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Table of Contents

Antenna synthesis based on fractal approach and DRA technologies

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***Abstract*—The paper presents the results of the study combined antennas developed on the basis of dielectric resonator elements and a fractal approach. This approach allows to achieve a broadband and multi-band antenna systems. As a basic structure is considered, composed of a recursive tree and passive dielectric resonators. To simplify the analysis of the characteristics of the proposed antennas, their arrangement is limited by the fractal on the level of the first three iterations, and the number of dielectric resonators does not exceed four. Due to the complexity of describing the interaction of the antennas of non-Euclidean geometry with radio waves for their synthesis and analysis selected methods for the numerical simulation. An evaluation of the spatial-frequency characteristics of the designed antenna solutions used indicators such as return loss, beam pattern and voltage standing wave ratio.**

Keywords—amplitude-frequency response, antenna, beam pattern, dielectric resonator antenna, fractal, quasi-fractal, return loss, voltage standing wave ratio.

I. Introduction

Modern telecommunication systems data transfer needs to satisfy several conflicting requirements. It is influenced by the following factors:

– commissioning the mobile communication systems 5G requires a revision of the allocation of the frequency resource;

– support for the 5G network technology the IoT provides work at frequencies which were previously used in mobile communication systems;

– the widespread introduction of Wi-Fi equipment 802.11ac(ax), Bluetooth and WSN encourages the development of standardized means of telecommunications that are able to operate in these networks and with support for 5G;

– promising technologies (Digital Beam Forming (DBF), MIMO, MU-MIMO and Massive MIMO) focused on the use of multi-frequency signals based on OFDM;

– improvement of the technological production process ensures the miniaturization of telecommunication systems, which also affects the study of the characteristics of the antennas.

As you know [1], in the first phase for 5G in Europe, the planned frequency band: 694÷790 MHz, 3.4÷3.8 and 24.25÷27.5 GHz. It is expected that low frequency (e.g., 3.4-3.6 GHz) and wide bandwidth will provide the opportunity for the mass availability of speeds up to 100 Mbit/s. It is important to reach the mass market of the IoT [2]. Low frequencies will also be used for secure connection of different devices to a 5G network, for example, vehicles (frequency 700 MHz and 3.6 GHz). This option 5G can be used for industrial automation for applications that are delay-sensitive, to connect unmanned vehicles. In most countries, as expected, under system 5G will be allocated a continuous band with a width of 300-400 MHz. It can be expected that the individual operator will be provided up to 100 MHz continuous bands in the range 3.4-3.8 GHz. High frequency and wide bandwidth can be used to connect the user with peak data speeds up to 20 GB/s (in the range 24.25-27.5 and 37-43.5 GHz). These ranges are the most likely for global commercialization of 5G in the field of high frequencies.

All of the above requires the implementation of combined integrated antenna solutions that have appropriate levels of broadband and multi-band [3].

II. Analysis of Recent Studies and Publications, Which Discuss the Problem

Currently, the synthesis of such antennas is possible in several ways, for example: the use of metamaterials [4]; the use of electrically small antennas [5]; the introduction of fractal [6] or quasi-fractal geometric structures [7]; the introduction of elements based on dielectric resonator antennas (DRA) [8]; the implementation of combinations of the technological approaches.

In general, antennas based on fractal or quasi-fractal and dielectric resonators, in a theoretical context not yet investigated.

The analysis of publications concerning quasi-fractals shows that most developed micro-strip antenna solutions, for example: [9], as well as elements on the basis of the Serpinski fractal. Pretty good version of a detailed description of such structures is given in [10].

On the other hand, in [7, 8, 11] given the options of integration of the classical emitter (ring vibrator) with a quasi-fractal dielectric resonators (the total number to five), which are synthesized from simple geometric shapes at first iteration fractals. The use of the term "quasi-fractal" due to the fact that peripheral elements are superimposed on the central, there is a strict progression of repeatability of elements every time you change the scale or is incomplete or inaccurate, the similarity of the structure and its elements [11].

Thus, systematization of the results of the analysis of such antennas is only beginning to develop.

In this sense, it is advisable to evaluate antenna solutions, where the geometry of the emitter and/or dielectric structures describes the fractal (quasi-fractal). All this testifies to the importance given in research results.

III. The Aim of Research

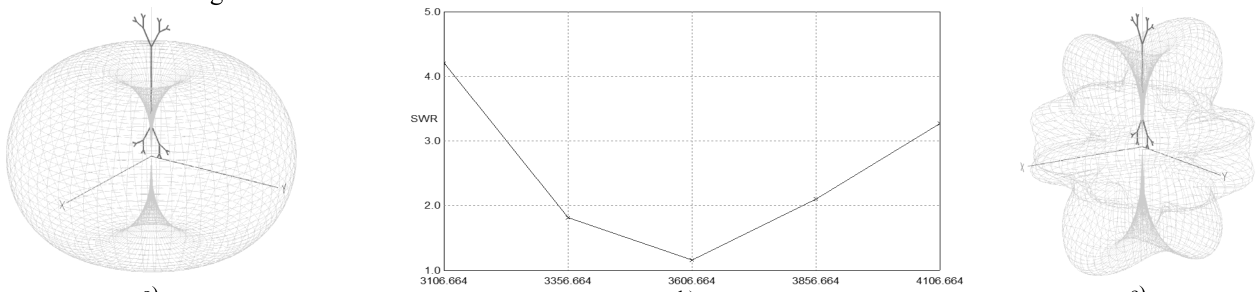
Thus, the purpose of this article is to increase the efficiency of antenna systems by the use of fractal approach and technology DRA.

IV. Main Results of the Study

You should note that for the analysis of the properties of the antenna broadband supports necessary to evaluate such characteristics as bandwidth. However, there are several variants of this definition, for example: stripe direction and the antenna gain; bandwidth efficiency; frequency range polarization; the band in which aged set as a circular polarization antenna (the so-called axial ratio); band on the criterion of impedance or return loss [12]. For the latter use different definitions of impedance in the frequency range, such as: $VSWR$=3; module S_{11}, less than -10 dB; the maximum real impedance, etc. The choice of a particular indicator depends on the scope of the antennas. As a result, the article introduced assumptions, which include the concept of bandwidth for Voltage Standing Wave Ratio (VSWR), not to exceed level 2 – $BW_{VSWR<2}$, and focus on the first resonance. To estimate the spatial-frequency characteristics of the designed antenna solutions used return loss (namely, the parameter S_{11} of a scattering matrix), Beam Pattern (BP) and VSWR.

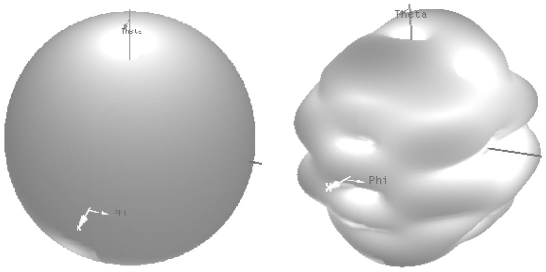
To ensure multi-band combination antenna the proposed fractal approach. In this case, the emitter is synthesized in the form of a recursive 2D tree 3rd iteration (I=3) with the segmentation angle of 60° (Fig. 1), the base model which is developed in the program MMANA-GAL 1.2.0.20 version [1]. This model was provided by simultaneous operation in the range of 3.4-3.8 and 24.25-27.5 GHz. So, for the frequency of the first resonance (F_1=3.6067 GHz) VSWR equal to 1.06 (without matching circuits), and the bandwidth was $BW_{VSWR<2}$=513.628 MHz, and the frequency of the 3rd resonance (F_3=23.6 GHz) VSWR equal to 2.36. The inclusion of schema matching Z and VSWR allowed to obtain for F_3 – $BW_{VSWR<2}$≈4.5 GHz. The wire radius is 0.5 mm. Unfortunately used version of the software MMANA-GAL has limitations, including the use of elements of DRA. With the aim of eliminating this deficiency in the article was reproduced above mentioned fractal model of the 2D-tree in the program HFSS [13] with characteristics that confirm the coincidence with the initial model, for example, Fig. 2. In turn, the lack of this software built-in mechanism for defining the parameters of the device approval according to Z and VSWR requires additional use of charts Wolpert-Smith and/or program ANSYS Designer [14]).

The next step of the synthesis of antenna design was a transition from the basic model to a combined antenna with a single-port power circuit which contains four identical dielectric resonators with ε=50 and the emitter (recursive 2D tree (I=3) with the angle of segmentation 60°), which can be accommodated in the plane of the resonator or perpendicular to it (Fig. 3).



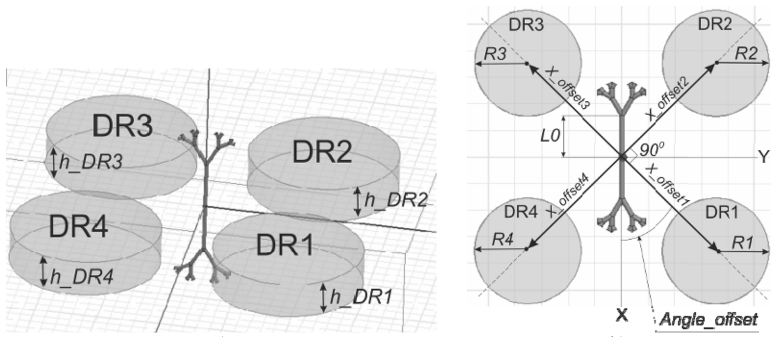
a) b) c)

Fig. 1. An example of spatial frequency characteristics of the model of the radiator in the program MMANA-GAL: a) – BP for F_1; b) – VSWR for F_1 (without your approval); c) – BP for F_3



a) b)

Fig. 2. BP model 2D-trees of the 3rd iteration with the angle of the segmentation 60° in HFSS: a) – F_1; b) – F_3

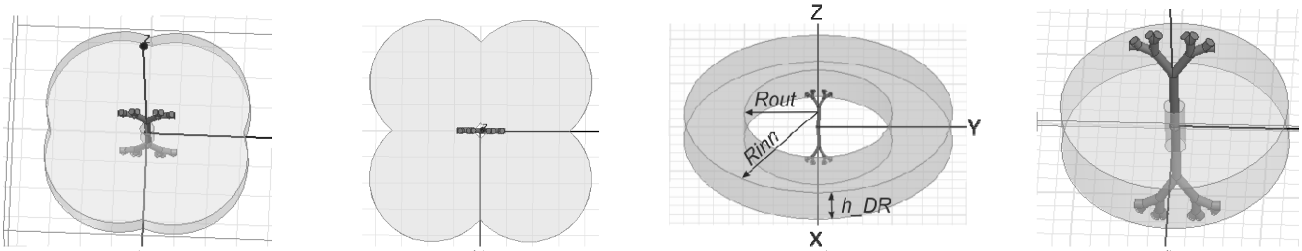


a) b)

Fig. 3. The structure of the combination antennas: a) – the vertical positioning of the fractal emitter; b) – the horizontal positioning of the fractal emitter

Unlike initial model, the size of the recursive tree took into account the size of the discrete power port, which was designed for impedance of 50 Ohms. The estimation of the spatial-frequency characteristics of the antenna from its geometry was conducted by changing the parameters of the resonators and the distance between them and the emitter. This allowed us to explore the degenerate layout located at vertical fractal tree (Fig. 4).

The studies determined the optimal geometry of the combined antenna according to the criterion of maximum $BW_{VSWR<2}$ for the first resonance frequency F_1 in the conditions of overlap of the frequency band 3.4-3.8 GHz and the lack of coordination Z and VSWR. The fragments obtained are shown in Tables I and II (by default, the variable *Angle_offset*=45°), and for degenerate structure (single ring resonator) in Table III.



a) b) c) d)

Fig. 4. Degenerate layout of the antenna: a) – X_offset1÷4=6 mm; b) – X_offset1÷4=13 mm; c) – at the confluence of the resonators in one ring; d) – minimizing the inner diameter of the ring resonator

TABLE I. SIMULATION RESULTS OF ANTENNA WITH A VERTICAL EMITTER (FIG. 3.A)

№	*R*1÷4, mm	*h_DR*1÷4, mm	*X_offset*1÷4, Mm	Min. return loss F_1, dB	$BW_{VSWR<2}$, GHz	F_1, GHz	Note
1	12	6	6	-19.3	0.2478	3.1	Fig. 4.a
2	12	6	13	-20	0.2402	3.1	Fig. 4.b
3	12	6	20	-15	0.3062	3.3	
4	12	6	23	-13	0.2917	3.4	
5	12	6	25	-13.2	0.2925	3.45	
6	12	6	30	-14.2	0.3620	3.6	
7	12	6	35	-16.5	0.3298	3.6	
8	12	6	40	-20.5	0.3292	3.6	
9	12	6	45	-22.1	0.3396	3.6	
10	12	8	50	-20.1	0.6258	3.6	
11	14	8	50	-21	0.5517	3.6	
12	14	10	50	-20.3	0.6182	3.6	
13	14	14	50	-17.8	0.6187	3.7	
14	14	14.5	50	-15.5	0.6219	3.7	
15	14	14.6	50	-12.7	0.6219	3.7	

TABLE II. SIMULATION RESULTS OF ANTENNA WITH HORIZONTAL EMITTER (FIG. 3.B)

№	*R*1÷4, mm	*h_DR*1÷4, mm	*X_offset*1÷4, Mm	min. return loss F_1, dB	$BW_{VSWR<2}$, GHz	F_1, GHz
1.	14	14.7	50	-20.8	0.5799	3.6
2.	14	14.7	55	-20.5	0.5463	3.6
3.	14	14.6	55	-18.7	0.5844	3.6
4.	14	14.5	55	-19	0.5820	3.6
5.	15	14.4	50	-18.2	0.5899	3.6
6.	15	14.7	55	-23.5	0.5463	3.5

TABLE III. SIMULATION RESULTS OF THE ANTENNA WITH RING RESONATOR (FIG. 4.C)

№	*h_DR*, mm	R_{inn}, mm	R_{out}, mm	Min. return loss F_1, dB	$BW_{VSWR<2}$, GHz	F_1, GHz	Note
1.	14.7	78	50	-22	0.5660	3.68	
2.	6	78	40	-16.1	0.5162	3.7	ε=52
3.	6	12	2.2	-19.7	0.2728	3.3	Fig. 4.d
4.	6	12	1.2	-14.1	0.2677	3.3	
5.	6	12	1	-14.2	0.1103	3.4	

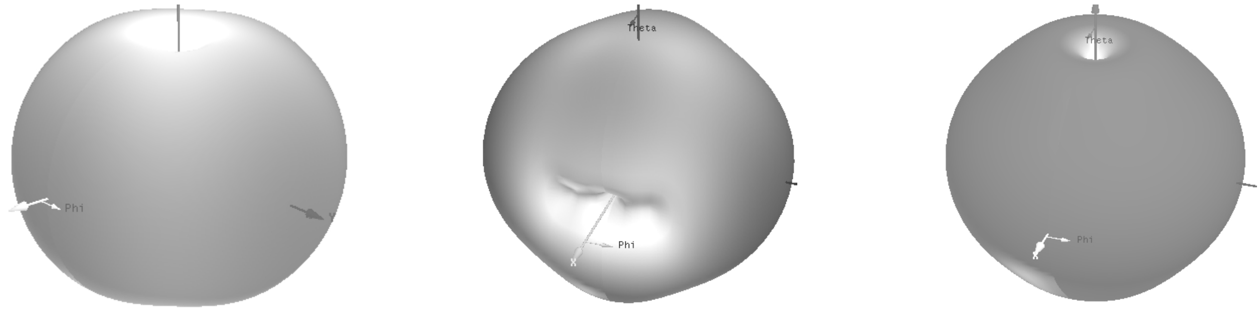
Examples of estimation of spatial-frequency characteristics for the selected criterion for layouts that meet selected criteria, is shown in Fig. 5-7. Its specification within the range 3.4-3.8 GHz is shown in Fig. 8-9. At intervals of 3-4, 14-16 and 24-28 GHz was used for calculations step 0.1 GHz, for other intervals – 0.5 GHz.

The results obtained confirm the following provisions.

1. Fractal emitter in the form of recursive 2D tree (*I*=3) with the angle of segmentation 60° and a diameter of wire 1 mm provides multiple ranges of 5G (3.4-3.8 i 24.25-27.5 GHz), that is, the proposed combo antenna is multi-band.

2. The adopted assumption without the use of the device of coordination of Z and VSWR does not affect the ability cover the entire range 3.4-3.8 GHz ($BW_{VSWR<2}$=3.9-3.4=0.5 GHz). In this case, minimum return loss at F_1=3.6 GHz is -30.5 dB, and the relative bandwidth is equal to: $\delta F = BW_{VSWR<2}/F_1 = 0.5/3.6 \cdot 100\% \approx 14\%$. It allows classifying the synthesized antenna as broadband.

3. Based on the results of [1] introduction the coordination of Z and VSWR will significantly increase the level of broadband supports not only the frequency F_1, but in areas of higher resonances.



a) b) c)

Fig. 5. BP combined antenna for F=3.6 GHz: a) – the layout № 10 Table I; b) – the layout №5 Table II; c) – the layout №1 Table III

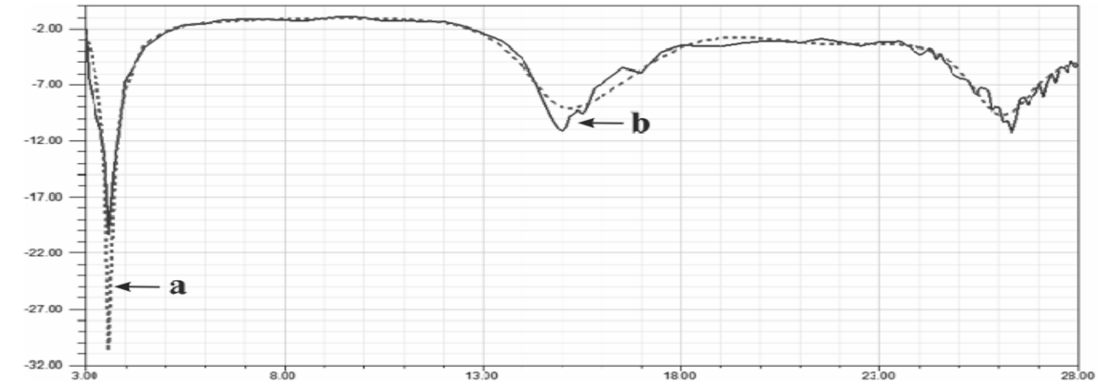


Fig. 6. Return Loss of the combined antenna: a) – emitter without resonators; b) – the layout №10 Table I

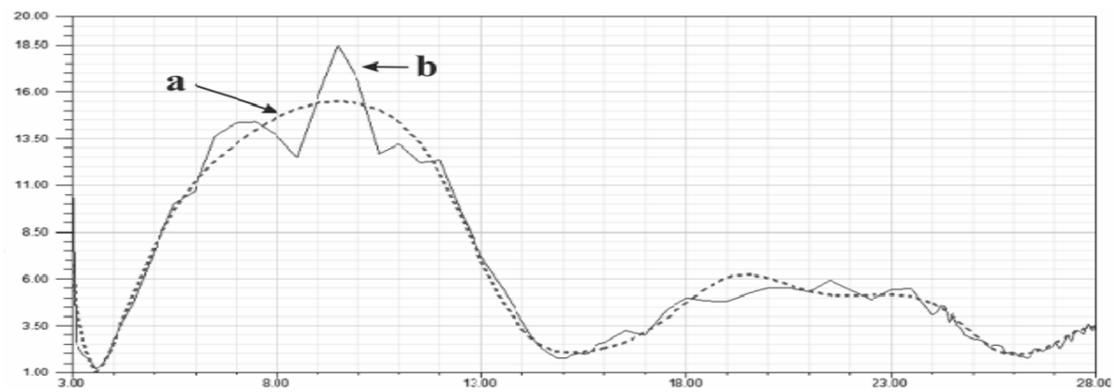


Fig. 7. VSWR of the combined antenna: a) – emitter without resonators; b) – the layout №10 Table I

4. The use of cylindrical dielectric structures as resonators also improves the figure, for example, for layout №10 Table I – $\delta F \approx 17.38\%$; №5 Table II – $\delta F \approx 16.39\%$; №1 Table III – $\delta F \approx 15.72\%$.

5. Get the value of the parameter S_{11} indicate the alignment of the amplitude-frequency characteristics of the antenna in the areas of resonant frequencies that can be useful during a simultaneous operation in several ranges.

6. The parametrical optimization of the combination antenna is not allowed to identify the layout with the dielectric resonators, which would ensure not only the alignment of the failure characteristics of the return loss at the resonant frequencies, but increased it at the highest resonance, for example, F_3. This motivates the search for new geometries of resonators.

7. The influence of mutual arrangement of the radiator and resonators on the shift of the resonance frequency and the form of the BP provides the possibility of adjusting the spatial-frequency characteristics of the antenna system by selecting the required layout.

Overall, the practical realization of proposed antenna solutions may rely on choice of another criterion parametric optimization of the model. At the same time, it has the possibility of using uneven dielectric resonator structures as well as their arbitrary angular orientation relative to the emitter.

V. Perspectives of Further Reseach

Considered in the initial conditions do not cover the entire set of antenna solutions based on integration of fractal approach and technology DRA. Therefore, the generalized directions of further research on the advanced antenna solutions can be summarized as follows:

1) Application of steel structures (for example, the top and bottom of the recursive tree differ in the geometric dimensions, angles of segmentation etc.);

2) Development quart on the basis of incomplete or inaccurate similarities of structure elements. As an example, should result in a transition from recursive 2D-trees (*I*=3) with a segmentation angle 60° to quasi-fractal 3D-tree by duplicating one of the branches, as shown in Fig. 10;

3) The synthesis of new geometric form of DRA, based on fractal approach. Thus, in Fig. 11 shows options of dielectric resonator structures, the basis for which is the Minkowski fractal first (*I*=1) or second (*I*=2) iteration of a square frame [1]. Thus, a possible implementation of partial structures (Fig. 11.f). The use of such structures in antennas greatly enhances their properties. For example, a combined antenna (Fig. 12.a) consisting of quasi-fractal 3D-trees (*I*=3) with the angle of segmentation 60° and cylindrical dielectric resonators synthesized based on the Minkowski fractal (*I*=2) square frame with a rotation angle of 45° in the plane YoZ, provides control of the variation of the gain between the resonant frequencies of the antenna (Fig. 12.b).

In conclusion, we should specify about the prospects for the development of integrated antenna systems: a combination of several different fractals and/or quasi-fractal, scutoids [15], emitting surfaces, application of metamaterials, and materials with high dielectric constants [16], etc. In addition, the potential of modern 3D printing technologies and the availability of conductive polymers [17] significantly expand the technological basis of the antenna technology.

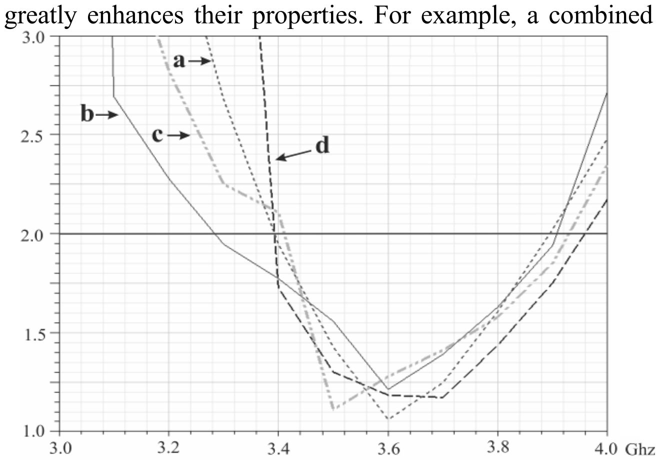


Fig. 8. VSWR of the combined antennas: a) – emitter without resonators; b) – the layout №10 Table I; c) – the layout №5 Table II; d) – the layout №1 Table III

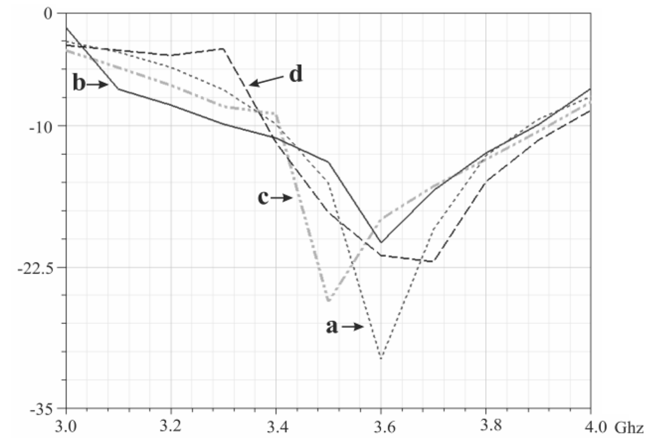


Fig. 9. Return Loss of the combined antennas: a) – emitter without resonators; b) – the layout №10 Table I; c) – the layout №5 Table II; d) – the layout №1 Table III

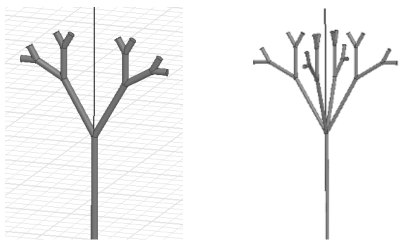


Fig. 10. An example of the formation of quasi-fractal 3D-trees (I=3) with segmentation angle 60°

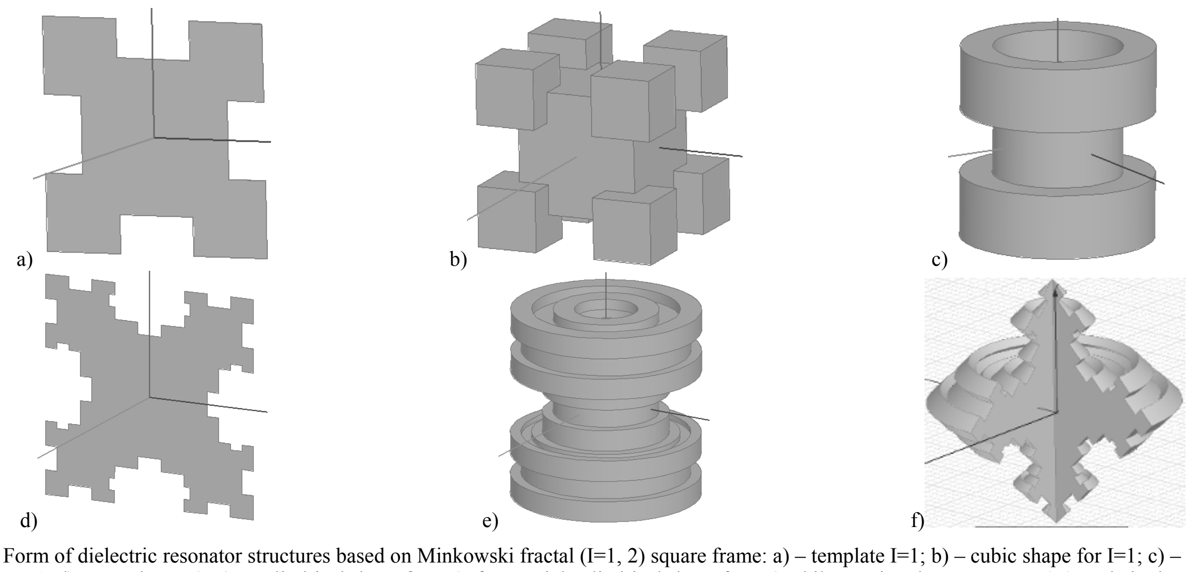


Fig. 11. Form of dielectric resonator structures based on Minkowski fractal (I=1, 2) square frame: a) – template I=1; b) – cubic shape for I=1; c) – cylindrical shape for I=1; d) – template I=2; e) – cylindrical shape for I=2; f) – partial cylindrical shape for I=2 while rotating the pattern at a 45° angle in the plane YoZ

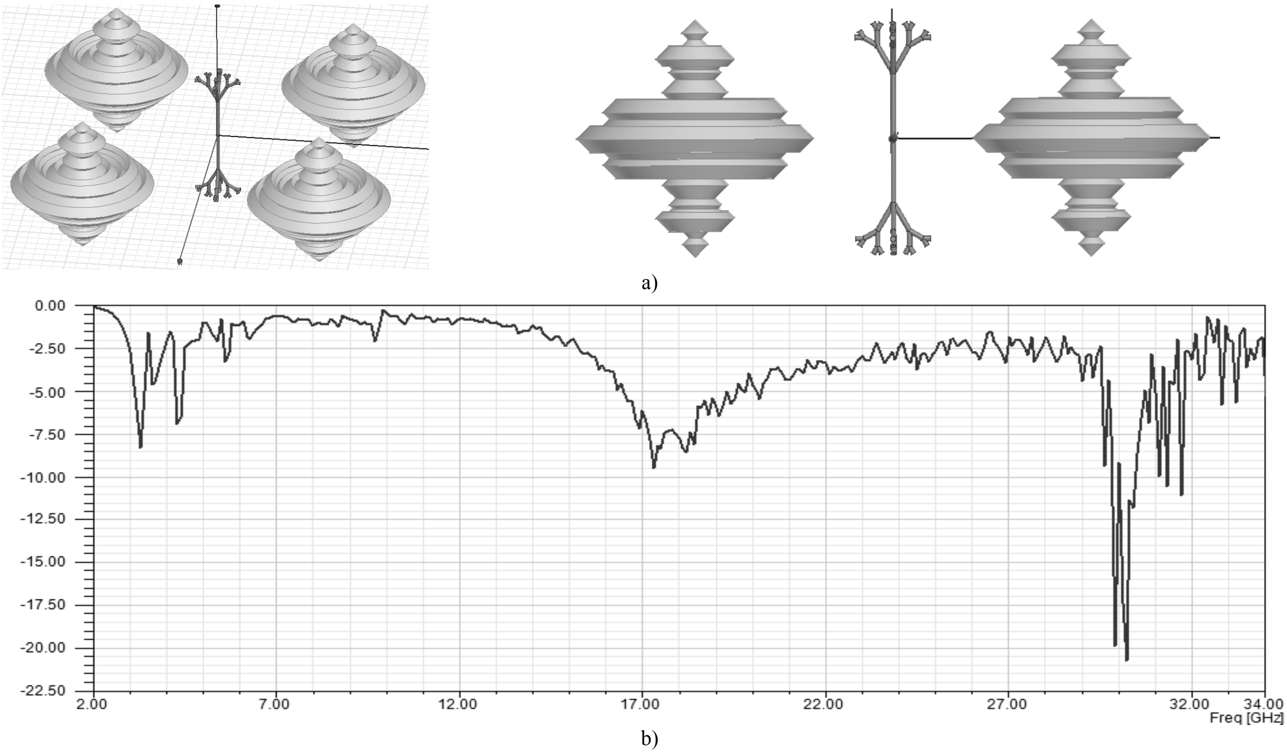


Fig. 12. Quasi-fractal combined antenna: a) – structure; b) – a graph of return loss without the use of the device of coordination of Z and VSWR

CONCLUSIONS

The results confirmed the theoretical statements on the desirability of broadband and multi-band antennas, on the basis of the fractal approach and technology DRA. Improvements suggested in the article model on the basis of the inclusion in the composition of the power system device coordination of Z and VSWR.

Overall, the considered integration of technology significantly expands the range of perspective antenna systems with non-Euclidean geometry, and the use of parametric optimization simplifies their practical implementation.

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