Progress In Electromagnetics Research Letters, Vol. 125, 9-15, 2025

(Received 18 December 2024, Accepted 15 January 2025, Scheduled 26 January 2025)

CPW-Fed Minkowski Island Fractal Slot Antenna for Wideband Application

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ABSTRACT: This paper proposes a CPW-fed wideband slot antenna with a modified Minkowski fractal island geometry. The antenna comprises a CPW-fed monopole placed within a modified Minkowski fractal island slot. The resonance introduced by the fractal slot combines with the monopole's resonance, resulting in an expanded operational frequency range. The interaction between the monopole and fractal slot significantly broadens the bandwidth. Return loss measurements confirm a wide bandwidth extending from 2.27 GHz to 7.91 GHz, achieving a fractional bandwidth of 111% covering WLAN, WiMAX, Wi-Fi, and 5G sub-6 GHz bands.

1. INTRODUCTION

The era of rapidly evolving wireless communication systems requires antennas that can function over a wide range of frequencies. This is essential for achieving high data rates and uninterrupted connectivity across various communication platforms. Wideband antennas capable of covering extensive frequency bands can address these needs. The ability of wideband antennas to operate over a wide frequency range makes them ideal for modern wireless communication systems that necessitate flexibility and adaptability. Research is being conducted to develop innovative designs that enhance antenna bandwidth. Researchers have adopted different techniques to enhance the bandwidth of antennas.

Slot antennas are considered one of the effective methods for achieving wide bandwidth. A slot antenna consists of a slot or an array of slots cut into a conducting surface. The slots create multiple paths for current flow, resulting in multiple resonant frequencies and a broader bandwidth [1, 2]. One of the key advantages of slot antennas is their ability to produce a wide impedance bandwidth while maintaining a simple structure. The slot antenna technique has been explored by various researchers using different design modifications to enhance bandwidth [3–9]. These include adding metallic strips, incorporating L- and inverted T-shaped slots to generate additional resonances, using a semi-elliptical radiating patch with a modified ground plane, and using round corners. Feeding methods such as coplanar waveguide (CPW) and microstrip line feeds have also been investigated, with CPW-fed designs showing better bandwidth performance.

Researchers have explored the use of monopole antennas for bandwidth enhancement. Various techniques that they adopted include altering the geometry of the radiating element and employing different feeding mechanisms. One can change the geometry of the radiating element by incorporating slots, stubs, notches, or fractal shapes into the monopole structure and ground plane modifications. These design adjustments allow monopole antennas to achieve multiple resonances and wider impedance bandwidth [10–13].

Applying a fractal geometry in an antenna is another method to improve the bandwidth. Fractal antenna provides multiband operation, improved bandwidth, and reduced size. The articles in [14, 15] provide a historical review of different fractal designs and comprehensive overview of the field of fractal antenna engineering, covering design methodologies and related research. Standard fractal geometries used in antenna design include Sierpinski gasket, Koch curve, Piano, and Minkowski island [16–19]. One can reduce the size of the radiating elements by incorporating these complex patterns while still achieving good radiation efficiency, making them ideal for applications where space is limited. These geometries increase the antenna's effective length within a compact physical size, thereby supporting multiple frequency bands.

A CPW-fed broadband circularly polarized rectangular slot antenna has been proposed in [20] and has used a triangular fractal slot in the tuning stub to improve the bandwidth. A microstrip slot antenna discussed in [21] has used three different fractal structures: Giuseppe Peano, Koch, and Apollonian. Apollonian-type fractals showed better performance in terms of its bandwidth and gain. A printed trapezoidal fractal-shaped wide slot antenna operating at 1.9 GHz is proposed in [22]. A size reduction of 61% has been achieved in comparison with the reference antenna operating at 3 GHz.

The antenna discussed in [23] has a printed parasitic slot with a Minkowski fractal patch for wideband application. It is observed that the radiator size has been reduced by using the Minkowski patch compared to the conventional square patch.

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doi:10.2528/PIERL24121805

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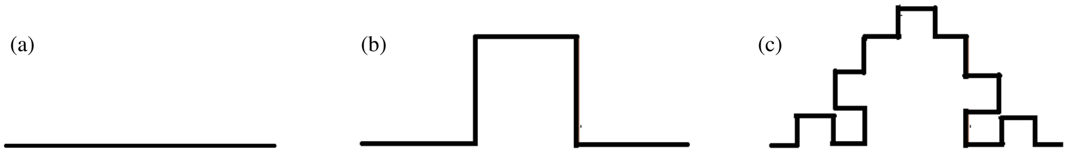

FIGURE 1. The generation of Minkowski fractal. (a) Initiator. (b) First Iteration. (c) Second Iteration.

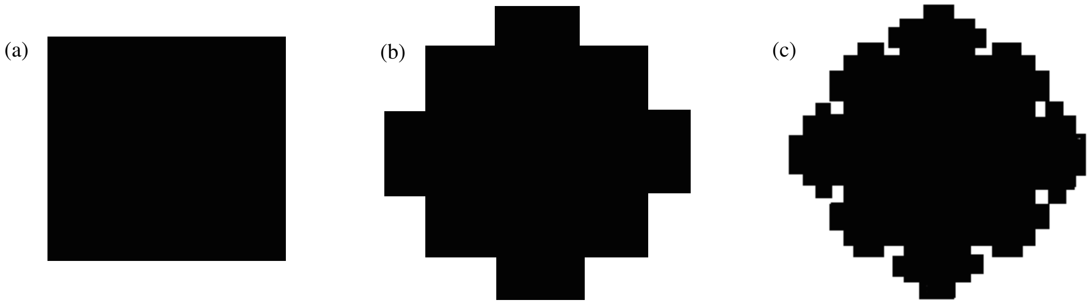

FIGURE 2. The generation of Minkowski island fractal structure: (a) Initiator. (b) First Iteration. (c) Second Iteration.

It also increases the bandwidth of the antenna. Four stubs were introduced in the design to enhance the bandwidth and radiation pattern further. A circularly polarized Microstrip Patch Antenna with a Minkowski Fractal Slot for Wireless Communication was reported in [24]. In this work, a Minkowski fractal slot has been incorporated on a truncated square patch, and a proximity-coupled feeding method is used. A compact Minkowski fractal antenna has been proposed in [25]. The third iteration reduced the resonance frequency, and a circle-shaped Split Ring Resonator is used to generate additional frequency without increasing the antenna size. The work reported in [26, 27] uses Minkowski fractal geometry in a Dielectric Resonator Antenna (DRA) for the bandwidth enhancement.

CPW-fed antennas have gained popularity due to their uniplanar structure, ease of fabrication, and circuit integration. A CPW consists of a central strip conductor with ground planes on either side, all on the same plane. CPW-fed slot antennas feature a relatively wide bandwidth while keeping a simple and uniplanar structure [3, 6, 7, 10, 12, 16, 20].

Fractal geometries, slot antennas, and CPW antennas each offers unique advantages in enhancing antenna bandwidth. Fractal geometries use self-similarity to support multiple resonances; slot antennas create multiple current paths for broad impedance bandwidth; and CPW-fed antennas combine low loss and easy integration for wideband performance. Also, most Minkowski-based studies have been reported in microstrip technology. However, Minkowski fractal-based work on CPW fed slot antenna has not yet been explored. The recent developments in terahertz communication [28–30] have demanded antennas suitable for terahertz system integration. The uniplanar structure of CPW-fed slot antenna is highly adaptable for such applications.

This paper presents a CPW-fed Minkowski Island Fractal Slot antenna for operation over a wide frequency band of 2.27 GHz to 7.91 GHz. It covers the WLAN frequency 2.4 GHz (2.4–2.48 GHz) & 5 GHz frequency bands (5.15–5.35 GHz & 5.725–5.825 GHz in United States & 5.15–5.35 GHz & 5.4–5.725 GHz in Europe), WiMAX (2.3–2.4 GHz/2.5–2.69 GHz/ 3.4–3.69 GHz/ 5.25–5.85 GHz), 5G sub-6 GHz band (3.3–4.2 GHz and 4.4–5.0 GHz), and Wi-Fi (2.4–2.4835 GHz/5.15 GHz–5.895 GHz/5.925 GHz–7.125 GHz).

2. GENERATION OF MINKOWSKI ISLAND STRUCTURE

A fractal is a geometric shape or pattern that is created through an iterative process. Each iteration produces a new shape that is a scaled-down version of the original. Fractals exhibit self-similarity, meaning that they display similar patterns at different levels of magnification or scale, often resulting in intricate and complex structures that maintain their form across various scales. The self-similarity property of fractals is utilized in antenna design to create multiple resonances, which can be modified to get a wide operational bandwidth.

The Minkowski fractal is generated through a recursive process that transforms a simple geometric shape into a highly complex structure. The process starts from a basic geometry called ‘Initiator’ such as a square. Self-similar structure can be created using the iteration process by applying the Minkowski transformation to the initial shape. This involves dividing each side of the square into equal parts and replacing the middle part with a smaller square that extends outwards or inwards. This creates a “stepped” or “zigzag” edge on each side of the initial square. Each iteration increases the complexity of the shape and enhances the fractal properties. Different stages of Minkowski fractal generation are shown in Figure 1.

Based on this principle, we have designed a Minkowski Island Slot Antenna. In the proposed design, we employ a Minkowski fractal island slot structure. The initial configuration is a Euclidean square slot. By applying the Minkowski transformation iteratively, the final structure has been derived after two iterations of this transformation. Figure 2 illustrates the various stages involved in the generation of the Minkowski fractal island.

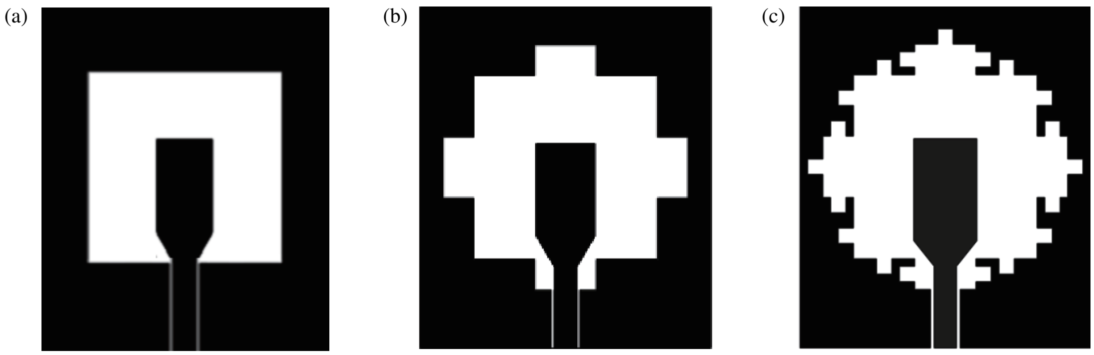

FIGURE 3. The evolution of the design stages. (a) Initiator. (b) First iteration. (c) Second iteration.

TABLE 1. Optimized parameter values of the proposed antenna.

Parameters	L	W	L_1	L_2	L_3	$Wf1$	Wf	d	Wp
Values (in mm)	28.5	33.5	8.8	2.5	8	6.2	2.2	0.35	1

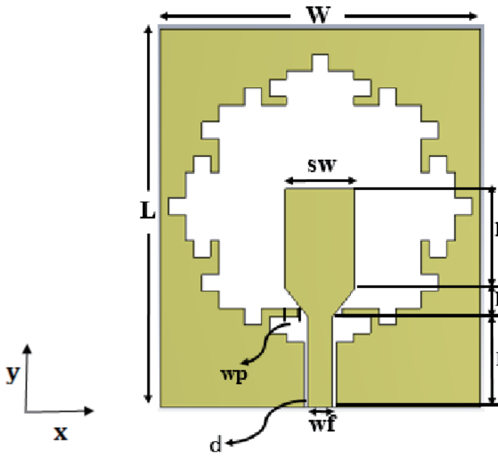

FIGURE 4. Proposed Minkowski Island fractal slot antenna.

3. ANTENNA DESIGN

The antenna is designed on a low-loss substrate of relative permittivity $\varepsilon_r = 4.3$, loss tangent 0.025, and thickness 1.6 mm. The antenna design is simulated with CST Microwave Studio Software. The schematic diagram of Minkowski Island Fractal Slot Antenna is depicted in Figure 4. The initial design, depicted in Figure 3(a), features a square slot with dimensions of 18 mm × 18 mm removed from the copper coating on the substrate. A monopole antenna is introduced within the slot fed by CPW (Coplanar waveguide) feed. The Minkowski transformation is applied to the initial design to enhance the antenna's performance. This process involved dividing each side of the square slot into three equal segments and replacing the central segment with a smaller rectangle that extends 3 mm outward, as shown in Figure 3(b). Further application of the Minkowski transformation to this design resulted in the structure depicted in Figure 3(c).

To enhance the bandwidth, the structure has been slightly modified by extending the length of the protrusion near the base or "neck" of the monopole.

The optimized parameter values are shown in Table 1.

4. PARAMETRIC STUDY

The basic structure resulted in a single band with a bandwidth ranging from 2.68 GHz to 3.3 GHz, resulting in a fractional bandwidth of 20.74%. Improvement in the performance has been observed in the first iteration, which led to a bandwidth

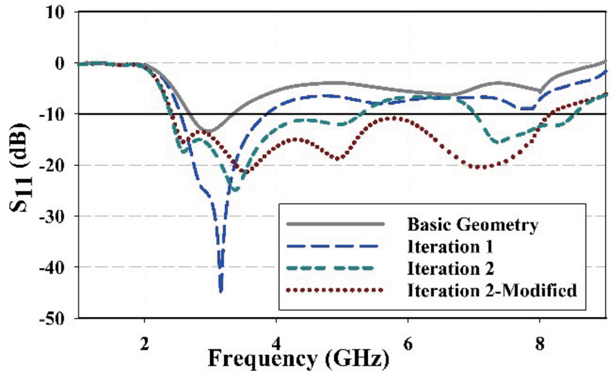

FIGURE 5. Simulated S_{11} of the proposed antenna at different iteration levels.

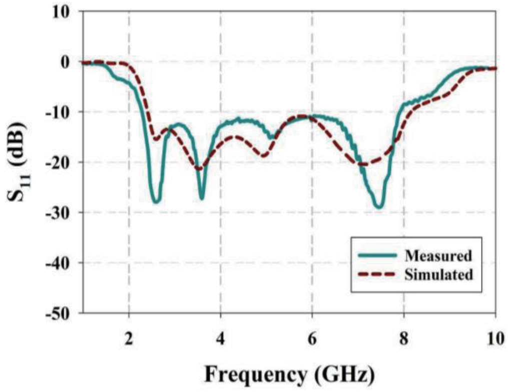

FIGURE 6. Return loss of the proposed antenna.

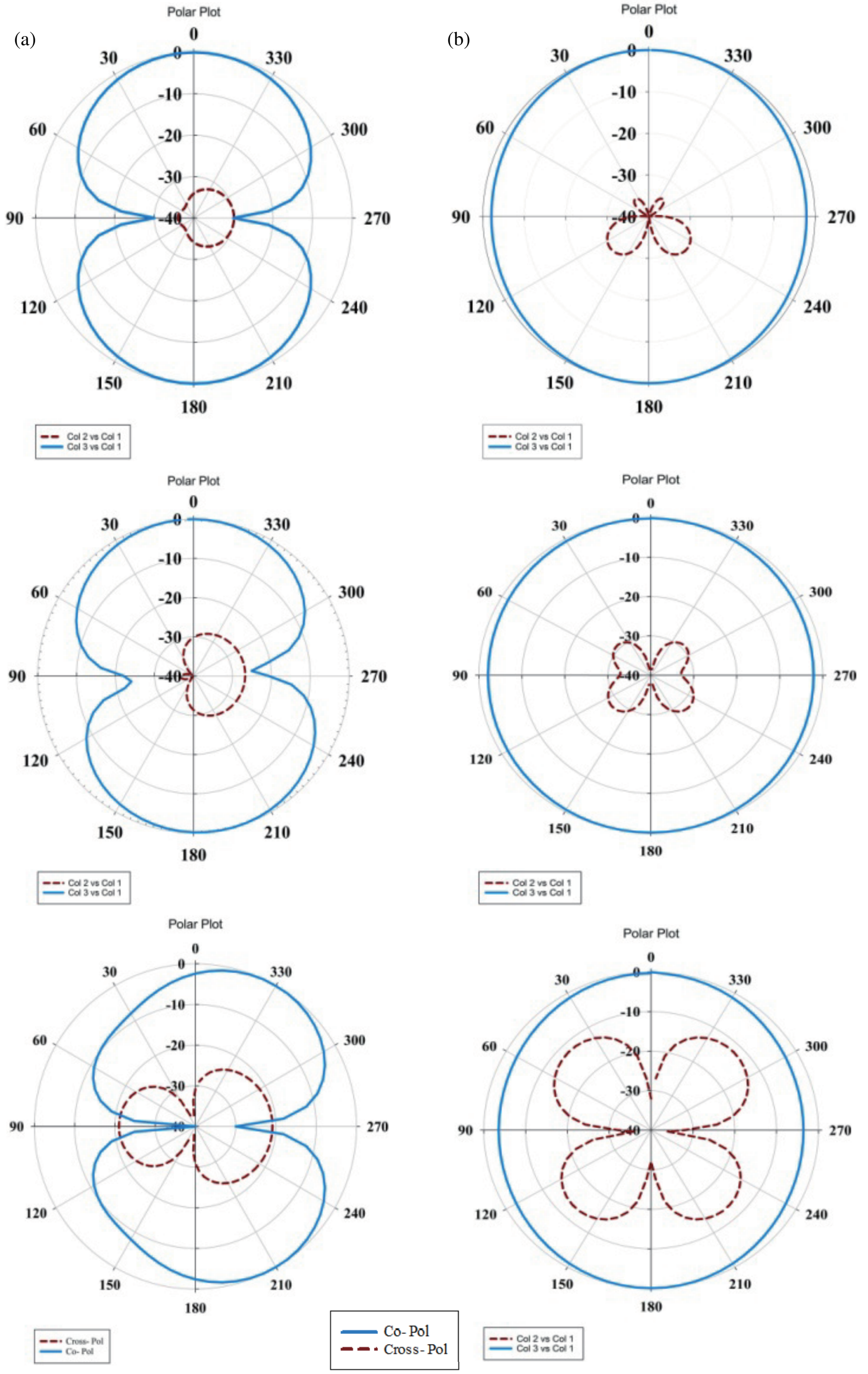

FIGURE 7. Normalized radiation pattern measured on E-plane (a) and H-plane (b) at 2.45 GHz, 3.5 GHz & 7.4 GHz.

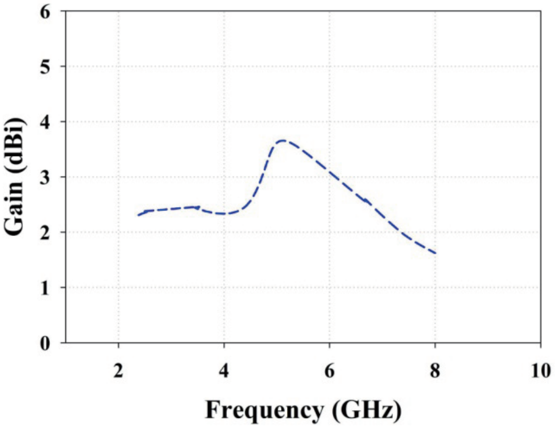

FIGURE 8. Variation of measured gain with frequency for the CPW fed Minkowski Island fractal slot antenna.

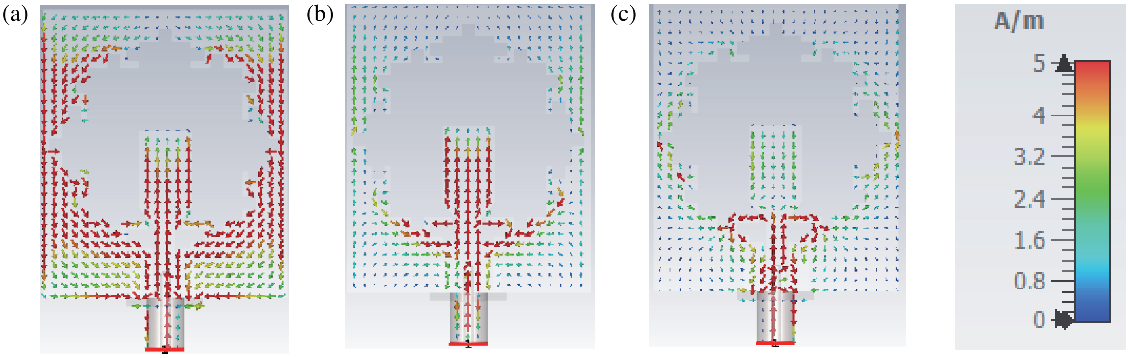

FIGURE 9. Surface current at 90° for different frequencies -2.45 GHz, 3.5 GHz, 7.4 GHz.

ranging from 2.54 GHz to 3.88 GHz. The fractional bandwidth is expanded to 41.74%. The second iteration performed better, with bandwidth ranging from 2.38 GHz to 5.28 GHz and 7 GHz to 8.51 GHz. However, the range between 5.28 GHz and 7 GHz falls outside the allowed -10 dB return loss criteria.

By slightly modifying the protrusion length near the base, or "neck," of the monopole antenna, the bandwidth has been expanded to cover this frequency range (between 5.28 GHz and 7 GHz). The modified second iteration unlocked the benefit of a quad-band structure (2.58 GHz, 3.52 GHz, 4.92 GHz, 7.14 GHz) with a bandwidth ranging from 2.40 GHz to 8.17 GHz, resulting in a fractional bandwidth of 109%. The addition of protrusion resulted in better impedance matching and improved bandwidth. The variation of S_{11} of the proposed antenna at different iteration levels is shown in Figure 5.

5. RESULTS AND DISCUSSION

The prototype of the proposed antenna with the dimensions listed in Table 1 has been fabricated using an FR-4 substrate. Frequency domain measurements were conducted using E5071C Vector Network Analyzer. The return loss of the proposed antenna is shown in Figure 6.

The measured results closely match the simulated values. Although there are minor variations, the measured result demonstrates improved broadband matching performance. Return loss measurement indicates a wide bandwidth ranging from 2.27 GHz to 7.91 GHz, yielding a fractional bandwidth of 111%.

Minor deviations from the simulated results could be attributed to slight variations in the characteristics of the substrate and the effect of SMA connector. Variations in the dielectric constant are expected as the antenna operates over the S-band and C-band. Also, soldering effects have not been accounted in the simulation studies. Nevertheless, the measured results exhibit an excellent fractional bandwidth compared to the simulated values.

The normalized radiation patterns at various frequencies are shown in Figure 7. The antenna shows omnidirectional co-polarization pattern in the H-plane and figure of eight pattern in the E-plane. Cross-polarization is significantly lower than co-polarization across most directions. An omnidirectional radiation pattern provides uniform signal strength in all directions. It is particularly advantageous for mobile users, as it maintains consistent connectivity regardless of their location or movement relative to the antenna.

The measured gain of the antenna in the operating band is plotted in Figure 8. A comparison of the antenna characteristics of the Minkowski island fractal slot antenna at different iteration levels is presented in Table 2.

The surface current distribution of the proposed antenna is shown in Figure 9. In Figure 9(a), the surface current den-

TABLE 2. Comparison of the antenna characteristics of the Minkowski island fractal slot antenna at different iteration levels.

Iteration Level	No. of Bands	Bandwidth (GHz)	Frequency (GHz)	Gain (dBi)	Fractional Bandwidth
Iteration 0	1	0.62	2.9	2.41	20.74%
Iteration 1	1	1.34	3.15	2.1	41.74%
Iteration 2	2	2.9	2.5 & 3.35	2 2.74	75.7%
		1.51	7.3	2	19.47%
Iteration 2 Modified	1	5.64	2.45 3.5 7.45	2.39 2.47 2.01	111%

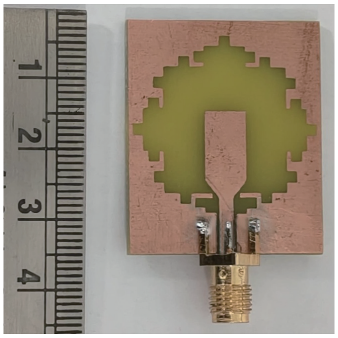

FIGURE 10. Photograph of the fabricated CPW fed Minkowski Island Fractal Slot Antenna.

sity is spread over a larger area, indicating longer wavelengths. It can be observed from Figure 9(b) & (c) that at higher frequencies, current density decreases and is concentrated near the monopole indicating shorter wavelengths. Figure 10 shows a photograph of the fabricated antenna.

6. CONCLUSION

The design and development of a CPW-fed wideband fractal antenna featuring a Minkowski island geometry for wireless applications is presented. This innovative design combines a monopole structure with a fractal slot to achieve a broader bandwidth. The use of the fractal slot introduces multiple resonances, which effectively combine with the inherent resonance of the monopole resulting in a broader bandwidth. This antenna demonstrates remarkable wideband performance, operating across a frequency range of 2.27 GHz to 7.91 GHz. This wide coverage corresponds to a fractional bandwidth of 111%, making the antenna highly suitable for various modern wireless applications. These include Wireless Local Area Networks (WLAN), Worldwide Interoperability for Microwave Access (WiMAX), Wi-Fi, and the emerging 5G sub-6 GHz bands. The antenna also exhibits a good radiation pattern and moderate gain over the useful bandwidth. The antenna's ability to operate across such a broad frequency spectrum, uniplanar structure, omnidirectional radiation pattern, and compact design makes it well suited for devices requiring seamless connectivity across multiple communication standards.

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