A Compact Fractal-Shaped O-Ring Monopole Antenna for Modern Broadband Wireless Applications

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Abstract: - In this letter, the design of a compact planar Fractal-shaped O-ring monopole antenna based on the Sierpinski carpet concept is studied and proposed for modern broadband wireless applications. The planar fractal-shaped O-ring monopole antenna is on the basis of Sierpinski category construction and then modifies the state of the plane inward with a radius of 27mm over the two iterations. The antenna structure is low profile and easy to be fabricated, and it has performed the simulation and measurement with the result VSWR ≤ 2 that can achieve a wide impedance bandwidth 636% from the frequency band 1.57GHz ~ 10GHz. The geometric scale factor of the Sierpinski fractal is according to the same scale element that defines the geometrical self-similarity. In our experiments, the results show that use of fractal-shaped O-ring into monopole antenna structure can effectively improve input impedance matching, and obtain a larger bandwidth and better radiation pattern, while also having predictable multi-band characteristics.

Key-Words: - Fractal, Sierpinski, Broadband monopole.

Received: February 9, 2021. Revised: July 13, 2021. Accepted: July 31, 2021. Published: August 24, 2021.

1 Introduction

Wireless products have to be attractive, light-weighted and at the right size. It is a trend in the development of wireless devices. In recent years, wireless technology has developed rapidly, and it is foreseeable that the wireless system needs to support a greater coverage bandwidth, such as Global Positioning System (GPS, 1575MHz), Mobile Wireless Communication system(2G/3G/4G) bands operating at 698-960 MHz/1710-2690MHz, wireless local area network (WLAN) bands operating at 2.4-2.484 GHz/5.15-5.825 GHz, 6 GHz unlicensed spectrum for the European markets between 5.925 GHz to 6.425GHz, for the US markets between 5.925 GHz to 7.125GHz, and Sub-6 GHz 5G bands operating at 3.5 GHz/4.7 GHz. According to the market demand and trend, a wider or multiple band antenna design for modern broadband wireless applications has become more and more popular. Challenges of how to miniaturize them, especially for highly integrated modern broadband wireless applications arise. There are many antenna structures in the papers [1,2,3] that can meet broadband requirements, such as bow tie dipole, bow tie slot and spiral structures. However, the size of these antennas will be a challenge to be integrated in modern wireless applications. In order to minimize the impact of this dimension challenge, the circular disc monopole structure was proposed [4], but its size still needs to be miniaturized. In our studies, many broadband antenna articles [5,6] have chosen ultra-wideband (UWB) wireless technology to demonstrate their antenna design and performance achievements because UWB has been permitted by U.S. Federal Communication Commission (FCC). Its frequency range has been allocated from 3.1GHz to 10.6GHz; nevertheless, it can’t effectively satisfy the current wireless system applications, especially for lower frequency band from 1 - 3GHz.

The Sierpinski gasket is a fractal named after the Polish mathematician Waclaw Sierpinski who described it in 1916 [7]. The original Sierpinski gasket is constructed by subtracting a central inverted triangle from a main triangle shape. After the subtraction, three equal triangles remain on the structure, each one being half of the size of the original one [8]. Printed fractal antennas have attracted much attention in wireless communication because of their low profile and the easiness to be fabricated [9,10,11]. These papers have shown that the proposed antennas can be miniaturized and obtain wider input impedance matching.

Contribution

In this paper, a compact planar fractal monopole antenna for modern broadband wireless application is demonstrated. The novelty in the structure is brought by introducing an O-ring fractal-shaped with 2 iterations of self-similarity inside, which facilitates in extending the impedance bandwidth. A significant contribution of the presented paper is:

- The proposed antenna achieves a 6.36:1 wide impedance bandwidth with 2:1 VSWR from 1.57GHz ~ 10GHz and the simulation and experimental results are studied and analyzed.

Details of the proposed antenna and its performances are given in the next two sections.

2 Antenna Design and Parametric Studies

2.1 Antenna Configuration

Fig. 1 depicts the basic geometry of the proposed planar fractal-shaped O-ring monopole antenna, which was modified by Sierpinski category fractal, and plotted the inward iteration. The antenna overall height of h_n is 54mm, and the Sierpinski fractal has the scale factor as given

$$\delta = \frac{h_{n+1}}{h_n} = 0.33 \quad (1)$$

where n represents the iteration and h represents the height of the O-ring.

The proposed antenna has different scale factors by the 1st and 2nd iteration. It is fabricated on a thickness of 0.8mm FR4 glass epoxy substrate (the relative permittivity is 4.4) with its outer radius 27mm and inner radius 26mm. The iterative variation of the O-ring *Øa, Øb, Øc* is equal to 54mm, 18mm, 6mm, respectively. A circular aluminum plate with radius *Rg* = 35mm and thickness *Wg* = 0.8mm was used for grounding plane. The proposed antenna radiator between ground plate the gap = 0.8mm, and the RF SMA connector was connected through the ground plate center point of circle and antenna radiation element directly. The geometric structure and dimensions of the proposed antenna was simulated by using electromagnetic simulator Ansoft HFSS. The final optimized parameters of the antenna are listed in Table 1.

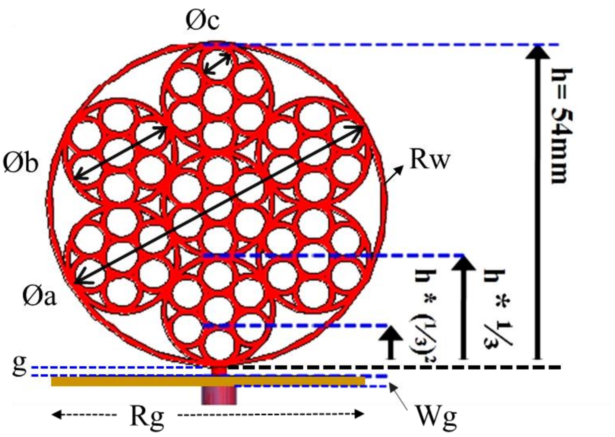

Fig.1: Geometry and dimension of a compact planar fractal-shaped O-ring monopole antenna.

Table 1. Optimized dimensions of the proposed antenna.

Parameters	*Rw*	*Wg*	*g*	*Rg*
Value (mm)	**1**	**0.8**	**0.8**	**70**
Parameters	*Øa*	*Øb*	*Øc*	
Value (mm)	**54**	**18**	**6**	

2.2 Antenna Design Guideline

The first strategy is to decide the circle radius and total height of the O-ring monopole antenna. From here we know the lower band edge frequency of printed monopole antenna can be estimated by the standard formulation [12,13]. If L is the height and r is the effective radius of the planar monopole antenna in centimeters, which is determined by equating area of the planar and cylindrical monopole antennas, then the lower band edge frequency f_L is given as

$$f_L = \frac{c}{\lambda} = \frac{7.2}{(L + (t \times r) + p)} \quad GHz \quad (2)$$

where c is the velocity of light in free-space, λ is the free-space wavelength. p is the length of the 50 Ω feed line and t is the PCB thickness in centimeters.

According to the formulation (2), the printed monopole antenna of the O-ring height and the size of the ground plate can be approximately calculated to be 50mm. After calculation, f_L = 1.364GHz is obtained and it meets the research requirement for the lowest frequency of desired band in the initial O-ring monopole antenna. In order to effectively implement the iteration variation of fractal with simulation and measurement, we adjusted the outer circle diameter to 54mm and the inner circle diameter to 53mm, making the circumference trace width to be 1mm. The planar fractal monopole antenna was modified by the Sierpinski carpet concept, which is generated through using two iterations of the decomposition algorithm on the O-ring antenna, named initiator. Compared to the structure of three antennas, the initiator and iterators are generated by the geometric ratio of the O-ring that requires the midpoint of the circles to be merged in the same place. The first iteration shrinks the circle to 1/3 diameter to generate it, and the second iteration uses the Sierpinski carpet algorithm to obtain a circle with twice mathematics (equal to 1/9 diameter). The proposed antenna structure evolution is shown in Fig. 2.

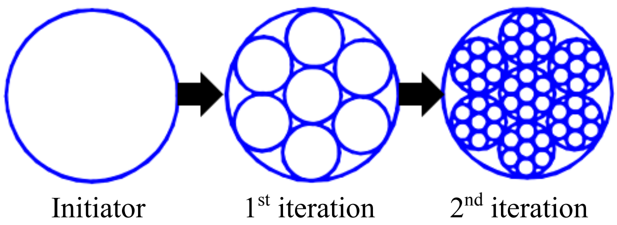

Fig.2: The Iteration of compact planar fractal-shaped O-ring based on the Sierpinski carpet concept.

2.3 Parametric Studies

The key parameters *Øa*(N=0), *Øb*(N=1), *Øc*(N=2), and *g* that affect the resonance frequencies and bandwidth are studied in this section.

Fig 3. shows the relationship between the parameters *Øa*, *Øb*, *Øc* and the bandwidth. Note that the bandwidth can be significantly improved when the O-ring parameters *Øa*, *Øb* and *Øc* are properly adjusted. As a result, the f_L of initiator is trendily closed to 1.3GHz that almost matches the formulation calculation for $|S_{11}| \leq$ -10dB. Moreover, the 1st iteration can improve the bandwidth from 1.57GHz ~ 4.93GHz and the 2nd iteration is greater in amount for the bandwidth from 1.65GHz ~ 9.85GHz. Meanwhile, it's also observed when the number of iterations gradually increases that f_L will be 5 ~ 10% higher than the lowest frequency before iterating.

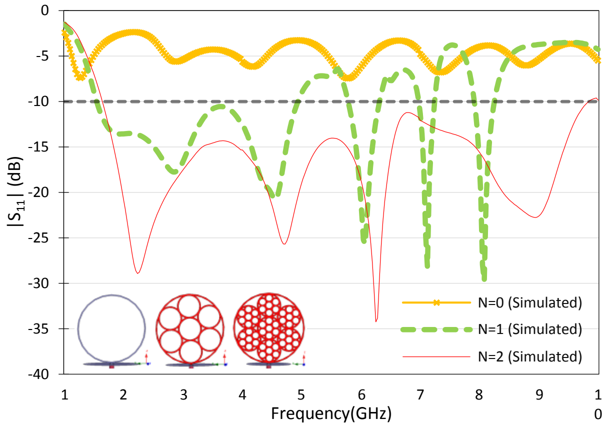

Fig.3: Simulated reflection coefficient of the proposed antenna in different iterations.

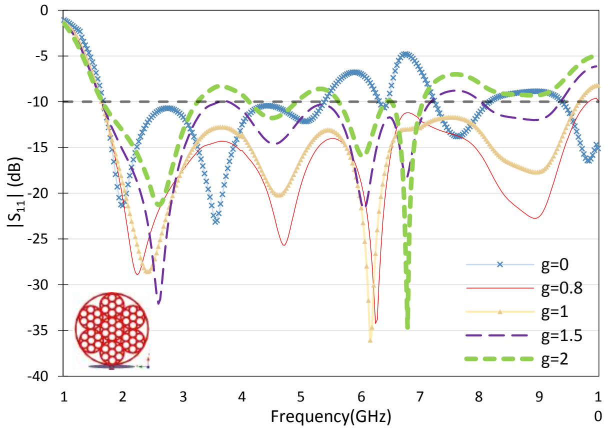

Fig.4: Simulated reflection coefficients at different value of *g*.

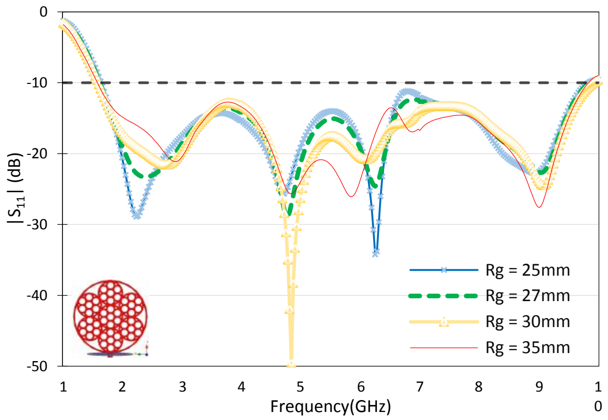

Fig.5: Simulated reflection coefficients at different value of *Rg*.

Fig. 4 shows the relationship between the parameter *g* and bandwidth. It can be seen that the best impedance bandwidth from 1.65GHz to 9.85GHz is *g* = 0.8mm, and a larger or smaller gap distance will gradually decrease the bandwidth performance. To realize the bandwidth coverage for the lowest frequency 1.57GHz as the initial research purpose, the radius of the ground plate the parameter *Rg* needs to be adjusted appropriately. For different *Rg*, the reflection coefficient curve of the antenna is almost unchanged. However, it can be seen that f_L is slighted moved to the lower band with limited changes. The relationship between the parameter *Rg* and the bandwidth is shown in Fig. 5.

2.4 Current Distributions

The simulated current distributions of the initiator and the 1st and 2nd iteration fractal-shaped O-ring monopole antennas are demonstrated in Fig. 6. It can be seen that the wide impedance bandwidth of the 1st and 2nd iteration antennas are getting better and better. The reason is that the number of iterations increases, the contact area of the fractal surface current path becomes larger. Fig. 7(a) shows the current density near the second resonance at 4.7GHz, indicates approximately a second order harmonic. Fig. 7(b) illustrates a more complicated current density at 6.25GHz, corresponding to the third order harmonic.

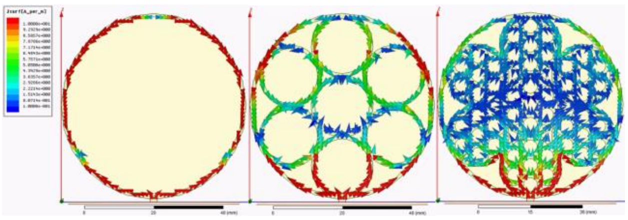

Fig.6: The proposed antenna Current Distribution at different iterations at 2.41GHz.

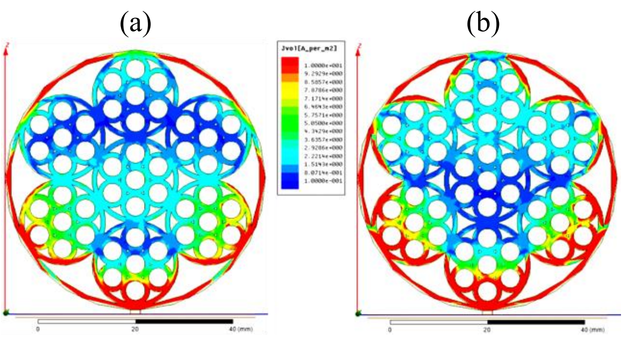

Fig.7: The Current Density of the proposed antenna for (a) 4.7GHz and (b) 6.25GHz.

3 Simulated and Measured Results

The proposed antenna prototype fabricated with eagle view is shown in Fig. 8. Meanwhile, the simulation and measurements were caried out to demonstrate the performances. The simulated and measured VSWR are shown in Fig. 9. The impedance bandwidth results with VSWR ≤ 2 are 597% and 636% for the lowest frequency at 1.65GHz and 1.57GHz, respectively.

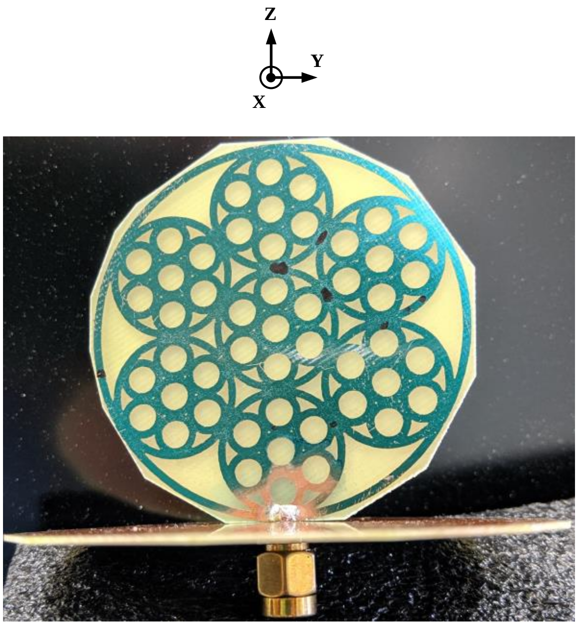

Fig.8: Fabricated prototype of the proposed antenna.

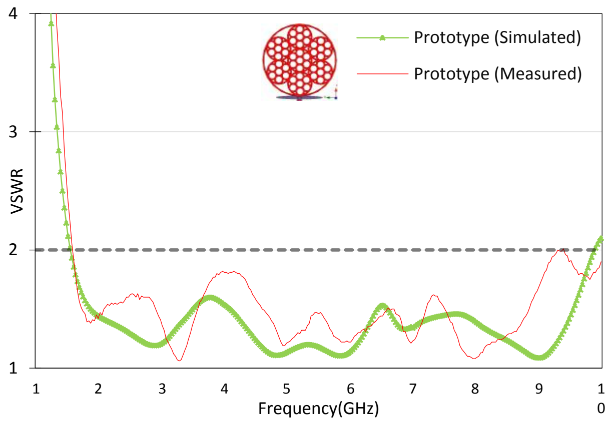

Fig.9: Measured and simulated VSWR of the proposed antenna.

The radiation patterns have been simulated and also measured inside a 3D anechoic chamber. The measured and the simulated normalized radiation patterns at 1.57, 2.4, 3.7, 4.5, 5.8, 6.5 and 7.12 GHz are plotted in Fig. 10, Fig. 11, Fig. 12, Fig. 13, Fig. 14, Fig.15, Fig. 16 respectively. The measured xy-plane patterns are very close to those obtained in the simulation. It is noticed that the xy-plane pattern is omnidirectional at lower frequencies (1.57, 2.4 GHz) and begins to deform into an elliptic-shape radiation pattern at mid-higher frequencies (3.5, 4.7, 5.8 GHz) and at the highest frequencies (6.5, 7.12 GHz), a defective circular-shape radiation pattern is formed. The measured xz-plane patterns follow the shapes of the simulated ones, though the agreement is not as good as the xy-plane patterns. In the xz-plane, the simulated and measured radiation pattern has a little error at 3.5GHz and higher frequencies. That should be precision differences in the antenna fabrication like the gap between antenna and ground plate or feed connector. The simulated xz-plane pattern is like a traditional monopole at 1.57 and 2.4 GHz. With the increase of frequency (3.5GHz and higher frequencies), it starts to form notches and get more directional at around $\pm 45^{o}$ from the Z-direction.

Fig. 17 illustrates the measured peak gain and efficiency of the proposed antenna. It is shown that the maximum gain occurs at the direction of $\theta = 90^{o}$ when the frequency is equal and lower than 3 GHz; at higher frequencies (from 3.5 to 7.12 GHz), the peak gain will be shifted from xz-plane to yx-plane and it shifts to the direction when $\theta = \pm 30^{o}$ and ranges from 3.34 to 6.55 dBi due to the more directional radiation properties.

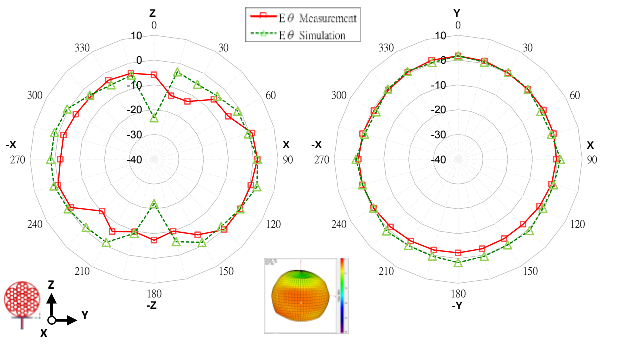

Fig.10: Measured and simulated normalized radiation patterns of the antenna at 1.57GHz in xz-plane(Left) and xy-plane(Right).

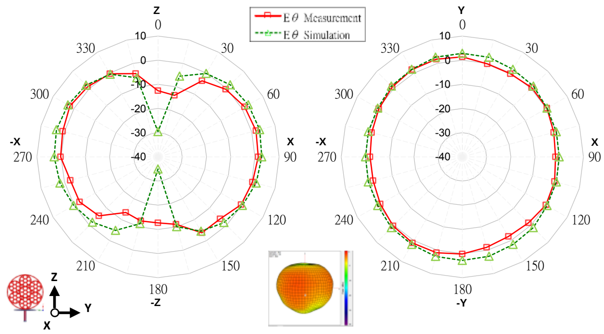

Fig.11: Measured and simulated normalized radiation patterns of the antenna at 2.4GHz in xz-plane(Left) and xy-plane(Right).

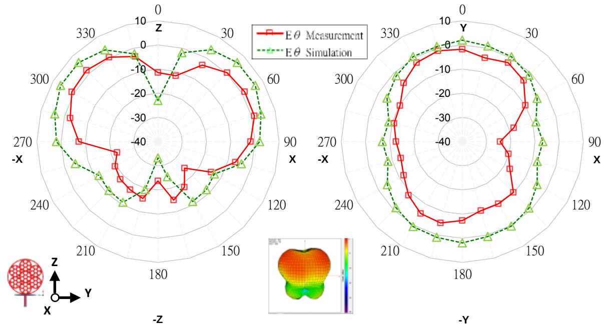

Fig.12: Measured and simulated normalized radiation patterns of the antenna at 3.5GHz in xz-plane(Left) and xy-plane(Right).

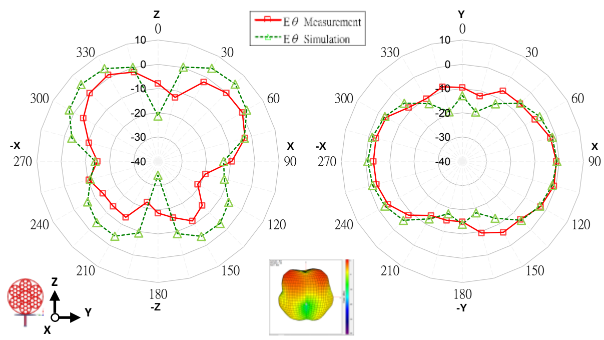

Fig.13: Measured and simulated normalized radiation patterns of the antenna at 4.7GHz in xz-plane(Left) and xy-plane(Right).

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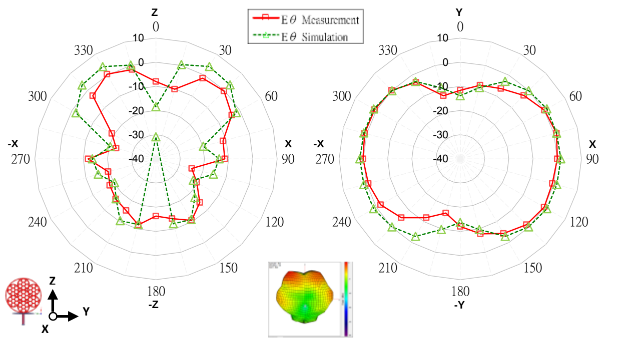


Fig.14: Measured and simulated normalized radiation patterns of the antenna at 5.8GHz in xz-plane(Left) and xy-plane(Right).

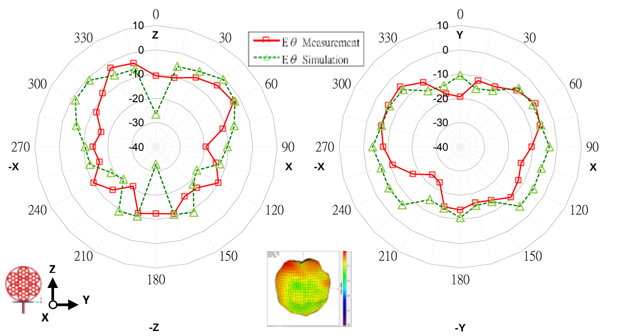


Fig.15: Measured and simulated normalized radiation patterns of the antenna at 6.5GHz in xz-plane(Left) and xy-plane(Right).

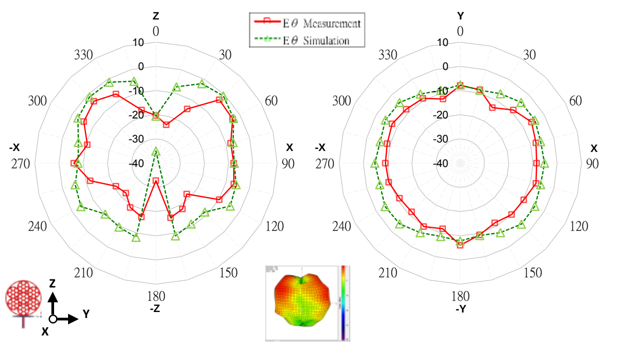
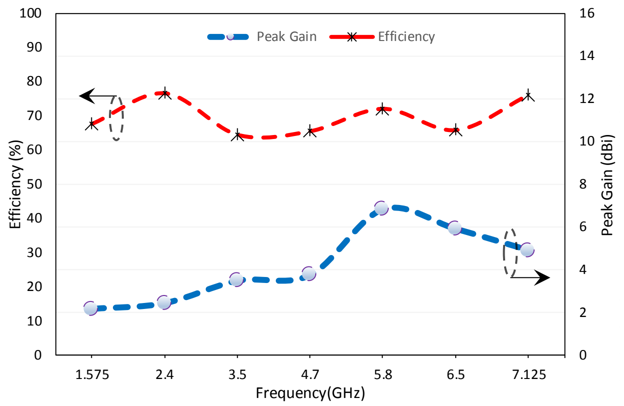


Fig.16: Measured and simulated normalized radiation patterns of the antenna at 7.12GHz in xz-plane(Left) and xy-plane(Right).



Frequency	1.575GHz	2.4GHz	3.5GHz	4.7GHz	5.8GHz	6.5GHz	7.125GHz
Peak Gain(dBi)	2.1	2.4	3.5	3.7	6.8	5.9	4.9
Efficiency(%)	67.7%	76.6%	64.5%	65.5%	72.1%	65.8%	76.1%

Fig.17: Measured & Simulated antenna peak gain & efficiency versus frequency of the proposed antenna.

4 Conclusion

A compact planar Fractal-shaped O-ring monopole antenna based on the Sierpinski carpet concept for modern broadband wireless applications is presented in this paper. The antenna structure is low profile and ease of fabrication, and it has achieved a 636% wide impedance bandwidth from the frequency band 1.57GHz ~ 10GHz for VSWR ≤ 2. The geometric scale factor of the Sierpinski fractal is according to the same scale element that defines the geometrical self-similarity. In our experiments, the simulated and measured results are in good agreement and the results show that use of fractal-shaped O-ring into monopole antenna structure can effectively improve input impedance matching, obtain a larger bandwidth and better radiation pattern. This antenna is applicable in many systems such as mobile home gateways, Picocell, etc.

Future Work

To be enhanced the practicability and flexibility of the proposed antenna in mainstream wireless technology. The focus of future work is summarized.

- Miniaturization, and single side with ground plane structure.
- Dual-polarization or MIMO capability.
- Directivity and stable the radiation gain in the whole impedance bandwidth.

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Conflicts of Interest

The author(s) declare no potential conflicts of interest concerning the research, authorship, or publication of this article.

Contribution of individual authors to the creation of a scientific article (ghostwriting policy)

The author(s) contributed in the present research, at all stages from the formulation of the problem to the final findings and solution.

Sources of funding for research presented in a scientific article or scientific article itself

No funding was received for conducting this study.

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