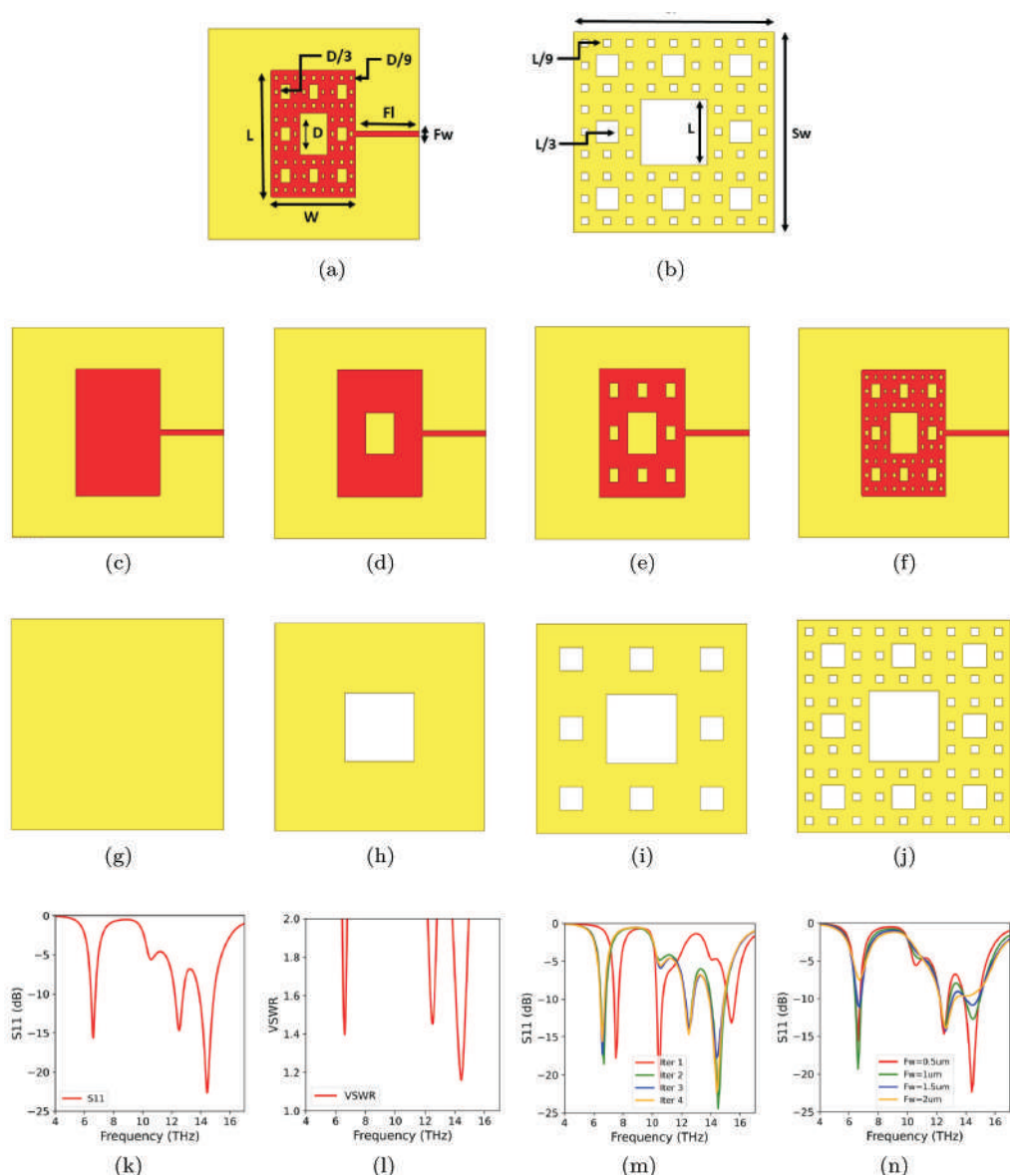


Fig. 1. (a) Top view of the proposed antenna; (b) Bottom view of the proposed antenna; (c–f) Iteration stages of the radiating patch antenna: (c) First iteration; (d) Second iteration; (e) Third iteration; (f) Fourth iteration; (g–j) Iteration stages of the ground plane: (g) First iteration; (h) Second iteration; (i) Third iteration; (j) Fourth iteration; (k) Return loss of the proposed antenna; (l) VSWR of the proposed antenna versus frequency; (m) Return loss of each iteration versus frequency; (n) Effect of feed width on the return loss of the proposed antenna

of the proposed antenna is shown in Fig. 1, where (a) displays the top view and (b) illustrates the bottom view. The evolution of the radiating patch through its fractal iterations is presented in Fig. 1(c)–(f), and the corresponding ground

plane iterations are shown in Fig. 1(g)–(j). Each stage incrementally increases the complexity and performance potential of the antenna.

The antenna is designed and simulated in HFSS v15 using the finite element method (FEM) for accurate electromagnetic analysis. It operates from 4–17 THz, making it suitable for on-body and high-frequency communication systems. Optimized design parameters are summarized in Table 1. The antenna employs a rectangular microstrip patch ($12\text{ }\mu\text{m} \times 8\text{ }\mu\text{m}$) on a polyamide substrate ($\epsilon_r = 4.3$, $h = 1.6\text{ }\mu\text{m}$), ensuring compactness for terahertz applications.

T a b l e 1
Design parameters of the proposed antenna

Parameter	Value (μm)
Substrate width (Sw)	20
Substrate length (Sl)	20
Substrate height (h)	1.6
Feed width (Fw)	0.5
Feed length (Fl)	6
Patch width (W)	8
Patch length (L)	12
Inside distance (D)	4
Inside length (L)	6.66

To enable multiband operation, a fourth-iteration Sierpinski Carpet fractal is applied symmetrically to the patch and ground planes. This self-similar geometry introduces multiple resonant modes, achieving wideband performance while preserving miniaturization. The ground plane initially measures $20\text{ }\mu\text{m} \times 20\text{ }\mu\text{m}$, with dimensions scaled by $\left(\frac{1}{3}\right)^{(n-1)}$ at each fractal iteration. Thus, the dimensions of the patch and ground at iteration n are given by:

$$(1) \quad L_n = L_0 \times \left(\frac{1}{3}\right)^{(n-1)}$$

$$(2) \quad W_n = W_0 \times \left(\frac{1}{3}\right)^{(n-1)}.$$

For the ground:

$$(3) \quad G_n = G_0 \times \left(\frac{1}{3}\right)^{(n-1)},$$

where $L_0 = 8\text{ }\mu\text{m}$ and $W_0 = 12\text{ }\mu\text{m}$ are the initial patch length and width, and $G_0 = 20\text{ }\mu\text{m} \times 20\text{ }\mu\text{m}$ is the initial ground size.

The number of sub-rectangles at iteration n follows a cumulative pattern, where each iteration introduces 8 new sub-rectangles for each existing sub-rectangle from the previous iteration. The total number of sub-rectangles after n iterations is given by:

$$(4) \quad N_n = \sum_{i=0}^{n-1} 8^i.$$

Thus, for each iteration:

- After the first iteration, $N_1 = 1$ sub-rectangle.
- After the second iteration, $N_2 = 9$ sub-rectangles.
- After the third iteration, $N_3 = 73$ sub-rectangles.

3. Results and discussion. The proposed antenna design was simulated using HFSS v15 across a frequency range of 4–17 THz. It features a polyamide substrate with a relative permittivity of 4.3 and a loss tangent of 0.004. To improve bandwidth and introduce multiband characteristics, the geometries of both the patch and the ground plane were iteratively refined using a Sierpinski carpet structure, up to the fourth iteration.

Fig. 1(k) shows the reflection coefficient (S_{11}), with three resonances at 6.59 THz, 12.49 THz, and 14.42 THz, corresponding to return losses of -15.62 dB, -14.66 dB, and -22.61 dB, and bandwidths of 300 GHz, 590 GHz, and 1050 GHz, respectively. The VSWR values in Fig. 1(l) remain below 2 (1.39, 1.45, and 1.16), confirming efficient power transfer and impedance matching. The fourth fractal iteration yields the best performance in terms of bandwidth and return loss (Fig. 1(m)). Feed-width optimization (Fig. 1(n)) identified $0.5 \mu\text{m} \times 6 \mu\text{m}$ as the optimal configuration.

Gain results (Fig. 2(a–c)) show increasing values with frequency, reaching 1.99 dBi, 4.89 dBi, and a peak of 7.25 dBi at the three resonances, attributed to improved current confinement and radiation efficiency. The radiation patterns in Fig. 2(d–f) remain stable and directional, while surface current distributions (Fig. 2(g–i)) highlight strong edge currents that enhance radiative efficiency through the fractal design.

Table 2 summarizes the performance of several reported multiband THz antennas in terms of the number of operating bands, dielectric substrate, gain, impedance bandwidth, and return loss. The majority of designs employ polyamide as the dielectric material, which is favoured for its low loss and compatibility with THz fabrication techniques. Other substrates, such as RO3210 and Duroid 6010, have also been explored but often yield comparatively lower gain.

In terms of the number of bands, earlier works such as [2] and [3] demonstrated dual-band operation, while [5] and [8] achieved triple-band performance with moderate bandwidths. Notably, the design in [6] provides the largest single-band bandwidth (450 GHz), though at the expense of relatively low gain (3.47 dBi).

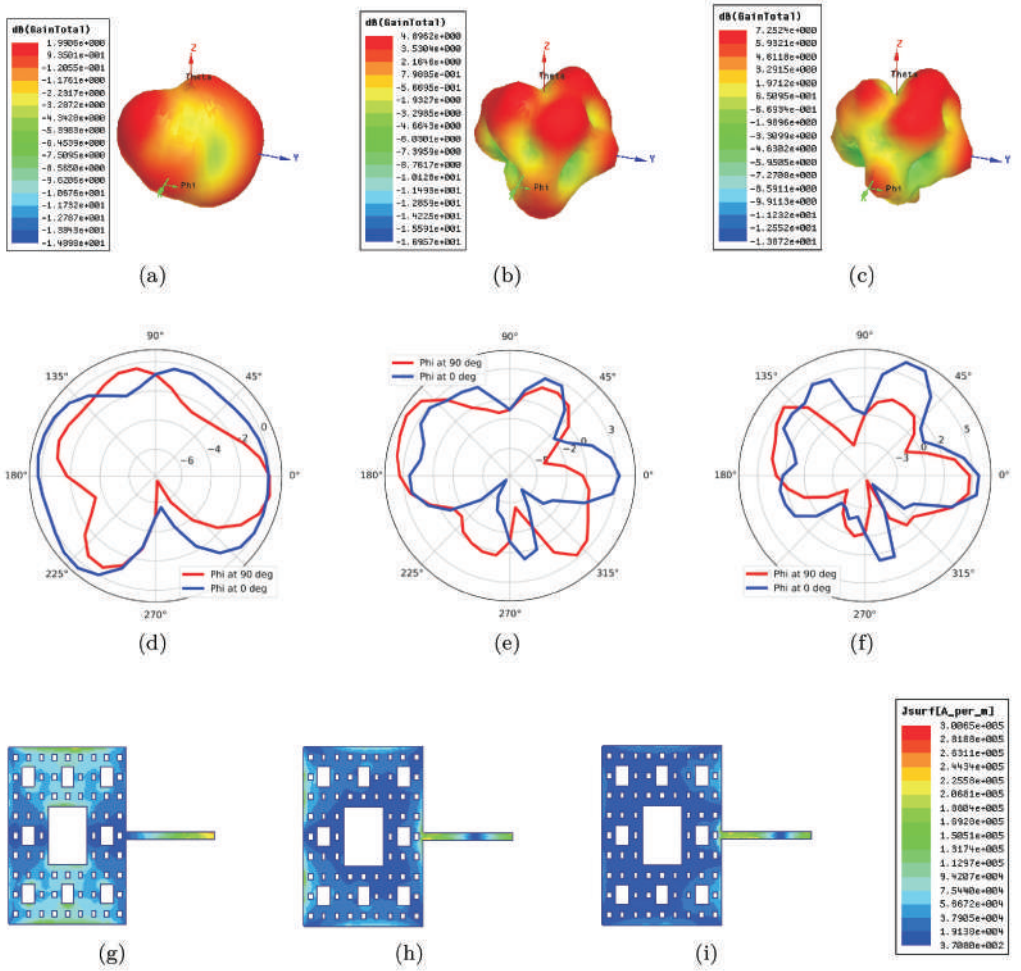


Fig. 2. (a–c) Gain characteristics of the proposed antenna at (a) 6.59 THz, (b) 12.49 THz, and (c) 14.42 THz. (d–f) Radiation pattern characteristics of the proposed antenna at (d) 6.59 THz, (e) 12.49 THz, (f) 14.42 THz. (g–i) Current distribution of the proposed antenna at (g) 6.59 THz, (h) 12.49 THz, (i) 14.42 THz

The proposed antenna (Prop) stands out by achieving triple-band operation with a remarkably wide total bandwidth of 1050 GHz, significantly exceeding those reported in prior studies. While its gain (7.25 dBi) is comparable to other polyamide-based designs [2, 3, 8], the improvement in bandwidth highlights its potential for broadband THz applications such as high-capacity communication and sensing. In terms of return loss, the proposed design achieves acceptable values (−15 dB, −14 dB, −22 dB), though some prior works [3, 8] reported deeper nulls, indicating better impedance matching at certain resonances.

T a b l e 2

Comparison of reported multiband THz antennas

Ref	No. bands	Dielectric material	Gain (dBi)	BW (GHz)	R-loss (dB)
[2]	2	Polyamide	8.36	50	−35, −17
[3]	2	Polyamide	9.45	110	−37, −41
[5]	3	RO3210	5.5	310	−28, −12, −13
[6]	1	Duroid 6010	3.47	450	−20
[8]	3	Polyamide	7.66	25	−31, −19, −64
Prop	3	Polyamide	7.25	1050	−15, −14, −22

4. Conclusion. This work presented a fourth-order Sierpinski Carpet fractal antenna for multiband THz applications. The design achieved resonances at 6.59 THz, 12.49 THz, and 14.42 THz, with return losses of −15.62 to −22.61 dB and a peak gain of 7.25 dBi. Symmetric fractal structures on both patch and ground enhanced bandwidth and radiation while maintaining compact size. The antenna shows strong potential for sensing and imaging applications, with future work focusing on experimental validation.

REFERENCES

- [1] KUMAR P., V. SIVAKUMAR, V. RAO et al. (2024) A defected ground structure based ultra-compact wider bandwidth terahertz multiple-input multiple-output antenna for emerging communication systems, *Heliyon*, **10**(17), e36842.
- [2] AMRAOUI Y., I. HALKHAMS, R. EL ALAMI et al. (2025) Terahertz dual-band antenna design with improved performances using FSS-based metasurface concept for wireless applications, *Scientific African*, e02566.
- [3] AMRAOUI Y., I. HALKHAMS, R. EL ALAMI et al. (2024) A new approach to designing a multiband antenna using photonic crystals and load graphene for terahertz application, *Results in Engineering*, **22**, 102327.
- [4] AMRAOUI Y., I. HALKHAMS, R. EL ALAMI et al. (2024) High isolation MIMO antenna array for multiband terahertz applications, *Results in Engineering*, **23**, 102842.
- [5] ABOLADE J. O. (2023) Miniaturized multiband antenna for terahertz applications in wireless body area network, *Results in Optics*, **10**, 100340.
- [6] KRISHNA C. M., T. ISLAM, N. SUGUNA et al. (2023) A micro-scaled graphene-based wideband (0.57–1.02 THz) patch antenna for terahertz applications, *Results in Optics*, **12**, 100501.
- [7] XIONG B., W. XIE, Y. ZHU (2024) Designing a Novel THz Band 2-D Wide-Angle Scanning Phased-Array Antenna Based on a Decoupling Surface, *Appl. Sci.*, **14**(19), 8618.

- [8] LI G., C. HUANG, R. HUANG et al. (2024) Design of a high-gain and tri-band terahertz microstrip antenna using a polyimide rectangular dielectric column photonic band gap substrate, *Photonics*, **11**(4), 307.
- [9] NASIR N., A. AZZOUZ, H. AL HAMADI (2024) High-gain dual-band terahertz antenna using polyimide for 6G applications. In: 2024 IEEE Future Networks World Forum (FNWF), 687–691.

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