Proceedings of 29th International Scientific Conference. Transport Means 2025.

Study of the Radiating Properties of a Fractal Antenna in the Form of a Sierpinski Napkin

V. Ruban[1], D. Ruban[2]

[1]*Ukrainian State University of Science and Technologies, Lazarian St., 2, 49010, Dnipro, Ukraine,*
E-mail: v.o.ruban@ust.edu.ua
[2]*Oles Honchar Dnipro National University, 72 Nauky Avenue, 49000, Dnipro, Ukraine,*
E-mail: di01an07na2000@gmail.com

https://doi.org/10.5755/e01.2351-7034.2025.P626-629

Abstract

The paper investigates the radiation characteristics of a microstrip fractal antenna in the form of a Sierpinski napkin, which is used to provide communication in high-frequency ranges, including advanced defense technologies. The mathematical modeling and computer study of the antenna by the finite difference time-domain method (FDTD) are performed. The influence of the iterative order of the fractal and the use of a metamaterial substrate on the radiation characteristics and matching of the antenna is studied. The frequency range of 2.5-10 GHz is investigated with the determination of optimal power supply parameters. The obtained results can be used in the development of small-sized multiband antennas for military communication systems, unmanned aerial vehicles (UAVs) and electronic warfare (EW). In today's war in Ukraine, when technological superiority plays a decisive role in the conduct of hostilities, the development of compact, adaptive and low-observable antenna systems is critical. The antenna under consideration has several strategic advantages. In particular, its multi-frequency capability allows it to operate effectively in a wide frequency range, which is important for building stable communication channels in the conditions of active use of enemy electronic warfare. The compact size and the ability to integrate with metamaterials provide a reduction in electromagnetic detection, which is critical for covert communication systems. Its design can be used in antenna systems for tactical UAVs, which play a key role in conducting aerial reconnaissance, adjusting artillery fire, and ensuring continuous communication between units. In addition, the development of such antenna systems contributes to the improvement of navigation and positioning systems in conditions where satellite signals can be jammed or distorted by the enemy. The potential integration of the proposed antenna into autonomous unmanned platforms, mobile command posts, and wireless communication systems on the battlefield will increase the situational awareness of troops and their combat effectiveness. Thus, the results of this study can contribute to the development of high-tech solutions for the defense sector of Ukraine and strengthen its capabilities in the field of wireless communications, which is a key factor for the successful conduct of combat operations in modern conditions.
KEY WORDS: *microstrip antenna; power supply method; reflection coefficient; directional coefficient; microstrip line; scattering matrix parameter; gain; fractal antenna; iteration; metamaterial; patch; patch antenna*

1. Introduction

Wireless information transmission systems are playing an increasingly important role in today's environment. The growing number of people using mobile phones, tablets and other wireless devices has accelerated the development of wireless communication technologies and systems, including antennas. Wireless communication is the transmission of information between two or more points that are not connected by an electrical conductor. Modern military operations depend heavily on the effectiveness of communication, intelligence and electronic warfare (EW) systems. The high saturation of the battle space with unmanned aerial vehicles (UAVs), reconnaissance systems and electronic warfare (EW) equipment requires the use of the latest antenna technologies that combine multi-frequency, low visibility and high radiation efficiency. One of the most promising solutions is fractal antennas, which, due to their self-similar structure, provide compact dimensions, a wide range of operating frequencies and increased resistance to interference.

Microstrip antennas are used to track airborne targets, as navigation aids on cars and other moving objects, and are also used in communication channels between ships or satellites. The size of the antenna used in communication systems depends on the frequency used ($f > 1$ GHz). The shape of a microstrip antenna is highly variable. Some of the most common shapes are rectangle, square, circle, and triangle. This paper is devoted to the consideration of a triangular antenna, its design and modeling.

One of the most urgent tasks for the further development of modern mobile devices is to reduce the size of their antennas to the point of integration in a single system-on-chip (SoC) package. Therefore, in the last decade, the search for unconventional approaches to the realization of microwave technology has intensified significantly. Developers of microwave devices and antennas are increasingly using new materials and media with unusual electrodynamic properties. These are the so-called metamaterials, including chiral and percolation media, optomagnets, photonic and electronic crystals. Metamaterials can be used as substrates for printed miniaturized antennas, helping to reduce the size of the radiators, increase their bandwidth and radiation efficiency. Moreover, their structure can be either homogeneous or composite, which is formed from several types of media with different properties. By selecting their size and ratio, the resonant frequency of the printed antenna can be adjusted.

A fractal antenna is used as one of the options for expanding the multi-band antenna for a mobile phone. The fractal approach makes it possible to place antenna elements more densely (compared to elementary radiators with the same magnitude of their mutual influence). This determines the relevance of research in this area. The main content of the work is the study of a fractal antenna in the form of a Sierpinski napkin.

2. Literature Review

Modern antennas used in military and telecommunication systems must provide high radiation efficiency, compactness, and resistance to interference. Microstrip antennas are a promising solution for such tasks, in particular in military communication systems, unmanned aerial vehicles (UAVs), and electronic warfare (EW). Fractal structures, such as the Sierpinski napkin, make it possible to extend the frequency range of an antenna without significantly increasing its size. Microstrip antennas are compact, lightweight, and technologically simple to manufacture antenna structures that are widely used in wireless communications, military communications systems, navigation, and electronic warfare. They consist of a radiating element (patch) located on a dielectric substrate with a metallized backside (screen) [1, 2].

The main types of microstrip antennas are determined by the shape of the radiating patch: ***rectangular -*** the most common type, providing stable radiation characteristics and relatively simple design; ***round -*** used in antenna arrays and systems requiring circular polarization; ***square -*** have similar characteristics to rectangular ones, but are more symmetrical in field distribution; ***triangular -*** provide miniaturization of the structure and the possibility of creating fractal antennas***;*** ***fractal antennas -*** antennas with a multi-frequency structure using self-similar geometric shapes, such as the Sierpinski napkin. Fractal designs allow to significantly reduce the size of the antenna while maintaining radiation efficiency in a wide frequency range. This makes them promising for use in mobile combat systems, drones, and covert communications, which is especially important in modern warfare. The main types of fractal antennas include: ***Sierpinski napkin -*** a triangular structure formed by recursively removing the central triangles; ***Sierpinski's carpet*** is a fractal structure based on a square, which is created by sequentially cutting out the central parts; ***Koch snowflake -*** a fractal obtained by gradually adding smaller triangles to the sides of the main triangle; ***Minkowski curve -*** broken, consisting of repeating segments, which increases the length of the conductor while maintaining compactness; ***Hilbert curve -*** a continuous fractal curve that fills the area; ***Cantor set -*** a fractal structure obtained by sequentially removing parts of segments. ***H-Tree and Pythagorean Tree*** are hierarchical tree-like structures. These antennas have important advantages, in particular, a reduction in size while maintaining effective radiation parameters, which makes them effective for use in modern wireless communication systems [2-6].

Based on the above, it can be seen that the design of a triangular patch antenna based on a fractal structure in the form of a Sierpinski napkin has the prospect of reducing the mass and size parameters by removing part of the radiating surface, which is an urgent task of improving antenna devices for mobile communications. The frequency range of the study is from 2.5 to 10 GHz to ensure the development of the next generations of communication equipment. The aim of this work is to obtain the radiation characteristics (angular radiation patterns in terms of gain and directivity, efficiency) and matching (frequency dependence of the S11 coefficient) of the studied microstrip antennas based on the Serpinsky napkin, provided that the substrate is made of FR4 dielectric with a grounded surface made of metamaterial [7-9].

The study of a triangular microstrip patch antenna based on the fractal structure of the Sierpinski napkin is relevant because of the possibility of reducing the weight and dimensions of the antenna, which is important for communication devices. The frequency range of the study is from 2.5 to 10 GHz to ensure the development of the next generations of communication equipment. The main goal is to study the radiation characteristics and match the studied microstrip antennas based on the Serpinsky napkin, provided that the substrate is made of FR4 dielectric with a grounded surface made of metamaterial. Various software packages are used to model and calculate antennas. The most popular among them are MMANA-GAL and 4NEC2, which are based on the NEC kernel. They are well suited for analyzing antennas represented as linear conductors, but have certain limitations, in particular, regarding the thickness of the conductors and the length of the segments. In the professional field, more powerful software packages such as ANSYS are more often used [10]. It is ANSYS HFSS that is most suitable for accurate modeling of microstrip and fractal antennas, in particular for the study of antennas in the form of Sierpinski napkins.

3. Study of Triangular Antenna Characteristics

Triangular microstrip antennas are a promising option for wireless communications because they provide compactness, tuning flexibility, and radiation efficiency. In this study, the finite difference time-domain (FDTD) method was used to analyze the behavior of the electromagnetic field in the antenna structure. The main object of the study was an equilateral triangular microstrip antenna located on a dielectric substrate using metamaterials.

A mathematical model of the antenna was constructed, which takes into account the main parameters, such as the length of the triangle side, the thickness of the substrate, and the relative permittivity of the material. The modeling results are compared with known analytical dependencies and other studies to verify the obtained results.

One of the key parameters of the antenna is the reflection coefficient S11, which determines the level of antenna matching with the power line. We investigated the dependence of this coefficient on different options for connecting the microstrip line: to the middle of the triangle side; to the top of the triangle. The results showed that the best matching is achieved when connecting the microstrip line to the middle of the triangle side, which provides the minimum value of the S11 coefficient. To optimize the matching, the effect of the microstrip line width on the antenna parameters was investigated. Different ways of feeding the triangular antenna were investigated by numerical modeling. Among the available feeding methods, the feeding by connecting the microstrip line to the middle of the triangle side and to the triangle vertex was investigated. Among these methods, the method of feeding to the middle of the antenna side is preferred, since the other method has a significantly higher (about 30 %) value of the scattering matrix parameter S11, i.e., the reflection coefficient. The influence of the strip width (different wave impedances) on the degree of matching was studied, and it was found that the strip with a width of 0.6 mm is the best. For the method of power supply through the middle of the triangle side, we investigated: a) the parameters of the S11 scattering matrix and obtained calculated data of the frequency of 6.99 GHz, which differs from the calculations by approximate formulas within 1%.

The analysis of the triangular antenna in the Wi-Fi band (2.4 GHz) is performed to determine the possibility of its application in modern wireless networks. The length of the triangle side required to provide a resonant frequency of 2.4 GHz is calculated. The results obtained indicate the possibility of effective use of this antenna in wireless communication systems. Comparison of the parameters of the triangular antenna at resonant frequencies of 2.4 GHz and 7 GHz showed that the best matching and radiation efficiency are achieved at a frequency of 7 GHz. This indicates the feasibility of using the antenna in higher frequency communication bands, such as 5G.

The directivity and gain coefficients of the antenna were analyzed. The results showed that the antenna's efficiency is close to 1, which indicates the high efficiency of the device. A three-dimensional radiation pattern was also constructed, which confirms the good radiation properties of the triangular antenna.

4. Research of Fractal Antenna

Fractal antennas are a promising area in the development of antenna technologies due to their unique geometric properties. They have a self-similar structure, which allows them to achieve multifrequency, compactness, and improved radiation characteristics. One of the most common types of fractal antennas is the Sierpinski napkin antenna, which is formed by iteratively removing triangular fragments from the initial equilateral triangular shape.

At the first stage of the study, we considered an antenna with one iteration of the fractal structure. The antenna geometry is obtained by cutting the central triangle from the original equilateral triangle. This design allows us to change the resonant properties of the antenna, which affects its radiation characteristics. The main parameters analyzed during the study:

- Resonant frequency and its changes compared to the basic triangular antenna.
- Reflection coefficient (S11) to determine the antenna matching efficiency.
- The effect of microstrip line width on the matching characteristics.

The results show that when switching from a traditional triangular antenna to the first iteration of the fractal, a shift in the resonant frequency is observed, which can be used to tune the antenna in the desired range. In addition, due to the self-similar structure, multi-frequency radiation was achieved.

In the second iteration, the central triangular fragments were additionally removed from each of the triangles obtained in the first stage. This led to a further increase in the length of the effective perimeter of the antenna, which affected its parameters:

- The resonant frequency has decreased, which allows the use of such antenna at lower frequencies.
- The frequency bandwidth has been widened, which is an advantage for multi-band devices.
- The coordination of the antenna with the power line has improved with the optimal choice of microstrip width.

At the third stage of the study, an additional fractal partitioning was performed, which led to a significant complication of the antenna geometry. This stage made it possible to assess how the increase in the number of iterations affects the radiation characteristics, in particular, additional resonances appeared at higher frequencies, which expanded the capabilities of the antenna for use in broadband communication systems. There was a decrease in efficiency due to increased losses in the fractal structure. The optimal number of iterations depends on the specific requirements for the antenna: if compactness and multifrequency are required, 2-3 iterations are sufficient, since further fractal partitioning does not provide a significant improvement. The analysis of the obtained results showed that:

- The first iteration ensures minimal changes in the characteristics, which makes it possible to use such antenna in compact devices with one main operating frequency.
- The second iteration strikes a balance between reducing the resonant frequency and maintaining radiation efficiency.
- The third iteration significantly expands the frequency band, but reduces the efficiency, which can be critical for some applications.

Thus, the optimal degree of fractal iteration depends on the specific requirements of the antenna: for military communications and electronic warfare systems, it is better to use antennas of the second or third iteration, since they provide broadband and multi-frequency, which are key factors for secure communications in combat.

5. Conclusions

A mathematical model of a triangular microstrip antenna is constructed using the finite difference time-domain

(FDTD) method. The correctness of the constructed algorithm is verified by comparing it with known results for a triangular patch antenna. It was found that the results obtained with graphical accuracy coincide with the results of other works, which emphasizes the correctness of the constructed algorithm.

Based on the studies, it was found that the use of fractal geometry in the form of a Sierpinski napkin can significantly improve the characteristics of microstrip antennas, in particular, expand their frequency range and increase radiation efficiency. The effect of the number of iterations of the fractal structure on the antenna parameters has confirmed that an increase in the level of fractalization contributes to the emergence of additional resonant frequencies, which can be useful for multi-frequency communication systems. Optimization of the structure using metamaterial substrates allows to reduce the size of the antenna and improve its coordination with the power line.

The study of the triangular microstrip antenna showed that it has good matching and radiation characteristics. The best matching is achieved when fed by a microstrip line in the middle of the side, and the optimal width of the microstrip line is 0.6 mm. The antenna can operate effectively in the 7 GHz frequency band, making it promising for use in 5G and other wireless networks.

The obtained results demonstrate the prospects of fractal antennas for use in wireless communication systems, including military and navigation technologies, where compactness, multi-frequency and efficiency in a complex electromagnetic environment are important. Further research can focus on the practical implementation of such antennas and their testing in real-world conditions.

References

1. **Fadel, L.; Oyhenart, L.; Bergès, R.; Vigneras, V.; Taris,T.** 2016. A concurrent 915/2440 MHz RF energy harvester, International Journal of Microwave and Wireless Technologies 8(3): 405-413. https://doi.org/10.1017/s1759078716000179
2. **Безносова, О.; Бухаров, С.; Овсяніков, В.; Свинаренко, Д.; Ципко, Л.** 2019. Антени та антенні решітки для мобільних рухомих об’єктів. ЛІРА.
3. **Balanis, C.A.** 2016. Antenna Theory: Analysis and Design. Wiley & Sons, Incorporated, John.
4. **Garg, M.; Singh, N.** 2015. Rectangular Microstrip Patch Antenna, International Journal of Computer Science and Technology 6: 31-33.
5. **Priya, S.; Bhandari, J.; Chaitanya, M.** 2019. Design and Research of Rectangular, Circular and Triangular Microstrip Patch Antenna, International Journal of Innovative Technology and Exploring Engineering 8: 1-2.
6. **Pandey, S.; Markam, K.** 2016. Design and Analysis of Circular Shape Microstrip Patch Antenna for C-band Applications, International Journal of Advanced Research in Computer Science & Technology 4: 169-171.
7. **Werner, D.; Werner, P.** 1995. On the Synthesis of Fractal Radiation Patterns, Radio Sci 30: 29-45.
8. **Єфремова, А.; Белоусов, О.; Калашников, С.; Казарян, О.** 2014. Застосування фрактальних антен для бездротових широкосмугових мереж четвертого покоління, Університет Ім. В.І. Вернадського 3: 1-6.
9. **Singh, D.; Singha, A.** 2016. Review Paper on Fractal Antenna, International Journal for Scientific Research & Development 4: 222-225.
10. **Ruban, V.; Stoianov, O.; Niziaiev, K.; Synehin, Y.** 2021. Determining changes in the temperature field of a graphitized hollow electrode during metal processing periods in ladle-furnace, Eastern-European Journal of Enterprise Technologies 2(1(110)): 109-115. https://doi.org/10.15587/1729-4061.2021.230002