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Design and Fabrication of a Transparent Screen-Printed Decagonal Fractal Antenna Using Silver Nanoparticles

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Abstract

This study presents a compact, wideband fractal antenna fabricated using silver nanoparticles (AgNPs) and screen-printing technology. The antenna consists of a decagonal monopole patch and a mesh ground plane, both printed on a transparent polyethylene terephthalate (PET) substrate. The proposed antenna has a compact size of $18 \times 16 \times 0.55 \text{ mm}^3$, achieved by stacking two PET layers joined using double-sided tape. The antenna covers both C- and X-bands, with measured optical transmittance of 68.1% and radiation efficiency of 72%. The simulated -10 dB bandwidth (without bending) spans 4–10.8 GHz and 11.2–12.5 GHz, while the measured -10 dB bandwidth is 3.8–11.2 GHz without bending, 3–11.4 GHz at 30° bending, and 3–11.2 GHz at 45° bending, confirming that there was stable performance under flexure. The conductive patterns were formed using silver nanoparticle paste with a sheet resistance of $0.2 \Omega/\text{sq}$, followed by annealing in a vacuum oven at 140°C for 20 min. The proposed antenna was tested under 30° and 45° bending, and the measured S_{11} remained stable, confirming flexibility. The use of a flexible, optically transparent PET substrate enables installation on curved or see-through surfaces. Combining compact size, wideband performance, cost-effective fabrication, and optical transparency, the antenna demonstrates strong potential for application in X-band radar, C-band satellite communications, and S-band Wi-Fi.



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Keywords: transparent antenna; broadband antenna; fractal antenna; screen printing; metal mesh

1. Introduction

The rapid growth of wireless communication technologies in industrial automation, healthcare, transportation, and telecommunications has created a demand for antennas that exceed conventional performance criteria [1]. Modern applications require antennas that are mechanically flexible, optically transparent, and esthetically unobtrusive, which presents challenges for traditional designs [2]. The Internet of Things (IoT), with its forecast of billions of interconnected devices, has further intensified the need for innovative antenna solutions [3]. Such requirements are driving the development of antennas that can be integrated invisibly into everyday objects, buildings, vehicles, and clothing [4].

Fractal geometry offers a promising solution due to its inherent self-similarity, which enables multiband operation [5]. Mathematically described by Mandelbrot in the 1970s, fractals are characterized by self-similarity across scales, space-filling properties and non-integer dimensions [6]. Self-similarity allows a single antenna to resonate at multiple

frequencies determined by the fractal's scaling factor [7], while space-filling capabilities enable electrically large antennas to be realized within compact footprints [8,9]. Classical fractal antenna designs, such as the Koch snowflake, Sierpinski gasket, Minkowski loop, and Hilbert curve, have demonstrated size reductions of up to 90% without compromising electrical performance [10]. Werner et al. reported that fractal geometries naturally provide impedance matching over wide frequency ranges, reducing or eliminating the need for complex matching networks [11].

Recent advances in fractal antenna design have significantly improved both performance and manufacturability. Choi et al. developed screen-printed metamaterial absorbers based on fractal metal mesh structures that offer both optical transparency and flexibility for stealth applications [12]. Bark et al. presented optically transparent, dual-band metamaterial absorbers using screen-printed silver nanowire second-order cross-fractal structures, demonstrating the potential of combining fractal geometry with advanced printing techniques [13]. Hybrid approaches have also shown promise. Vallappil et al. designed Minkowski–Sierpinski fractal antenna arrays for next-generation wireless systems [14], while Benkhadda et al. achieved tri-wideband operation using Sierpinski hexagonal-shaped fractal antennas for wireless communication [15].

Traditional conductors, such as copper and aluminum, lack the optical transparency required for modern applications [16,17]. Various transparent antenna designs have been investigated to address this limitation, including a monopole antenna fabricated by chemical etching [18], MXene-sprayed dipole [19], and RF sputtering Monopole antennas [20,21]. Additionally, a Cu-meshed dipole antenna was developed using photolithography [22]. Mesh-based structures are frequently employed to enhance transparency, as demonstrated in dual dipole antennas [23] and printed planar inverted-F antenna [24].

Indium tin oxide (ITO) has been widely used for transparent antennas, but it suffers from several limitations, including brittleness, restricted mechanical flexibility, high production costs due to the scarcity of indium and relatively low electrical conductivity compared to metals [25]. To overcome these challenges, recent research has explored alternative transparent antenna technologies. Nguyen et al. demonstrated transparent and flexible patch antennas based on metal mesh films (MMF) for conformal Wi-Fi 6E applications, achieving dual-band operation while maintaining mechanical flexibility [26]. Advanced antenna designs have also incorporated metamaterial concepts; for example, Khan et al. showed that epsilon-near-zero (ENZ) metamaterials can enhance dual-band antenna performance while preserving radiation pattern stability [27].

Silver nanoparticles (AgNPs) have emerged as a promising alternative, offering electrical conductivity close to that of bulk silver, tunable transparency controlled by deposition parameters, excellent compatibility with flexible polymer substrates and broad fabrication adaptability [28]. AgNP-based inks enable low-temperature processing, making them compatible with temperature-sensitive materials. Their use in inkjet and aerosol-jet printing allows precise patterning without the need for expensive masks. AgNPs also support scalable manufacturing for large-area transparent electronics. Exposure of silver nanoparticles to water and UV light releases dissolved silver ions, both of which are highly toxic, thereby limiting the applications of silver nanoparticle inks [29]. Additionally, surface treatments can enhance their chemical stability and adhesion, ensuring long-term reliability in flexible and conformal antenna applications.

Printed antennas differ from conventional designs by employing additive manufacturing techniques such as screen printing, inkjet printing and gravure printing to deposit conductive materials directly onto substrates [30,31]. Traditional antennas, in contrast, typically use subtractive methods such as photolithography, metal deposition and chemical etching [31]. Silver nanowire inks can achieve optical transparency as high as 83% while

maintaining adequate RF performance. Screen printing is particularly advantageous, as it can deposit thick, low-resistance conductive layers in a single pass, making it ideal for conformal and flexible antennas on substrates such as polyethylene terephthalate (PET) [32], polyimide and paper. Moreover, screen printing with silver nanoparticle inks offers scalability, cost-effectiveness and compatibility with roll-to-roll processing, enabling mass production [33].

Figure 1 presents a comprehensive comparison between traditional manufacturing processes and the printing process. The printing approach offers a simple and cost-effective method to fabricate low-profile, transparent, and flexible antennas using conductive AgNP materials.

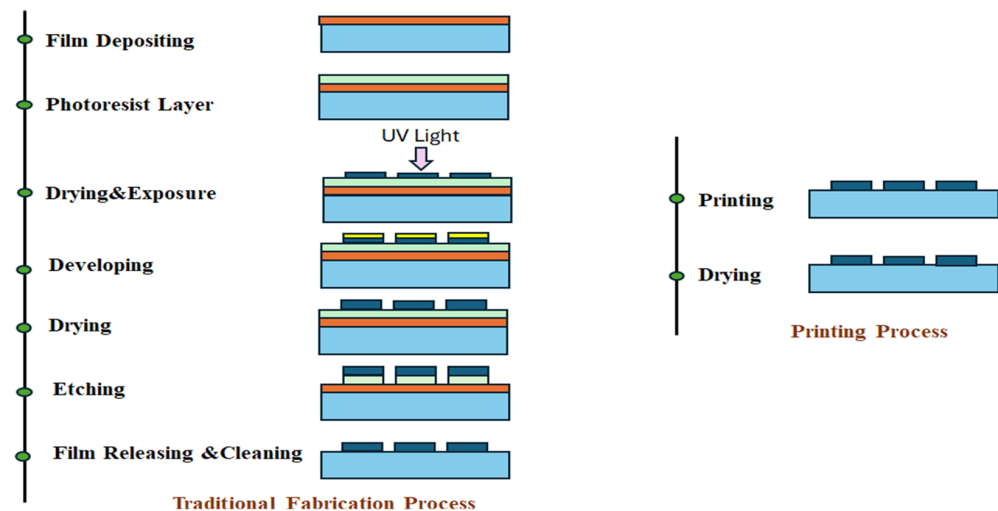


Figure 1. Traditional manufacturing processes and printing techniques.

In this work, we present a compact, wideband decagonal fractal antenna fabricated via screen-printing technology. The conductive pattern uses silver nanoparticles (Gap) with a sheet resistance of $0.2 \Omega/\text{sq}$, providing excellent conductivity while preserving optical transparency. Compared to conventional circular or square fractal shapes, the decagonal geometry offers greater symmetry and optimized current distribution, resulting in enhanced bandwidth and radiation efficiency. Both the ground and radiator were systematically transitioned from solid to mesh configurations, yielding a hybrid mesh-ground design that reduces weight and improves optical performance without degrading RF characteristics. Comparative simulations confirm that this decagonal hybrid design consistently outperforms traditional fractal geometries in bandwidth and efficiency.

Additionally, screen printing enables thick, low-resistance conductive layers in a single pass, making it well-suited for conformal and flexible antennas on PET substrates. As PET is lightweight and flexible, and the fabricated antenna retained this property after printing with mechanically stable AgNP layers, the proposed design may be considered a potential candidate for transparent and flexible applications.

2. Antenna Design and Analysis

2.1. Geometric Structure and Substrate Configuration of the Transparent Fractal Antenna

Figure 2 shows the proposed transparent fractal antenna, modelled in HFSS (ANSYS HFSS 17.2) with a 3D-integrated female SMA connector. The initial design was evaluated using a $50\text{-}\Omega$ wave port to verify impedance matching and establish baseline performance. For practical implementation, the wave port was replaced with a 3D SMA connector model. The front view of the proposed fractal antenna is illustrated in Figure 2b while the side view is depicted in Figure 2c.

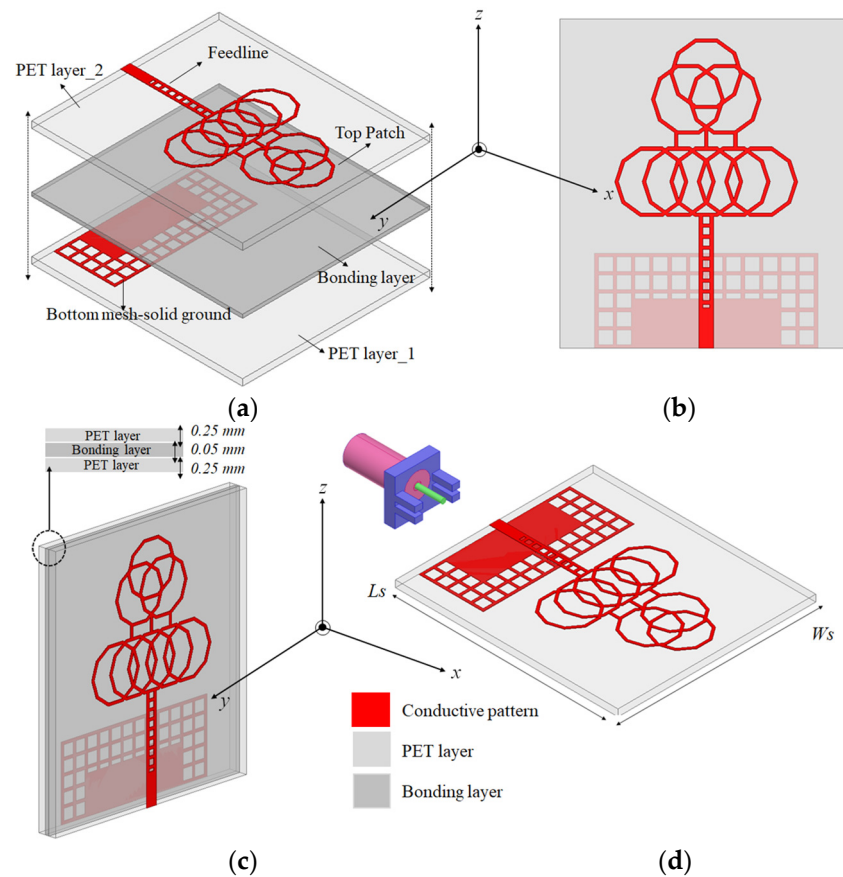


Figure 2. Exploded view of the proposed transparent fractal antenna substrate configuration: (a) two PET substrate layers with bonding layer; (b) front view; (c) side view; and (d) complete antenna stack-up showing the decagonal fractal patch and feedline on PET layer_2 and the mesh-solid ground plane on PET layer_1. The structure integrates the optimized SMA model.

The inner conductor length was optimized according to the manufacturer's datasheet, while the connector body and terminal geometries were refined to account for fabrication tolerances and to ensure reliable electrical contact. A solid ground area was included beneath the SMA interface to enable the secure application of conductive paste during assembly. The antenna has a compact layout with a substrate length (L_s) of 18 mm, a width (W_s) of 16 mm, and an overall thickness of 0.55 mm. It consists of two PET layers, each 0.25 mm thick, with a relative permittivity of dielectric constant 3.00 and a loss tangent of 0.02. The layers are bonded with a 0.05 mm-thick double-sided adhesive film with permittivity of 3.1, and loss tangent of 0.02.

As shown in Figure 2a, the top PET layer supports the radiating decagonal fractal geometry and feedline, while the bottom PET layer contains a hybrid mesh-solid ground plane designed to balance optical transparency with electromagnetic performance. The adhesive bonding layer between the PET sheets ensures both mechanical stability and maintains dielectric continuity. This multilayer transparent configuration combines flexibility, optical clarity and RF efficiency, making it suitable for flexible electronics, conformal surfaces, and glass-integrated wireless systems. Figure 2d illustrates the complete antenna stack-up, with the decagonal fractal patch and feedline on the top PET layer (layer_2) and the mesh-solid ground plane on the bottom PET layer (layer_1).

2.2. Geometric Structure

The antenna design starts with a solid circular patch, which is first converted into a solid decagon with a solid feed line. To improve optical transparency, this decagon is then

integrated with a hybrid mesh–solid feed line, combining conductive paths with open areas. The decagonal element is subsequently replicated laterally to form three, and then five, parallel elements connected by the same hybrid feed line, creating a wider base for current distribution. In the next stage, three additional solid decagons are placed above the five-element base, followed by another three decagons connected with uniform 0.2 mm-wide lines and a central decagon at the top. This layered structure increases the conductive area, providing continuous paths for surface currents while maintaining symmetry. Finally, to further enhance optical transparency, the solid decagons are converted into mesh structures by removing their inner regions, as illustrated in Figure 3. This stepwise design approach balances structural symmetry, optical transparency, and optimized antenna performance.

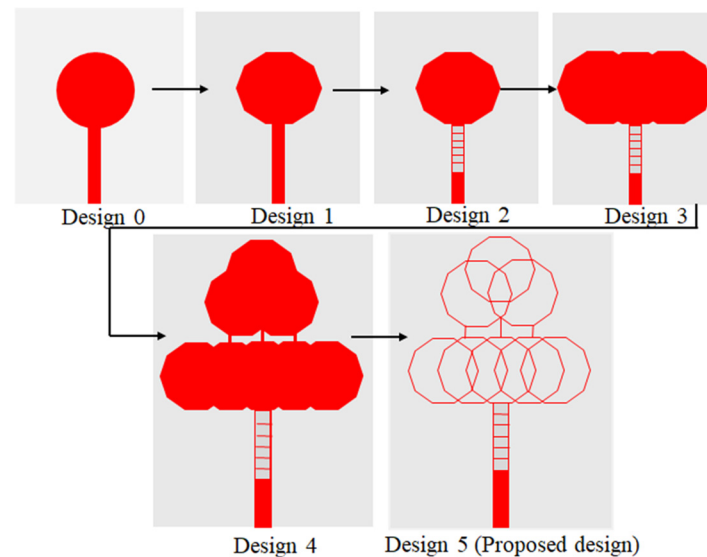


Figure 3. Design evolution of the proposed transparent fractal antenna.

Figure 4a illustrates the geometric layout of the proposed transparent fractal antenna, which employs a decagonal design connected iteratively via linking lines. The design process begins with a solid decagon having a side length of $a = 1.12$ mm, a radius of $r = 2$ mm and an internal angle of $\theta = 36^\circ$, integrated with a complete solid feedline, as shown in Figure 4b. In the next stage, a smaller decagon with a radius of 1.8 mm is subtracted from the initial design, producing a line-defined decagon with a line width of $Lw = 0.2$ mm. This configuration ensures a compact footprint and improved transparency while maintaining good electromagnetic performance, forming the basis of the proposed fractal mesh transparent antenna. The feedline consists of two segments: a solid section and a mesh section, with lengths of $L_{fs} = 4$ mm and $L_{ms} = 4$ mm, respectively, as shown in Figure 4c. The solid feed section is designed to ensure accurate simulation under real fabrication conditions, particularly when integrating the SMA connector. The mesh feed is constructed using square unit cells of $x = y = 0.4$ mm, each with a sideline width of 0.2 mm, resulting in a total feedline width of $W_{fs} = 0.8$ mm as shown in Figure 4c. This hybrid feedline connects to the main radiating structure, which consists of interconnected decagonal elements.

The antenna also incorporates a compact hybrid ground plane, divided into a solid region and a mesh. The dimensions of these sections, particularly their length and width, play a critical role in determining the operating bandwidth and impedance matching of the antenna. Figure 4d shows the geometric layout of the proposed fractal antenna's hybrid ground structure. The solid ground section, with a length of $L_{gs} = 8.2$ mm and a width of $W_{gs} = 3.2$ mm (total area 26.24 mm²), was optimized to securely accommodate the SMA connector, which is attached using conductive epoxy during fabrication. Although

non-transparent, this section was included in simulations to ensure accurate performance prediction. The remaining mesh ground section measures $L_g = 12.2$ mm in length and $W_g = 5.2$ mm in width, with mesh regions formed by square unit cells of $x = y = 0.8$ mm at both ends, balancing transparency with electromagnetic performance.

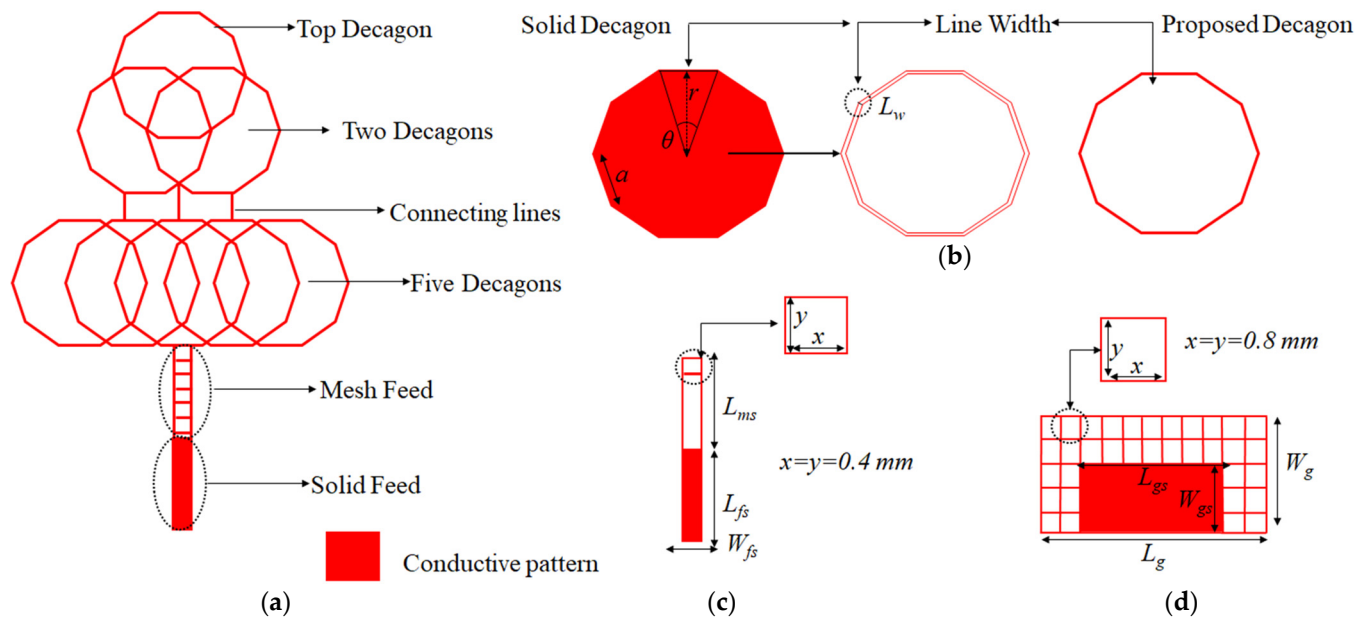


Figure 4. Geometric layout of the proposed transparent fractal antenna: (a) overall antenna structure featuring interconnected decagons fed by a hybrid feedline; (b) evolution of the decagonal geometry from a solid to a line-defined structure; (c) hybrid feedline with solid and mesh segments; and (d) hybrid ground plane combining mesh and solid sections with specified unit cell dimensions.

3. Results and Discussion

Figure 5 illustrates the simulated reflection coefficient (S_{11}) for different solid decagonal radiator configurations of the proposed antenna. Initially, a single circular radiator and a solid decagon radiator (Designs 0 and 1), each with identical dimensions and a solid feedline, exhibit a narrowband response centred at 12 GHz. A similar response is observed when using a hybrid feedline (Design 3), as shown in Figure 5a. Introducing three interconnected solid decagons with a hybrid feedline produces dual-band performance across 4.7–6.5 GHz and 10.8–13.7 GHz. Extending the structure by adding three more connected solid decagons (Design 4) broadens the operating bandwidth to 3.8–8.8 GHz, with a secondary resonance at 12 GHz. However, due to the opacity of solid structures, a mesh-based radiator (Design 5) was proposed by removing solid regions from Design 4 to improve transparency while maintaining wideband performance. The simulated realized gain of all designs is presented in Figure 5b for $\varphi = 0^\circ$ and $\theta = 90^\circ$. Among the designs, Design 4 achieves the highest simulated realized gain across the operating bandwidth.

Figure 6a presents the simulated reflection coefficient (S_{11}) for various design stages of the proposed mesh-based decagonal antenna (Design 5). The antenna employs interconnected decagons as radiating elements. Figure 6a shows the complete decagonal mesh structure, which achieves broadband impedance matching. To evaluate the impact of geometric variations, several configurations are shown in Figure 6b. Removing the top decagon (Design 5-5) results in a -10 dB bandwidth from 4 to 8 GHz with a peak reflection of -25 dB. Connecting the top three decagons to the main structure via a single central bridge (Design 5-4) introduces an additional band between 8 and 11 GHz, although the reflection coefficient at 8 GHz remains close to -10 dB. Adding two parallel bridges enhances performance, resulting in a simulated -10 dB impedance bandwidth of 4–10.8 GHz.

and 11.2–12.5 GHz, with strong resonances at 6.5 GHz (−28 dB), 9.8 GHz (−53 dB), and 12 GHz (−20 dB), confirming effective broadband operation.

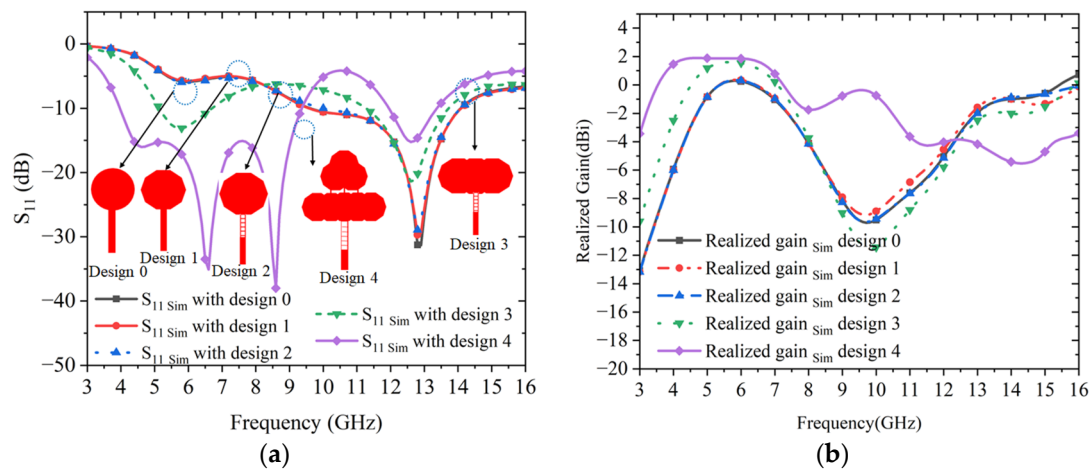


Figure 5. Simulated S_{11} of various design stages of the proposed fractal antenna: (a) S_{11} for solid antenna geometries (Design 0 to 4); (b) simulated realized gain for Design 0 to 4.

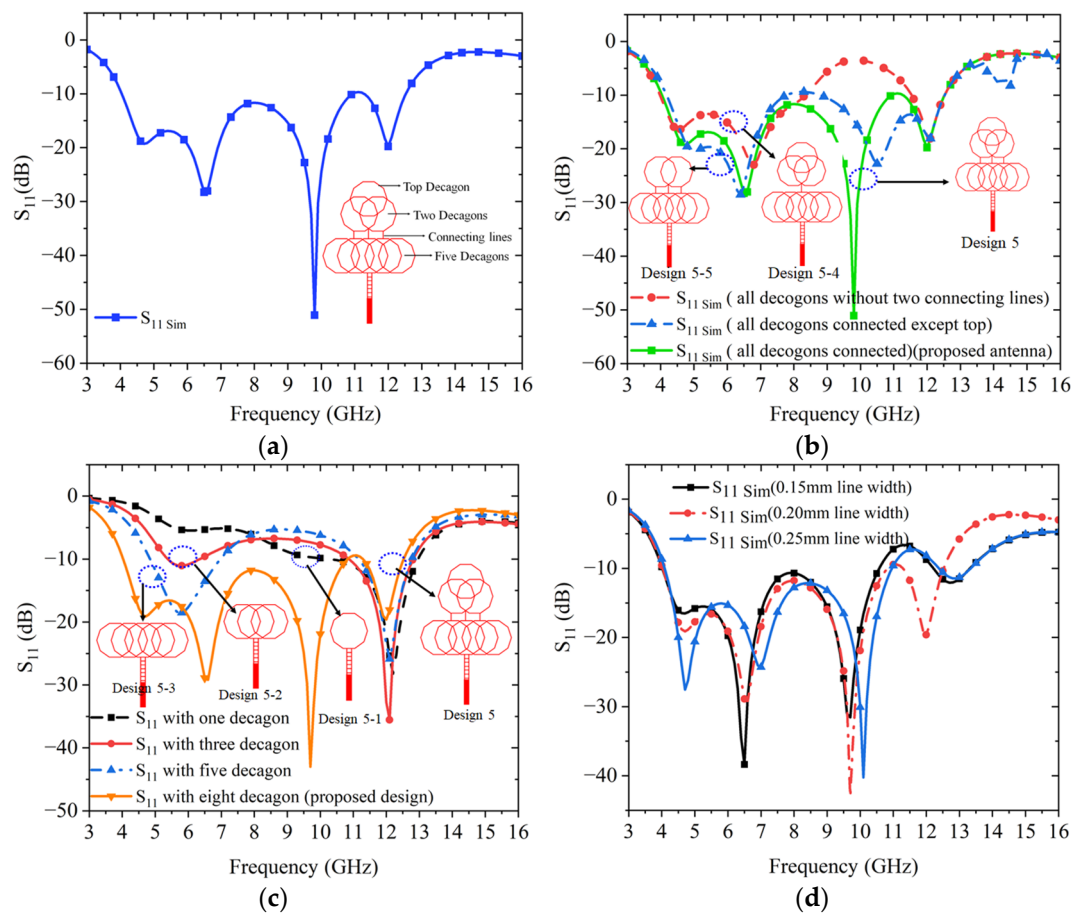


Figure 6. Simulated S_{11} of the proposed transparent fractal antenna at different design stages: (a) S_{11} for the complete decagonal antenna geometry. (b) S_{11} for variations in decagonal geometry and (c) S_{11} for different decagonal antenna configurations. (d) S_{11} of the proposed transparent fractal antenna with different line widths (Lw).

Figure 6c illustrates the design evolution. The initial design (5-1), featuring a single central decagon fed by a hybrid line, exhibited monopole-like behaviour with a resonance

near 12 GHz. Adding two side decagons (Design 5-2) improved impedance matching, while extending the structure to five side-by-side decagons (Design 5-3) produced dual-band operation from 4.5 to 7.6 GHz and from 10.3 to 13 GHz. The final design (Design 5) incorporates three additional interconnected decagons above the five-element base, achieving a wideband response with a simulated -10 dB impedance bandwidth of 4–10.8 GHz and 11.2–12.5 GHz. We found that increasing the number of top decagons with connecting lines broadened the bandwidth; further additions were limited by the available area on the PET substrate (18×16 mm). The step-by-step increase in bandwidth results from the self-similar arrangement of the antenna units. Each new unit introduces extra resonances, and the interaction between these resonances broadens the overall impedance bandwidth.

As shown in Figure 6d, a line width of 0.20 mm provides a wider impedance bandwidth compared to 0.15 and 0.25 mm. Although the 0.25 mm width also achieves good bandwidth, fabrication tolerances can lead to an increase in the actual printed width, thereby reducing optical transparency. Conversely, a 0.15 mm width presents practical difficulties due to the challenges of fabricating precise metal masks and achieving accurate alignment during manual screen printing. Considering these factors, a 0.20 mm line width was selected for the entire antenna structure, including both the radiating patch and the ground plane.

Figure 7a shows the ground plane configuration of the proposed transparent fractal antenna. To maintain optical transparency while ensuring RF performance, the ground plane is divided into two functional regions: a solid section for electrical continuity and mesh sections to enhance transparency. Both regions are optimized for practical integration with an SMA connector. Simulations revealed that using only the solid ground with the full eight-decagon geometry resulted in poor impedance matching and limited bandwidth. Adding mesh extensions to the left and right of the solid ground shifted the resonant band to 4–13 GHz based on -9 dB line, although the improvement in impedance matching was modest. In the final design iteration, a mesh section was also added above the solid ground region. This configuration significantly enhanced impedance matching, achieving a broad operating bandwidth from 4 to 13 GHz (FWB 105%).

The final antenna design employs a hybrid ground plane comprising meshed and solid regions. The mesh lines are maintained at a width of 0.2 mm, identical to that of the radiating element, allowing a unified mask layout for both ground and patch layers during the screen-printing process. Figure 7b presents a parametric analysis of the mesh decagon radius (r), showing that increasing (r) from 2 to 4 mm shifts the operational band to lower frequencies. Among the tested values, $r = 2$ mm offers superior impedance matching and a wider bandwidth for the full fractal decagon geometry while maintaining compact substrate dimensions. Figure 7c shows that the decagonal mesh geometry of the patch provides a wider bandwidth response compared to the circular, pentagonal, and dodecagonal mesh geometries.

3.1. Fabrication of the Proposed Antenna

The fabrication of the low-profile, transparent and wideband fractal antenna was carried out using commercial AgNP ink (Silver Electronic Paste, DM_SIP-2006) (DYCOTEC Materials, Calne, UK) printed on 0.25 mm-thick PET substrates to achieve the required optical transparency and flexibility. The screen-printing process employed a high-resolution 325-threads-per-inch polyester mesh screen. Strict cleaning protocols were maintained throughout the manufacturing process to ensure high print quality. Benzyl alcohol and ethanol were used as cleaning agents for the screen-printing mask. Benzyl alcohol served as the primary solvent due to its effectiveness in dissolving organic residues, while ethanol

was used for the final rinse to remove any remaining traces. A schematic of the complete screen-printing process is shown in Figure 8.

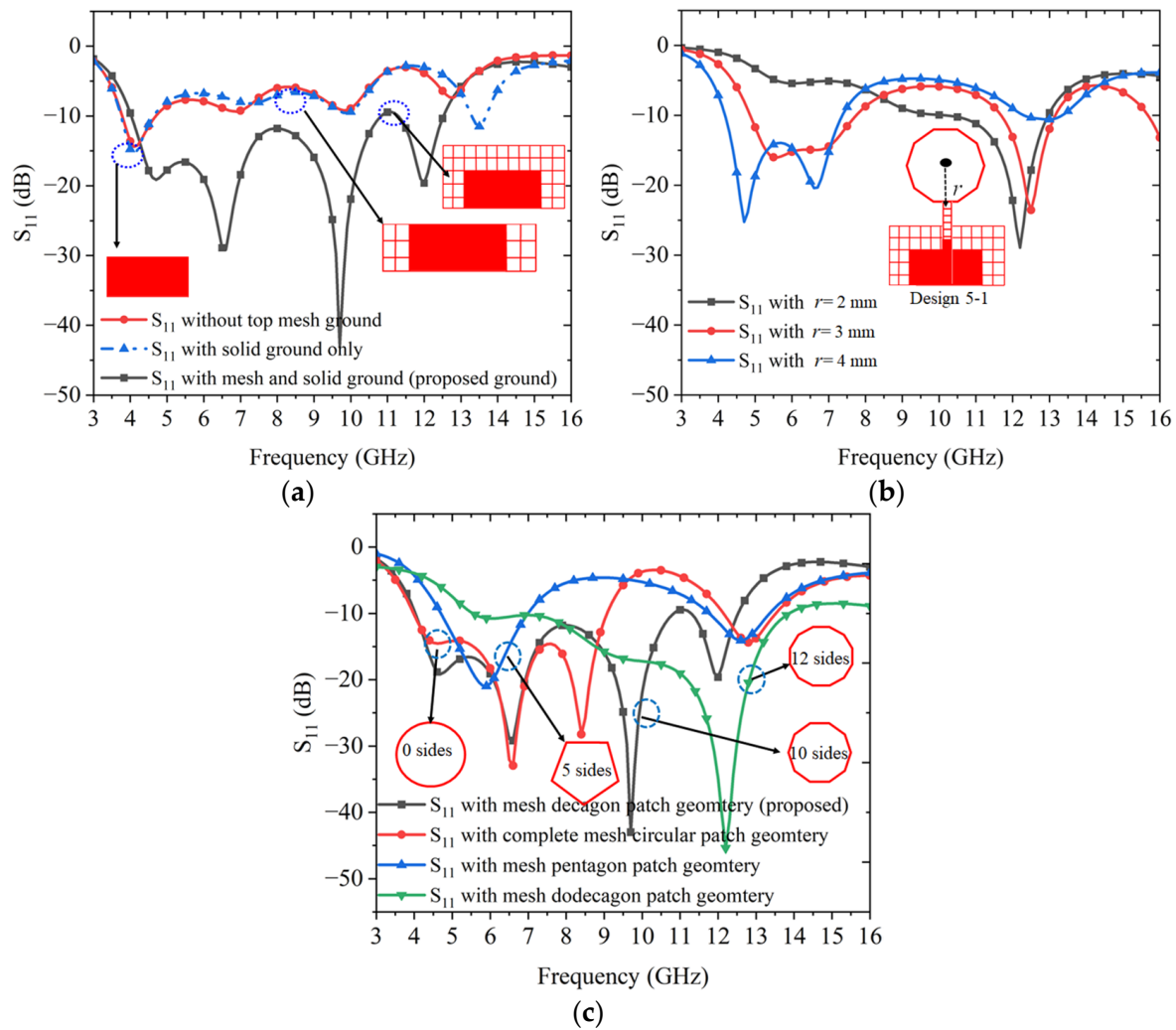


Figure 7. Simulated S_{11} of the proposed transparent fractal antenna: (a) S_{11} for different ground plane configurations. (b) S_{11} for different decagon radii. (c). S_{11} of the proposed antenna with different fractal geometries.

The decagonal monopole patch and mesh ground plane were designed in HFSS simulation software, with the PET substrate properties set to $\epsilon_r = 3.02$ (dielectric constant) and $\tan \delta = 0.02$ (loss tangent). Fabrication was performed using an auto-align screen printer (SJ-7320A). The HFSS antenna structure was transferred to the metal screen via photolithographic emulsion, and silver nanoparticle ink was deposited onto the PET substrate through the screen frame under precisely controlled printing parameters. Following deposition, the printed patterns were thermally cured at 140 °C for 20 min in a heating oven to improve the conductivity of the mesh pattern. The final printed structure consisted of silver nanoparticle conductive lines with a linewidth (Lw) of 0.2 mm and a spacing of 0.8 mm, offering an optimal balance between optical transparency and electrical conductivity for the antenna application.

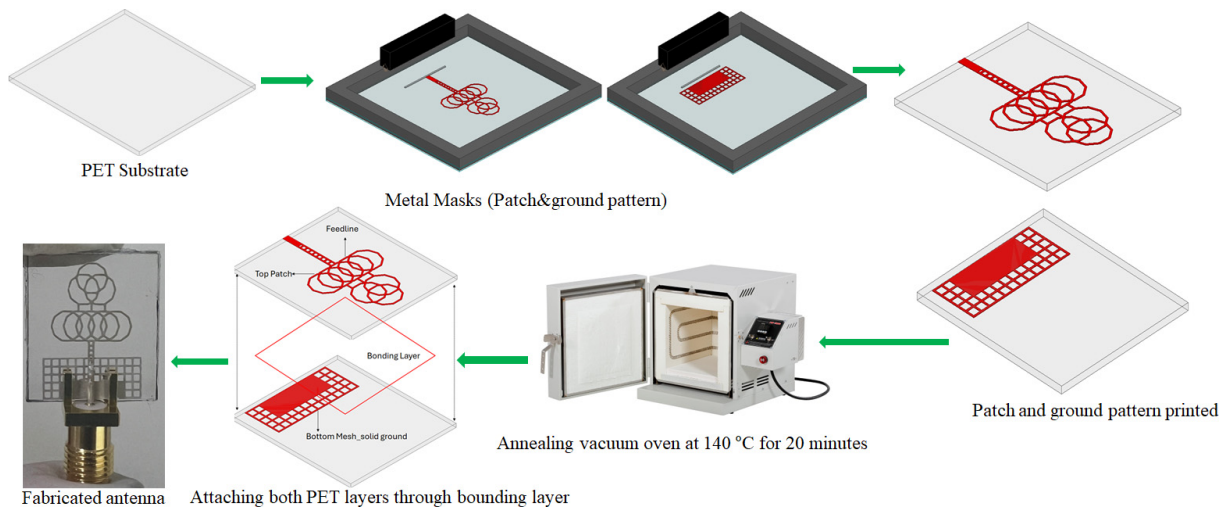


Figure 8. Schematic diagram of the antenna fabrication method.

3.2. Measurement Results of the Proposed Antenna

Figure 9a compares the simulated and measured S-parameters of the proposed antenna. The simulated -10 dB impedance bandwidth is 4–10.8 GHz and 11.2–12.5 GHz, while the measured bandwidth is 3.8–11.2 GHz without bending, 3–11.4 GHz at 30° bending, and 3–11.2 GHz at 45° bending, confirming stable performance. Figure 9b shows the antenna response under different bending angles, and Figure 9c depicts the antenna in bent configurations.

Figure 10a compares the simulated and measured realized gain in H-plane ($\theta = 90^\circ$). The measured gain shows fluctuations and drops below -10 dBi at higher frequencies, highlighting discrepancies due to fabrication tolerances and material imperfections. Figure 10b shows the radiation efficiency, with simulations consistently above 95%, while measurements vary between 40% and 70% and decline noticeably above 9 GHz. The observed discrepancies are mainly attributed to three fabrication-related factors: (1) SMA leg length; during soldering, the legs extended close to the antenna patch and ground, altering the impedance and performance; (2) SMA connector pin spacing; its 1.2 mm spacing exceeded the 0.55 mm substrate thickness, requiring extra silver paste that expanded the solid metallic area at the ground and feedline; and (3) printed line width increase; from 0.20 mm to 0.26 mm (Figure 11) due to fabrication tolerances, which modified the current distribution and overall antenna behaviour.

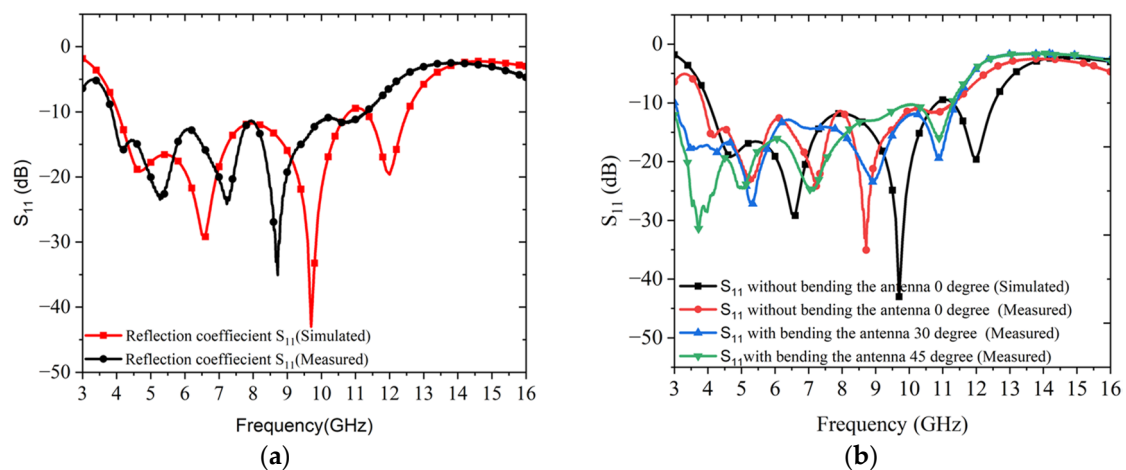


Figure 9. Cont.

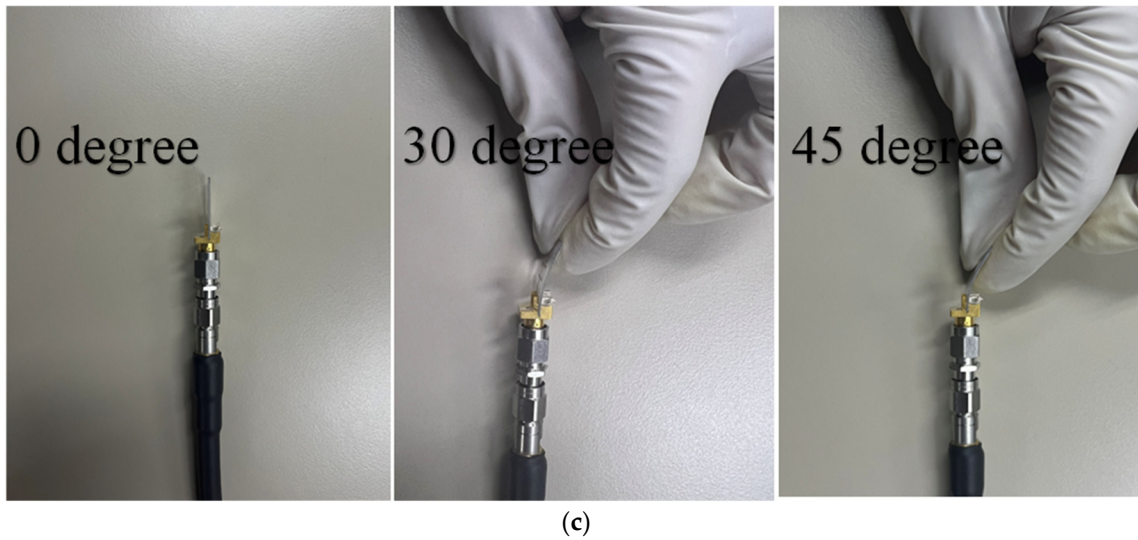


Figure 9. (a) Simulated and measured S_{11} comparison of the proposed antenna. (b) S_{11} of the antenna for different bending angles. (c) Proposed antenna under different bending angles.

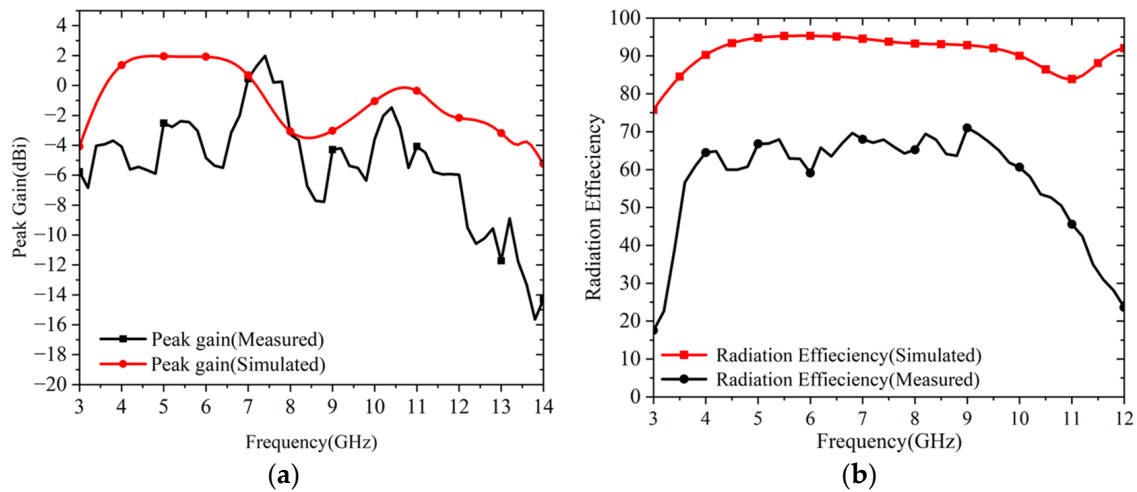


Figure 10. (a) Simulated and measured peak gain comparison of the proposed antenna. (b) Simulated and measured radiation efficiency comparison of the proposed antenna.

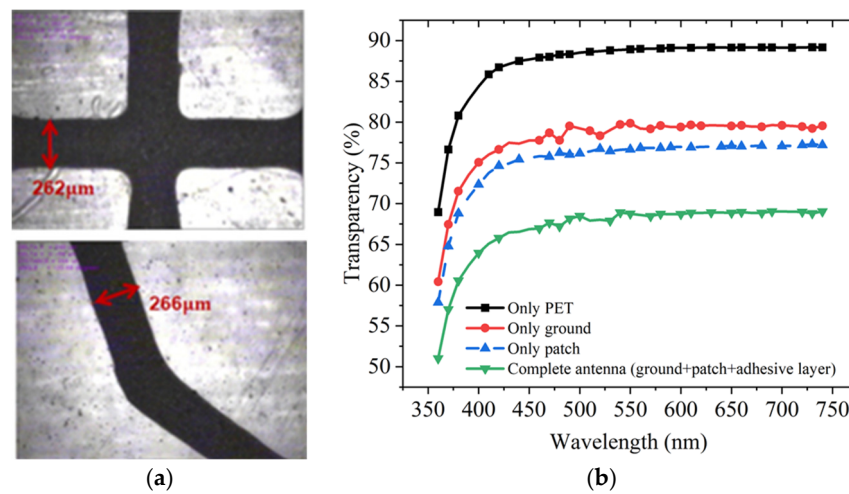


Figure 11. (a) Magnified microscopic image of silver nanoparticle mesh line width. (b) Measured optical transparency values for the proposed antenna.

Figure 11a shows a magnified microscopic image highlighting resolution error observed during screen printing. In the design and simulation phase, the intended line width (Lw) was 0.20 mm. However, in the fabricated sample, the measured width increased to 0.26 mm due to spreading effects during printing.

The numerical transparency corresponds to the empty (non-metallic) area of the antenna. There is a direct relationship between the line width and the antenna efficiency; however, this relationship is inversely related to the optical transparency. Figure 11b presents the measured optical transmittance of the proposed fractal antenna. Measurements were taken separately for the PET substrate, the patch, the ground, and finally for the complete antenna assembled with the adhesive layer. The maximum optical transparency was found to be 87% for PET, 77.6% for the ground pattern, 76.4% for the patch pattern, and 68.1% for the complete antenna.

In Table 1, the comparative analysis of transparent antenna technologies from 9 references [18–25,32] reveals fundamental trade-offs between optical transparency and electromagnetic performance. Sheet resistance values span from 0.018 Ω/sq (AgGL) to 10 Ω/sq (ITO-PET), with lower resistance materials achieving superior gains, as demonstrated by Cu-mesh dipole [22] reaching 2.4 dBi with 72.1% efficiency versus negative gains from higher-resistance materials. Optical transmittance inversely correlates with electrical performance, where highly transparent materials like Ag NM (85.29%) sacrifice antenna efficiency, while moderate transparency (49–73%) provides an optimal balance. Frequency coverage ranges from sub-GHz to 13 GHz with proportional dimensional scaling, while fabrication methods vary from traditional photolithography to emerging aerosol jet printing [25]. The present work demonstrates that successful transparent antenna design requires systematic optimization of conductivity, transparency, and geometric parameters rather than maximizing single performance metrics.

Figure 12 shows the simulated and measured realized gain patterns of the proposed fractal antenna. The gain was measured using a standard 2D far-field setup in an anechoic chamber. Calibration was first performed using a horn antenna with well-characterized gain at each angle. The proposed antenna was then measured at the same angles, and its gain was determined by comparison with the horn antenna results. Since the antenna exhibits a monopole radiation pattern, only the realized gain in the H-plane ($\theta = 90^\circ$) is presented. At 5 GHz, the simulated gain is 2.15 dBi, with the measured pattern showing minor deviations. At 7 GHz, the simulated gain decreases to 1.47 dBi, while the measured pattern remains in reasonable agreement. At 9 GHz, the measured gain is -0.65 dBi, and at 10 GHz, the simulated gain is 1.25 dBi, with the measured pattern closely matching the simulation, demonstrating improved directivity and radiation efficiency. Discrepancies between simulation and measurement are attributed to fabrication tolerances, line width variations, and SMA connector effects. Overall, the results confirm stable antenna performance across a wide bandwidth. Figure 13 depicts the fabricated transparent fractal antenna inside the anechoic chamber during measurements.

Table 1. Comparative analysis of the proposed antenna with existing works.

Ref.	Patch Material	Sheet Resistance (ohm/sq)	Substrate Materials	Fabrication Method	Antenna Type	Frequency (GHz)	Peak Gain (dBi)	Radiation Efficiency (%)	Optical Transmittance (%)	Antenna Size (mm ³)	Flexibility
[18]	AgHT-8	NA	PET	Chemical etching	bow-tie-shaped monopole antenna	3.89–5.97	5–7	NA	NA	58 × 78 × 0.9	NO
[19]	MXene	0.77	PET	Spray	Dipole	2.4	−7	NA	49	NA	YES
[20]	AgGL	0.018	Corning glass	RF sputtering	Monopole	2–6	6	NA	54.5	50 × 50 × 1.1	NO
[21]	ITO/Cu/ITO	4.7	Corning glass	RF sputtering	Monopole	0.8	−1.96	NA	61	150 × 150 × 0.7	NO
[22]	Cu-mesh	0.04	PET	photolithography	Dipole	0.6	2.4	72.1	70	290 × 105 × 1.2 169 × 105 × 1.2	NA
[23]	ITO-PET	10	Glass	Manual cutting	Fractal Meander Line Antenna	2.99–6.89	1.3	68	87	30 × 30 × 1.45	NO
[24]	Mesh	NA	NA	Manual cutting	Dual-band patch	2.4	2.2, 3.1	37, 44	50–70	44 × 50 × 2.1	YES
[25]	Metal Mesh Film	4	PET	Aerosol Jet printing	PIFA	2.4–2.5, 5–7.125	1.98, 3.7	24	73%	25 × 75 × 1	NO
[32]	Ag NM	8.45	PET	Screen printing	Bow-tie antenna	NA	NA	51.7	85.29	NA	YES
This work	AgNP	0.2	PET	Screen printing	mesh fractal patch	4–10.8, 11.2–13	3.15	72	68.1	18 × 16 × 0.55	YES

NA: Not Available.

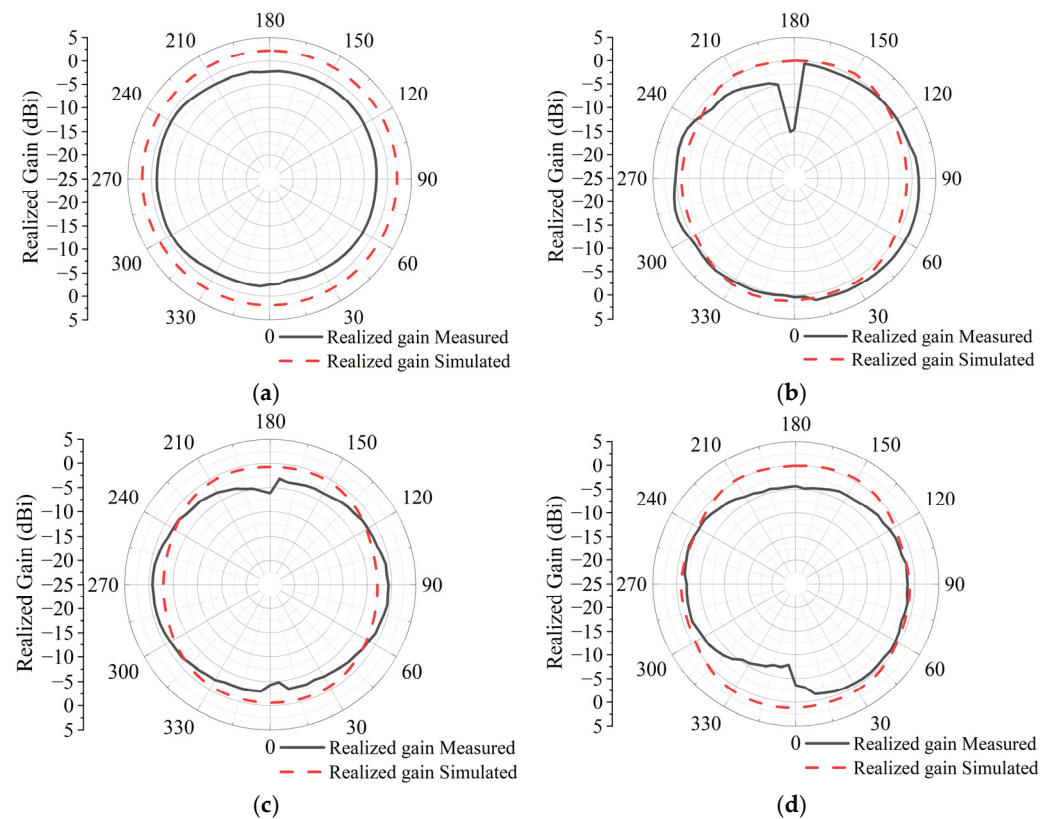


Figure 12. Simulated and measured realized gain comparison of the proposed fractal antenna at (a) 5 GHz, (b) 7 GHz, (c) 9 GHz and (d) 10 GHz.

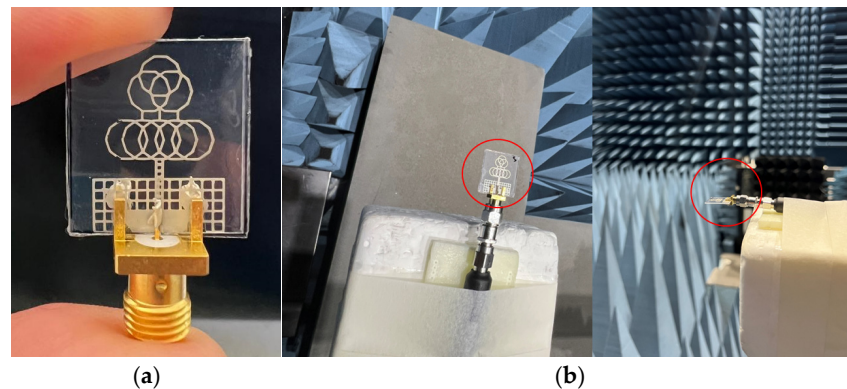


Figure 13. (a) Fabricated fractal transparent antenna. (b) Proposed antenna (circled in red) in the anechoic chamber, shown from various angles.

4. Conclusions

We present a compact, wideband fractal antenna fabricated via screen-printed silver nanoparticles (AgNPs) on a flexible PET substrate. The antenna achieves simulated -10 dB impedance bandwidth values of 4–10.8 GHz and 11.2–12.5 GHz with 68.1% optical transmittance. Measured -10 dB bandwidths remain stable at 3.8–11.2 GHz (no bending), 3–11.4 GHz (30° bending), and 3–11.2 GHz (45° bending), demonstrating flexibility within a compact $16 \times 18 \times 0.55 \text{ mm}^3$ form factor. The design incorporates two independent PET layers, one for the ground plane and the other for the radiating patch, which are stacked using adhesive. The decagonal fractal geometry, combined with a hybrid mesh–solid ground plane, successfully balances optical transparency and electromagnetic performance. The use of AgNP ink with a low sheet resistance of $0.2 \Omega/\text{sq}$ provides a cost-effective and scalable manufacturing process suitable for large-scale production.

The antenna's performance was validated through simulation and measurement, with realized gain patterns evaluated in the H-plane at 5, 7, 9, and 10 GHz. At 5 GHz, the simulated gain was 2.15 dBi with minor deviations in measurement; at 7 GHz, the simulated gain dropped to 1.47 dBi but remained in good agreement. At 9 GHz, the measured gain decreased to −0.65 dBi, while at 10 GHz, the simulated gain reached 1.25 dBi with closely matching measured patterns, confirming improved directivity and efficiency. Minor discrepancies are attributed to fabrication tolerances, line width variations, and SMA connector effects.

Overall, the results confirm that the proposed antenna delivers consistent wideband performance, structural compactness and visual transparency. These features make it a promising candidate for next-generation applications, including X-band radar, C-band satellite communications and S-band Wi-Fi systems, where both high electromagnetic performance and seamless visual integration are essential.

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