Using Additive Technologies to Create Broadband Antennas with Fractal Geometry
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Abstract: The paper presents the results of a study of the frequency dependence of the $S_{11}$ parameters of antenna samples with fractal geometry, created using 3D printing technology, followed by the deposition of a conductive copper coating by galvanization. It is shown that changing the dimension of the fractal at different iterations, shifting and dividing the resonant frequencies, it is possible to flexibly form the working bands of antennas in any frequency range and any width. The developed designs can be used to create broadband rectennas.

Keywords: fractal, fractal dimension, additive technologies, rectenna

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1. INTRODUCTION
Since obtaining a patent for the first photopolymer printer in 1986, additive printing (or 3D printing) technology has evolved significantly. Over the past 5-7 years, a large number of affordable commercial products have appeared on the 3D technology market. This is due to a significant reduction in the cost of technology and the emergence of its various variations. One of the important advantages of the technology is the ability to create parts of complex geometric shapes in one technological cycle, without the manufacture of additional equipment. 3D printing can significantly increase the flexibility of production and has already proven itself for the manufacture of not only instrument cases, but also for the creation of functional
parts of electronics, microwave circuits and antennas [1-3].

However, the suitability of the technology for creating broadband antennas requires further research. In the case of antennas, the material must have good conductive properties. Existing samples of conductive plastics used for 3D printing do not have them. Therefore, to create experimental samples of antennas using additive technologies, it is necessary to create a conductive coating. Surface metallization can be carried out by various methods: vacuum deposition (magnetron, cathode-arc), electroplating, conductive paint. Vacuum spraying allows to obtain a uniform dense metal coating, however, in the case of parts with complex shapes, it has a disadvantage in the form of a shadow effect. Conductive paint does not have good electrical conductivity, so a promising option is the use of galvanization technology [4,5].

In the modern world, the concept of wireless sensor systems is rapidly developing, consisting of hundreds and thousands of miniature autonomous sensor elements. One of the options for providing such elements with electricity are systems for collecting background electromagnetic energy based on rectennas [6-8]. The main criterion applicable to such rectennas is a wide frequency range of operation. Thanks to which a sufficient level of energy is provided, despite its low density at one, specific frequency. The criterion of wide-range is met by rectennas, which are based on the elements of fractals.

Unlike traditional methods, when smooth dipole antennas are synthesized, the theory of synthesis of fractal antennas is based on the idea of realizing the characteristics of radiation with a repeating structure on arbitrary scales [9]. This makes it possible to create new regimes in fractal electrodynamics. The complex structure of fractal antennas provides such extremely important properties as broadband and multi-band [10].

The principle of constructing a common H-fractal begins with a figure in the form of the letter H, in which the vertical and horizontal segments are equal. Then, to each of the 4 ends of the figure, a copy of it, reduced in half, is attached. To each end (there are already 16 of them) is attached a copy of the letter H, already reduced by 4 times. Etc. In the limit, a fractal will turn out, which visually almost fills a certain square. In it, the H-fractal is dense everywhere. That is, in any neighborhood of any point of the square, there are fractal points. The H-fractal completely fills its square (space-filling curve). Therefore, its fractal dimension is equal to 2 [11]. The total length of all segments in an ideal fractal structure is infinite. In antenna technology, tree structures of the H-fractal type are used if it is necessary that a large number of elements in a complex circuit receive the same signal at the same time.

Placed at the end of a whip antenna, the tree-like elements increase the bandwidth and somewhat shorten the antenna at a constant frequency due to the length of their branches. The main advantage of the H-tree is its ability to efficiently fill the space. This property manifests itself in both two-dimensional and three-dimensional versions.

In this paper, we consider the process of creating rectennas based on the
geometric fractal H-tree by 3D printing on a photopolymer printer, followed by the application of a conductive copper coating by galvanization.

2. EXPERIMENTAL TECHNIQUE

In Fig. 1a shows the basic structures used to build 3D models. In Fig. 1b shows images of modeled tree-like rectennas used to create 3D models. Antenna mock-ups were created using SLA technology (laser stereolithography) on an Anycubic photon S photopolymer 3D printer with a UV source with a wavelength of 405 nm. The print resolution was 50 µm in the $xy$ plane and 10 µm in the $z$ axis. Photopolymer resin Anycubic Gray 405 nm UV Resin was used. The photopolymerization of the resin was carried out in layers, the thickness of one layer was 50 µm, the exposure time was 110 s for the first 5 layers and 10 seconds for the subsequent ones. At the end of the formation process, the model was separated from the metal table, washed in a solution of a mixture of acetone (puriss.) and isopropyl alcohol (puriss.) with a component ratio of 1:1 by weight. Then it was placed in a UV camera for 3 hours for additional polymerization under the influence of UV radiation with a wavelength of 405 nm.

Fig. 1. Image: (a) the basic structure underlying the antenna ($x_1 = 40$ mm, $x_2 = 20$ mm, $x_3 = 10$ mm); (b) models used for radiation pattern modeling and 3D printing.
In Fig. 2a shows photographs of samples of tree rectennas obtained as a result of 3D printing.

The antenna was coated with a conductive copper coating by the classical galvanization method. For this, the antenna surface was preliminarily coated with a conductive graphite varnish (Solins GRAPHITE). To prepare the electrolyte solution, 1 L of pure distilled water, 180 g of copper sulfate (pure), 25 g of sulfuric acid, and 10 ml of ethyl alcohol (pure) were taken. The anode was a 3 mm thick copper plate located along the perimeter of the container with the electrolyte; the cathode was a model placed in the center of the container. The current density was 0.15 A/dm² at the first stage – the formation of a conductive layer on the entire surface of the model (6 hours) and 0.5 A/dm² at the second stage – increasing the thickness over the entire surface of the model (20 hours).

The construction of radiation patterns corresponding to the field strength in the far zone for the models considered in this work was carried out by modeling by the finite element method.

Fig. 2. Photos: (a) 3D models obtained as a result of printing; (b) collected experimental antenna samples, after copper plating by galvanization.
The frequency dependences of the reflection coefficient (parameter $S_{11}$) in the coaxial transmission line loaded on the antenna were investigated.

The measurements were carried out in two types of transmission lines:

– N-type, using a Tektronix 506 A vector network analyzer (VNA), frequency range 1...6 GHz;

– K-type, using Anritsu vector network analyzer (VNA), frequency range 1...30 GHz.

These types of transmission lines have a characteristic impedance of 50 Ω and differ in the size of the coaxial line, the type of connectors (N-type and K-type, respectively) and broadband – the limiting upper operating frequency, at which acceptable matching parameters are still maintained (11 GHz for the N-type transmission line and 45 GHz for K-type transmission line). An increase in the limiting frequency is achieved by using a smaller coaxial line [12].

The measurement process included the calibration of the analyzer in the used frequency range, the connection of the investigated object to the measurement transmission line, and the recording of the frequency response of the $S_{11}$ parameter.

The obtained frequency characteristics are shown in Fig. 3 (VNA Tektronix, N-type transmission line) and Fig. 5 (VNA Anritsu, K-type transmission line).

3. RESULTS AND DISCUSSION

In different regions of the frequency range, the structure of a fractal antenna works simultaneously both as a single conductor and as a set of smaller conductors. If the signal is transmitted and received at the lower frequency of the range, then the entire structure is involved. If higher frequencies are used, then smaller structural elements corresponding to shorter wavelengths are used. The number of resonances increases with the number of fractal iterations.

The broadband of fractal antennas is ensured by the fact that their structure works simultaneously both as a whole and as a set of smaller antennas. The larger the number of fractal iterations, the finer structures the antenna will contain, and the higher in frequency the resonances will be. However, with

![Fig. 3. Frequency dependence $S_{11}$ of the parameters of antennas with different iterations in the range of 1-40 GHz in the N-type transmission line a) 1; b) 2; c) 3.](image-url)
an increase in iterations, the effective length of the antenna decreases, the antenna sections are moved to another plane of polarization and often form countercurrents, which reduces the gain at each specific frequency.

In Fig. 4 show the radiation patterns for tree-like fractal antennas of 3 iterations

![Antenna radiation patterns](image-url)

*Fig. 4. Antenna radiation patterns corresponding to the field strength in the far-field with iteration a) 1, b) 2 and c) 3.*
based on the 3D model of the H-fractal in different planes and in different frequency ranges.

The radiation pattern of any fractal antenna will be frequency dependent, since at different frequencies, different parts of the structure will resonate; when the frequency changes, the phase of the signal and the strength of the current flowing through these structures will change. It can be seen from the figures that the antenna directivity pattern in the horizontal plane is uniform at almost all frequency ranges, which ensures signal reception from all directions.

The low-frequency (1 ... 6 GHz) region is characterized by a set of high-quality peaks, the number of which increases with an increase in the iteration order of the fractal structure. The intensity of the peaks in absolute value does not exceed 20 dB. This pattern is seen on both VNA Tektronix

Fig. 5. Frequency dependence $S_{11}$ of the parameters of antennas with different iterations in the range of 1-30 GHz in the K-type transmission line a) 1; b) 2; c) 3.
(N-type transmission line) and Anritsu VNA (K-type transmission line).

In the frequency range 7.5...30 GHz, bands are observed formed by individual peaks with different center frequency and quality factor. An increase in the iteration order leads to an increase in the intensity of individual peaks and an expansion of the total frequency band, in which the absolute value of the parameter $S_{11} = 10$ dB or more. It should be noted that this Raman spreading occurs both in the lower and upper parts of the range.

4. CONCLUSION

The revealed electrodynamic properties of the investigated fractal antennas make it possible to conclude that the investigated fractal antennas are broadband and multirange, as well as the dependence of the number of resonances on the order of iterations of the fractal curve. This mechanism allows to control the antenna pattern and resonances by manipulating the dimension and the number of fractal iterations. Changing the dimension of the fractal at different iterations, shifting and dividing the resonant frequencies, it is possible to flexibly form the working bands of antennas in any frequency range and any width.

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