JOURNAL OF NANO- AND ELECTRONIC PHYSICS
Vol. **14** No 1, 01015(5pp) (2022)

ЖУРНАЛ НАНО- ТА ЕЛЕКТРОННОЇ ФІЗИКИ
Том **14** № 1, 01015(5cc) (2022)

Design and Analysis of a New Fractal Compact Antenna for Ultra-Wideband Applications

N. Guebgoub[1,*], O. Mahri[1], T.A. Denidni[2], S. Redadaa[1]

[1] *Laboratoire des Télécommunications, Université 8 Mai 1945, Guelma, 24000-B.401, Algérie*
[2] *CEMT – INRS, 800 Rue De La Gauchetière Ouest, Bureau 6900, Québec, H5A 1K6, Canada*

(Received 06 January 2022; revised manuscript received 22 February 2022; published online 28 February 2022)

In this paper, a compact new fractal printed monopole antenna, inspired of Sierpinski gasket, for ultra-wideband (UWB) applications is reported. The proposed antenna is designed by developing a novel mathematical model and a new iterative procedure to generate a fractal geometric shape of the modified Sierpinski gasket (MSG). The recursive procedure to form an MSG as a radiating element is based on an equilateral triangular grid of nodes which is constructed by using a recursive sequence. The MSG radiating monopole is fed by coplanar waveguide (CPW) to achieve a 50 Ω impedance matching with a trapezoidal ground plane. Simulation and optimization of various parameters of the proposed fractal antenna are performed using CST Microwave Studio. The simulated results indicate that the proposed antenna possesses a moderate gain over the entire band with a peak of 4.77 dBi at 9.8 GHz. The stated antenna is also compared with the related literature reviews to differentiate its performance. The total size of the presented antenna is 19×20×1.52 mm^3, which is designed on Rogers RO4003C substrate (tanδ = 0.0027 and ε_r = 3.38). Moreover, a compact prototype is implemented and tested. The measured results of the reflection coefficient characteristics show good agreement with the simulated results. The designed antenna exhibits omnidirectional radiation patterns and covers the frequency range 2.22-10.7 GHz, making it suitable for wireless and UWB applications.

Keywords: Compact antenna, Fractal, Printed monopole, Sierpinski gasket, Wireless, Ultra-wideband.

DOI: 10.21272/jnep.14(1).01015 PACS number: 84.40.Ba

1. INTRODUCTION

With ever increasing demands for new wireless communication devices and advanced wireless communication systems with increasing importance of other wireless applications in both civil and military applications, wideband, efficient, low-cost and low-profile antennas are urgently required, which can be integrated into multiple mobile communication systems and applied in ultra-wideband (UWB) technology. In this perspective, patch antennas have significant importance in wireless communication systems, and they can easily meet part of that request.

Several papers have dealt with compact antennas [1-3] and developed many techniques for reducing the antenna size and broadening the antenna frequency band to achieve UWB operation [4-6]. Since the Federal Communications Commission (FCC) allocated the spectrum from 3.1 to 10.6 GHz for UWB applications in 2002 [7], recently, numerous challenges have arisen to overcome the inherent performance limitations of microstrip antennas to achieve a – 10 dB return loss bandwidth over the entire operating band.

Extensive research has been carried out in the past to increase the bandwidth of patch antennas, among which is the use of fractal geometry for shaping antenna elements [8, 9]. Fractal geometry provides a good method for achieving the desired miniaturization and multiband operation. Different geometries of Sierpinski gasket have been explored with the aim of achieving improved performances in terms of multiband and wideband, compactness and ease of design [10-12].

In this paper, a new geometry fractal antenna using an especial shape of modified Sierpinski gasket (MSG) is presented. Some of the more common fractal geometries have been found to be useful in developing new and innovative designs for antennas. The first fractal to be considered is the popular Sierpinski gasket [13]. The Sierpinski gasket fractal is generated by the iterative function system (IFS) method [14, 15]. The Sierpinski gasket is a special case of a wider class of fractals that can be obtained from the well-known Pascal triangle or mod-p Sierpinski gasket [16].

2. ANTENNA DESIGN AND CONFIGURATION

The geometry and configuration of the proposed fractal UWB antenna are shown in Fig. 1. Both the coplanar waveguide (CPW) feeding structure and the fractal patch are etched on the same side of the substrate symmetrically in relation to the center line (y-axis) of the antenna. Moreover, a CPW-fed line with a trapezoidal ground plane is used.

Due to the high reactance and low radiation resistance, impedance matching presents a significant challenge in designing electrically small antennas [17]. To overcome this issue, tree strips are employed: two symmetrical strips are inserted into the vertical edges of the substrate, and a third thin strip is introduced into the horizontal edge of the substrate. The accurate design of the proposed antenna needs to be adjusted and optimized using CST Microwave Studio simulator. A parametric analysis was carried out to obtain the optimal geometric parameters which are collated in Table 1. The antenna was fabricated by etching a 17.5 µm thick copper pattern on a 1.52 mm thick Rog-

guebgoub.nassima@univ-guelma.dz
nassima_gueb@yahoo.fr

ers RO4003C substrate (ε_r = 3.38, tanδ = 0.0027) of size 20×19 mm^2.

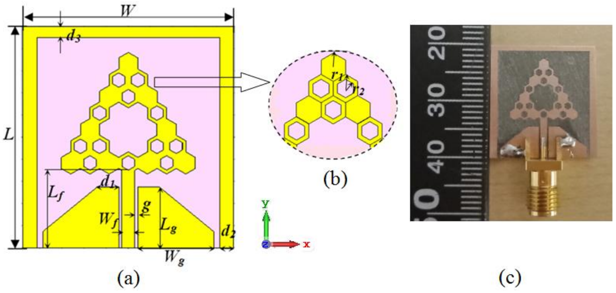


Fig. 1 – Geometry of the proposed UWB antenna (a), fractal patch (b), prototype of the proposed antenna (c)

3. DESCRIPTION OF MSG FRACTAL ANTENNA DESIGN

In this design, the fractal MSG antenna is based on a recursive sequence using equation (3.1) for constructing an equilateral triangular grid of nodes. To obtain self-similar fractal properties, we applied a new iterative procedure to generate the MSG fractal antenna.

The procedure for the geometric construction of this new fractal begins with an equilateral and equiangular triangular grid of nodes. Each side of the triangle contains K_n nodes, where K_n is a sequence defined by its first term $K_0 = 1$ and by the recurrence relation given by equation (3.1):

$$\begin{cases} K_{n+1} = 2K_n + 1 \\ K_0 = 1 \end{cases} \tag{3.1}$$

where K_n is an odd number.

The n-th term of the proposed progression is given by equation (3.2):

$$K_n = 2^{n+1} - 1 \,. \tag{3.2}$$

This general form can be demonstrated using the formula given by equation (3.3):

$$\sum_{i=0}^{n-1} 2^i = 2^n - 1. \tag{3.3}$$

The sum of the first n terms of the proposed sequence given by equation (3.4) represents the total of the nodes forming the equilateral triangle:

$$S_n = K_n . 2^n = \left(2^{n+1} - 1\right) . 2^n \,. \tag{3.4}$$

The recursive procedure to form an MSG as a radiating element is shown in Fig. 2, where three small hexagonal slots are introduced in the center on each side of the triangle of the first iteration K_1, as illustrated in stage 0 of Fig. 2e. We apply the same transformation for the triangle of the second iteration K_2 (step 0 of stage 1), also shown in Fig. 2b, as step 1 of stage 1. The middle nodes between the slots are eliminated, as illustrated in step 2 (stage 1) of Fig. 2c. Then we repeat this process on the three remaining triangles, shown in stage 0, for the constructed MSG, as shown in Fig. 2d. This is a new fractal that can be generated by carrying out this iterative process an infinite number of times. The proposed fractal UWB antenna was optimized to the second order.

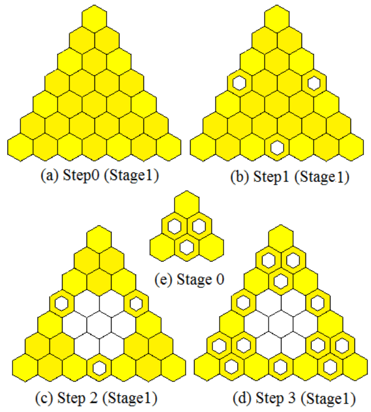


Fig. 2 – Iteration process: (a) step 0 for the 2nd iteration, (b) step 1 for the 2nd iteration, (c) step 2 for the 2nd iteration, (d) step 3 for the 2nd iteration, (e) the first iteration

4. PARAMETRIC STUDY

In this section, some parameters are studied to investigate the influence of these parameters on the antenna performance. This analysis is performed by varying one parameter while keeping the other parameters constant, as they are in Table 1.

Table 1 – Optimized geometrical parameters of the proposed fractal UWB antenna

Parameter	Dimension (mm)	Parameter	Dimension (mm)
L	20	g	0.25
W	19	d_1	1.95
Lf	7	d_2	1.25
Wf	1.2	d_3	1
Wg	6.85	r_1	1
Lg	5.5	r_2	0.65

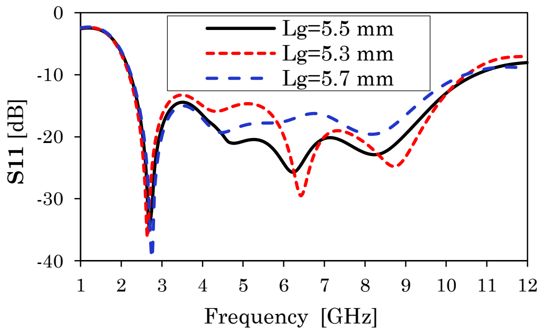
4.1 Effect of a Trapezoidal Ground Plane Parameter

The effect of the parameters of a trapezoidal ground plane on the return loss characteristics is shown in Fig. 3. It can be seen from Fig. 3a that the return loss is very sensitive to the length Lg, which is varied from 5.3 to 5.7 mm. The best $S_{11} < -10$ dB bandwidth and impedance matching are exhibited for Lg = 5.5 mm.

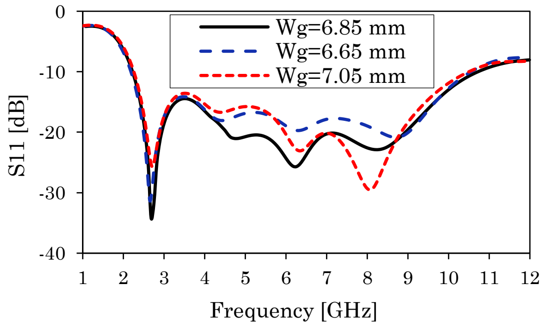
Fig. 3b shows the effect of a larger width of the trapezoidal ground plane Wg, the analysis is performed by varying it from 6.65 to 7.05 mm. The optimum performance is obtained for Wg = 6.85 mm.

4.2 Effect of Thickness of Parasitic Strips

The effect of parasitic strips width is carried out by varying the 1st thickness d_2 from 1 to 1.5 mm. From Fig. 4a, it can be seen that the best $S_{11} < -10$ dB bandwidth and impedance matching are exhibited for d_2 = 1.25 mm. The effect of the 2nd thickness d_3 is similar to the analysis of the 1st thickness, the best value is d_3 = 1 mm, as illustrated in Fig. 4b.

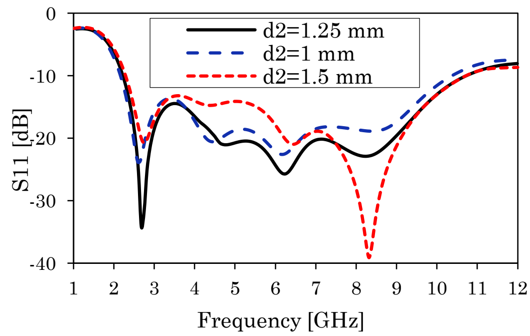


a

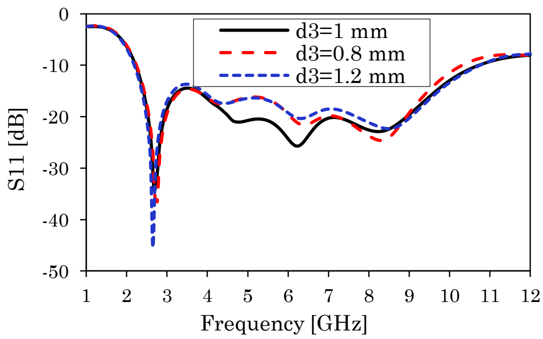


b

Fig. 3 – Effect of the ground plane parameter on the reflection coefficient S_{11} of the suggested antenna: (a) various ground lengths *Lg*, (b) various widths *Wg*



a



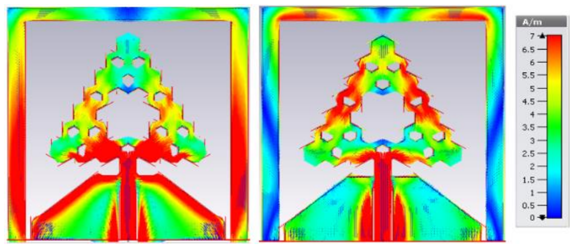
b

Fig. 4 – Effect of the thickness of parasitic strips on S_{11} of the suggested antenna: (a) various length d_2, (b) various length d_3

5. RESULTS AND DISCUSSION

5.1 Current Distribution Results

Fig. 5 shows the surface current distributions of the suggested antenna. The current distributions are calculated at two resonant frequencies of 2.68 and 6.25 GHz. At the first frequency, it can be seen that the surface current is concentrated on the lower edge of the patch and completely on the fed strip, and some parts are formed on the upper edge of the ground plane and on the parasitic vertical wires. For the second frequency, the surface current is spread mostly on the fed strip, upper and lower edges of the fractal patch, and on the lower edge of the horizontal wire.



a b

Fig. 5 – Surface current distributions of the proposed antenna at (a) 2.68 GHz and (b) 6.25 GHz

5.2 Input Impedance and Gain of Antenna

Fig. 6 represents the simulated input impedance variation of the proposed structure. The curve shows that the real part of the antenna input impedance characteristic is normalized to 50 Ohms and its value is 36.9-64.61 Ohms in the entire frequency range 2.22-10.7 GHz. While the imaginary part is nearly oscillating around the zero line, which indicates a good adaptation of the designed antenna throughout the operating band.

Fig. 7 shows the simulated gain versus the frequency of the suggested antenna. A gain of more than 2.61 dBi is obtained in the entire UWB spectrum. The peak is near 4.77 dBi at 9.8 GHz. We note that this type of UWB antenna is suitable for indoor and outdoor short-range communications.

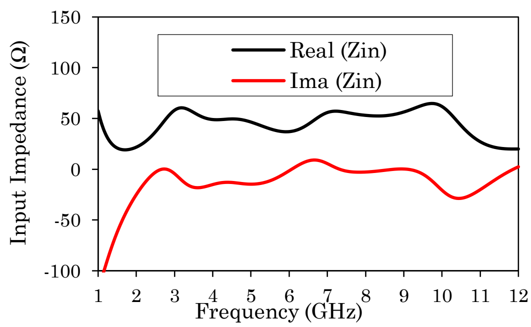


Fig. 6 – Input impedance of the proposed antenna (real and imaginary parts)

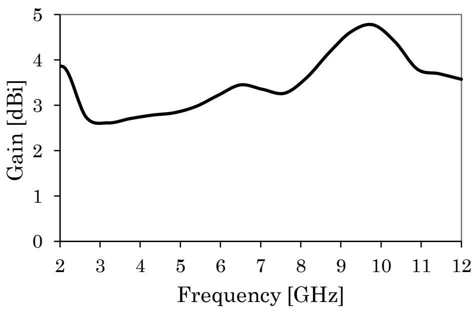


Fig. 7 – Simulated gain of the proposed antenna

A comparative study of the proposed antenna with other planar antennas in terms of size, occupied area and operation band is summarized in Table 2. From this comparative study, it is evident that the proposed antenna occupies the smallest area compared to the other mentioned designs, with sufficient bandwidth to cover the entire range of applications of interest.

Table 2 – Performance comparison of the proposed antenna with other reported UWB antennas

Ref.	Antenna size (mm)	Occupied area (mm^2)	Bandwidth (GHz)	Bandwidth (%)
[18]	34 ×43	1462	2.99-12	120
[19]	30 × 25	750	3.55-11.17	103.53
[8]	39 × 36.5	1423.5	3.1-13.65	125.97
[20]	28 × 28	784	3.41-15.37	127.36
This work	19 × 20	380	2.22-10.7	131.27

5.3 Experimental results

The proposed fractal UWB antenna prototype is fabricated with standardized technologies using a laser printer for printed circuits. The input reflection coefficient of the fabricated prototype is measured using an Agilent 8722ES vector network analyzer (VNA). The measured results seem to be in good agreement with the simulated return loss, as illustrated in Fig. 8. It can be observed that the measured impedance bandwidth covers from 2.22 to 10.44 GHz, which is 129.85 %, while the calculated one covers from 2.22 to 10.7 GHz, which is 131.27 %.

The far-field radiation patterns of the proposed fractal UWB antenna are also measured in a microwave anechoic chamber at two different frequencies of 2.68 and 6.25 GHz. The radiation patterns at these two different frequencies in the *E*- and *H*-planes are shown in Fig. 9: (a) co-polarization, (b) cross-polarization and (c) co-polarization, (d) cross-polarization), respectively. From the measured results, the radiation patterns of the proposed antenna are bidirectional in the *E*-plane, while the *H*-plane radiation pattern is nearly omnidirectional. However, some distortion of the radiation pattern can be observed due to the experience environment and reflections at the edges of the miniature fractal structure.

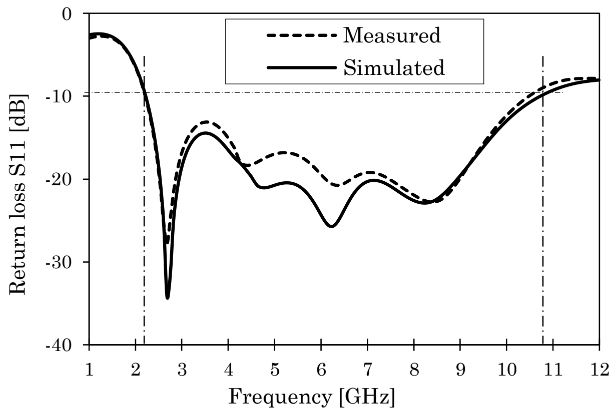


Fig. 8 – Simulated and measured reflection coefficients of the proposed fractal antenna

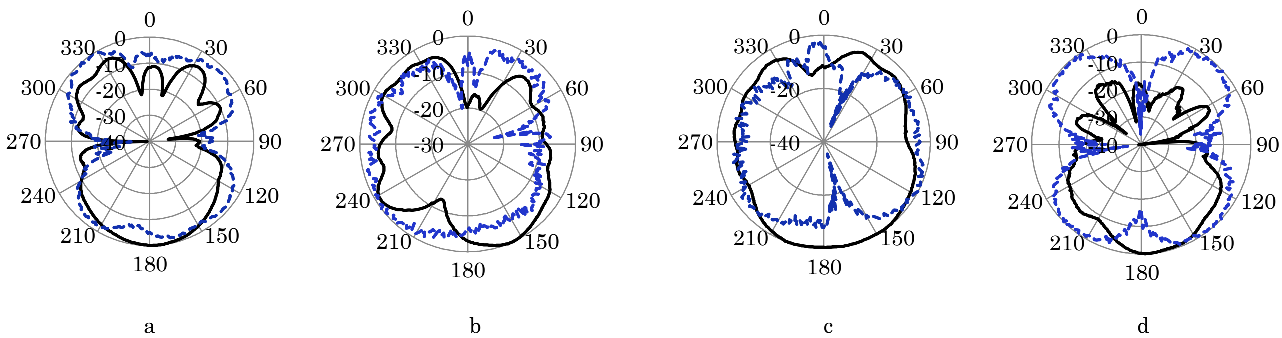


Fig. 9 – Measured normalized radiation patterns of the proposed fractal UWB antenna at 2.68 GHz (solid line) and 6.38 GHz (dashed line): (a) co-pol *E*-plane, (b) cross-pol *E*-plane (c), co-pol *H*-plane, (d) cross-pol *H*-plane

6. CONCLUSIONS

In this paper, a novel compact fractal antenna with CPW-feed line and a trapezoidal ground plane has been designed and fabricated with overall dimensions of $19 \times 20 \times 1.52\ mm^3$, which operates from 2.22 to 10.7 GHz, which is 131.27 %. Good agreement is obtained between the simulation and the measurement result of the reflection coefficient characteristics. The antenna exhibits a nearly omnidirectional radiation pattern in the *H*-plane and a bidirectional radiation pattern in the *E*-plane. The proposed design approach provides a miniature size and return loss performance of the proposed fractal antenna with moderate gain over the entire band and makes it suitable for wireless and UWB applications.

ACKNOWLEDGEMENTS

This work was supported by the Directorate General for Scientific Research and Technological Development (DG-RSDT) of Algeria under PRFU project number A25N01UN240120180001.

REFERENCES

1. A.T. Abed, M.S. Jit Singh, M.T. Islam, *IET Microw. Antennas Propag.* **12** No 14, 2218 (2018).
2. H.K. Ryu, J.M. Woo, *Electron. Lett.* **43**, 372 (2007).
3. P.L. Chi, K.M. Leong, R. Waterhouse, T. Itoh, *ISSSE*, 595 (2007).
4. H.S. Choi, J.K. Park, S.K. Kim, J.Y. Park, *Microw. Opt. Technol. Lett.* **40** No 5, 399 (2004).
5. H. Mardani, C. Ghobadi, J. Nourinia, *IEEE Antennas Wireless Propag. Lett.* **9**, 1076 (2010).
6. D.H. Kwon, Y. Kim, *IEEE Int. Symp. Antennas Propag.* **3**, 2947 (2004).
7. Federal Communications Commission, FCC02-48 (2002).
8. D. Aissaoui, L.M. Abdelghani, N. Boukli-Hacen, T.A. Denidni, *Microw. Opt. Technol. Lett.* **58** No 10, 2370 (2016).
9. S. Singhal, T. Goel, AC. Singh, *Microw. Opt. Technol. Lett.* **57** No 3, 559 (2015).
10. C. Raghavendra, B.P. Kalyan, K. Vijaykrishna, A. Vamsikrishna, *IJEAT* **9**, 2949 (2019).
11. A. Kumar, A.P. Singh, *Int. J RF Microw. Comput. Aided Eng.* **29** No 8, e21786 (2019).
12. Devesh, M.G. Siddiqui, A.K. Saroj, J.A. Ansari, *5th IEEE Uttar Pradesh Section Int. Conf. Electrical, Electron. Comp. Eng. (UPCON)*, (2018).
13. C. Puente, J. Romeu, R. Pous, and A. Cardama, *IEEE Trans. Antennas Propag.* **46** No 4, 517 (1998).
14. H.O. Peitgen, H. Jurgens, D. Saupe, *Chaos and Fractals New frontiers in science* (New York: Springer-Verlag: 1992).
15. H.D. Werner, S. Ganguly, *IEEE Antennas Propag. Magazine* **45** No 1, 38 (2003).
16. R. Jordi, S. Jordi, *IEEE Trans. Antennas Propag.* **49** No 8, 1237 (2001).
17. W.L. Stutzman, G.A. Thiele, *Antenna Theory and Design (*New York: Wiley: 1981).
18. A. El Hamdouni, A. Tajmouati, J. Zbitou, H. Bennis, A. Errkik, L. El Abdellaoui, M. Latrach, *TELKOMNIKA* **18** No 1, 436 (2020).
19. N. Seladji, F.Z. Marouf, L. Merad, S.M. Meriah, F.T. Bendimerad, M.Bousahla, N.Benahmed, *Mediter. Telecom. J.* **3** No 1, 21 (2013).
20. A. Tanweer, B.K. Subhash, C.B. Rajashekhar, *PIERC* **84**, 161 (2018).
21. A. Othman, N.I.S. Shaari, A.M. Zobilah, N.A. Shairi, Z. Zakaria, *Ind. J. Elec. Eng. Comp. Sci.* **15** No 3, 1197 (2019).

Проектування та аналіз нової фрактальної компактної антени для надширокосмугових застосувань

N. Guebgoub[1], O. Mahri[1], T.A. Denidni[2], S. Redadaa[1]

[1] *Laboratoire des Télécommunications, Université 8 Mai 1945, Guelma, 24000-B.401, Algérie*
[2] *CEMT – INRS, 800 Rue De La Gauchetière Ouest, Bureau 6900, Québec, H5A 1K6, Canada*

У статті повідомляється про нову компактну фрактальну друковану монопольну антену, яка нагадує трикутну серветку Серпінського, для надширокосмугових (UWB) застосувань. Запропонована антена розроблена за допомогою нової математичної моделі та нової ітераційної процедури для створення фрактальної геометричної форми модифікованої серветки Серпінського (MSG). Рекурсивна процедура формування MSG як випромінювального елемента заснована на рівнобічній трикутній сітці вузлів, яка побудована з використанням рекурсивної послідовності. Для узгодження імпедансу 50 Ом випромінюючий монополь MSG живиться від компланарного хвилеводу (CPW) із трапецієподібною заземлюючою площиною. Моделювання та оптимізація різних параметрів запропонованої фрактальної антени виконано за допомогою CST Microwave Studio. Результати моделювання показують, що запропонована антена має помірне посилення у всьому діапазоні з піком 4,77 дБі на частоті 9,8 ГГц. Зазначену антену також порівнюють з аналогами у відповідній літературі, щоб диференціювати її продуктивність. Загальний розмір представленої антени, яка розроблена на підкладці Rogers RO4003C ($\tan\delta = 0.0027$ та $\varepsilon_r = 3.38$), становить 19×20×1,52 мм^3. Крім того, реалізовано і протестований компактний прототип антени. Результати вимірювань коефіцієнта відбиття показують гарну узгодженість з результатами моделювання. Сконструйована антена демонструє діаграми спрямованості в усіх напрямах та охоплює діапазон частот 2,22-10,7 ГГц, що робить її придатною для бездротових та UWB додатків.

Ключові слова: Компактна антена, Фрактал, Друкований монополь, Серветка Серпінського, Бездротовий зв'язок, Надширокосмуговий.