Simulation of a Fractal Koch Antenna with a Metamaterial Surface

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***Abstract*—In this paper, computer modelling of the main parameters of an antenna with topology based on Koch fractal and meta-surface is performed. The simulation results of such an antenna on a 65 x 65 x 1.5 mm PCB with one and two layers of metamaterial are obtained. The influence of the metamaterial and its distance on the antenna parameters is also investigated. Based on the data obtained, the distance from the antenna to the meta-surface at which the required radiation pattern is achieved is determined.**

***Keywords*—antennas, Koch fractal, metamaterials, microstrip antennas, multi-band antennas.**

I. Introduction

Antennas play a crucial role in various radio communication systems, including radio broadcasting, television, and other radio technical systems. Their primary function is to emit or receive electromagnetic waves. However, the objective of an antenna extends beyond mere radiation of electromagnetic waves; it also encompasses the optimal distribution of the radiated energy in space. Consequently, numerous parameters exist to describe antenna characteristics, such as operating frequency, gain and radiation patterns, physical size, and efficiency, each with their inherent limitations [1]. To improve these parameters, several methods have been proposed, in particular, the utilization of microstrip antennas. These antennas were developed to meet the demand for low-profile antennas suitable for applications in aircraft, spacecraft, and other comparable contexts. First conceptualized in 1953, microstrip antennas demonstrate high operating frequencies despite their relatively small dimensions [2]. Another viable solution lies in the implementation of fractal antennas, which enable operation across multiple frequency bands while simultaneously reducing antenna size and increasing bandwidth. Introduced in 1995 by Nathan Cohen, fractal antennas were accompanied by a comprehensive description of their characteristics [3]. Furthermore, exploiting the unique properties of metamaterials has been proposed for antenna design. Antennas constructed using metamaterials first emerged in 2002 [4] and showcased notable improvements in crucial characteristics such as gain, directivity, bandwidth, and miniaturization. The utilization of fractal antennas, especially using metamaterials, in contemporary wireless transmission networks holds great promise due to the aforementioned benefits.

In order to make informed decisions regarding the selection of an appropriate antenna for a specific task, comprehensive knowledge pertaining to its inherent properties becomes imperative. Fractal antennas covered with meta-surface are a complex system due to the unique geometry of fractal structures and unusual electromagnetic properties of metamaterials. Not all geometrical shapes can be described analytically, and the variation of electromagnetic field characteristics by metamaterials is also difficult to account for and analyse using mathematical expressions. In this regard, the investigation and design of such antennas requires complex calculations. Therefore, it is necessary to resort to mathematical modeling of electromagnetic fields in specialised software to describe antenna parameters.

The primary objective of this research endeavor is to improve fractal antenna characteristics such as radiation pattern, directivity and gain, operating range of a Koch fractal antenna through application of metamaterials. This study involves several steps. The first step is to thoroughly review the existing scientific literature on microstrip antennas, fractal antennas, meta-surfaces and their applications in wireless communication systems. The next step is to use a suitable electromagnetic modeling software to develop an accurate and reliable simulation model of a Koch fractal antenna integrated with a meta-surface. The final step would be to analyze the obtained characteristics, deriving dependencies in the form of graphs and tables.

The rest of the paper is organized as follows. Section II discusses and reviews the related work. Section III describes the applied methods. The achieved results are discussed in Section IV, and Section V concludes the paper.

II. Literature Review

As antennas have developed, many technologies have been invented to improve the characteristics of classic antennas. This section reviews the techniques more related to the enhancement of microstrip antennas.

The first approach is the integration of fractal geometries in antenna design. The term "fractal" was first introduced by

Benoit Mandelbrot in the mid-1970s. The term means "to break" in Latin, which corresponds to the type of these curves [3]. Fractal geometry, which cannot be described by the rules of classical Euclidean geometry, allows mathematical description of many natural forms: coastlines, mountains, human lungs just to name a few [5]. Nurujjaman et al. [6] reviewed some fractals like the Sierpinski triangle, Koch curve, Dragon curve, Koch Island, H-fractal, Levy curve fractal, box fractal etc. His work presents the results of calculating the area, perimeter and dimensionality of fractals in the form of a table for different geometries. In addition, the study describes the main methods that are used to synthesis fractals.

Dr Nathan Cohen, Professor of Applied Science and Telecommunications at Boston University, was the first to work on fractal antennas. The first fractal antenna was assembled in 1988 and later in 1995, Cohen published the first paper on fractal antennas [3]. Fractals have an important property - self-similarity and space-filling [7]. Due to these properties fractal cycles allow on a finite surface to realise a line with arbitrarily large perimeter, which increases the radiation of the antenna itself. Thus, the use of fractals in antenna design makes it possible to create small antennas with longer wavelengths than its Euclidean counterparts. The first fractal antenna with the most fully studied electromagnetic and directional properties was the antenna based on Koch's fractal curve. The construction of the Koch curve is described in detail [8]. Kushkraftom specialists have conducted a number of experiments to compare and contrast the electrical properties of the Koch antenna with other radiators with periodic structure [9]. All the radiators analysed have multi-band properties, which can be observed by the presence of resonances in the plots. However, only for the Koch fractal antenna, there is a decrease in the peak values for the reactive and active component of the impedance as the frequency increases. From this, it was concluded that the fractal Koch antennas among the studied antennas are the most suitable for multi-band applications.

Siavash Malektaji et al. [10] proved that fractal antennas exhibit multiband and relatively broadband properties. The paper describes selected modelling results of fractal Koch antennas. Trends in voltage standing wave ratio (VSWR), S11 and other antenna parameters are investigated as a function of the initiator, generator and three fractal iterations.

Another way in which antenna performance can be improved is by utilising the unusual properties of metamaterials in the design of the antenna [11]. Meta-surfaces have become a revolutionary technology in the field of electromagnetic wave manipulation [12]. Metamaterials are artificial periodic structures with modified values of dielectric and magnetic permeability that allow controlling the laws of propagation and dispersion of electromagnetic waves.

The study of options for the use of metamaterials in antenna technology began relatively recently, but despite this, many experiments have been carried out and some results have been obtained. For example, in 2011, V. G. Veselago, A. A. Zhukov and others obtained a Russian Federation patent "Small-size microwave antenna based on metamaterial", which presents the idea of placing a plate of metamaterial over the radiating element of the antenna on a dielectric substrate [13]. According to the patent, this method of integrating a planar microwave antenna with a metamaterial allows to achieve narrowing of the antenna's radiation pattern while maintaining compact geometrical dimensions.

Changing the basic parameters of metamaterials - shape, dimensions, constant and variable period of the electrodynamic structure, makes it possible to create composite high-impedance surfaces that are used as resonators, filters, phase shifters, directional taps, antenna and other microwave devices. The most unique and important properties of metamaterials include the possibility of obtaining on their basis a negative refractive index, which is achieved with simultaneous negative dielectric and magnetic permeabilities of the structure. For example, Mousavi et al. in the study [14] improved the gain characteristics of a microstrip patch antenna using a metamaterial substrate with S-shaped elements. The main advantage of the presented S-shaped element structure is that it can simultaneously improve the gain and bandwidth of the antenna.

Metamaterials created by placing open-circuit ring resonators (SRRs) in a periodic array are among the most popular designs. Such meta-surfaces placed next to antennas as coatings improve the antenna gain. Shaalan et al. [15] investigate the design and modelling of a fractal Koch antenna integrated with two layers of meta-surface to improve its performance. The authors use computer simulations to analyse the behavior of the fractal Koch antenna with and without a meta-surface, focusing on its radiation characteristics, bandwidth and efficiency. The collected parameter table shows the improvements in the antenna parameters with and without meta-surface and without meta-surface.

This study utilizes the abovementioned methods to model antenna in special software Ansys HFSS to obtain more accurate and faster results.

III. Methods

To clarify, the purpose of this study is to improve the basic characteristics of Koch fractal antenna in the second iteration of the geometric pattern.

A. Koch curve

A Koch curve is a fractal curve that is constructed by the iterative process of dividing segments into three equal parts and replacing the middle part with an equilateral triangle. Fig. 1 shows the division of Koch's fractal structure for different iterations. At the zero iteration, the original line length is found. In the following iterations, the original line segment is divided into three sections where the middle part forms a triangular shape with a length equal to one third of the original length.

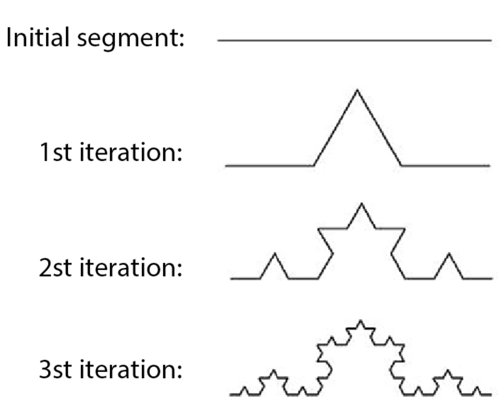


Fig. 1. Iterations of the Koch curve.

The initial shape of the model is a square with a side length of 20 mm. The generator represents the second iteration of the Koch curve, applied to each side of the square. The resulting shape of the model is shown in Fig. 2. The microstrip antenna is implemented on a 65 x 65 x 1.5 mm substrate. As material of the substrate is used dielectric FR4 with a relative permittivity $\varepsilon_r = 4.4$.

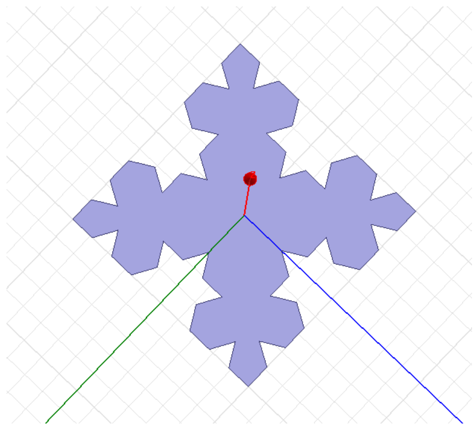


Fig. 2. The shape of Koch's fractal antenna.

B. Split Ring Resonator (SRR)

The meta-surface is a periodic structure made up of open circular ring resonators (SRRs). The structures with one main slit (SRR1) and with three (SRR2) slits as shown in Fig. 3. The size of one ring: 4 mm in length and width, the thickness of the ring is 0.4 mm, the width of the middle slit is 0.4 mm, width of additional slits - 0.2 mm.

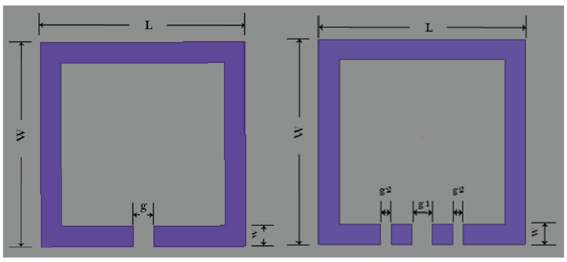


Fig. 3. Modified ring resonator with one and two slots.

The unit cells are made on FR4 substrate ($\varepsilon_r = 4.4$) 1.5 mm thick. The distance between the rings is 1.4 mm. The 144 rings are uniformly distributed on the substrates covering the Koch antenna. The relative permittivity, relative magnetic permeability and refractive index are determined by the Nicholson-Ross-Weir formula [17]:

$$\varepsilon_r = \frac{2}{jkd} * \frac{1-v_1}{1+v_1} \tag{1}$$

$$\mu_r = \frac{2}{jkd} * \frac{1-v_2}{1+v_2} \tag{2}$$

$$n = \pm\sqrt{\varepsilon_r \mu_r} \tag{3}$$

Where $v_1 = S_{21} + S_{11}$, $v_2 = S_{21} - S_{11}$, $k = \frac{\omega}{c}$,

ω - radian frequency,

d – substrate thickness,

n – refractive index.

The complete design of the fractal Koch antenna and the formed metamaterial coating is shown in Fig. 4.

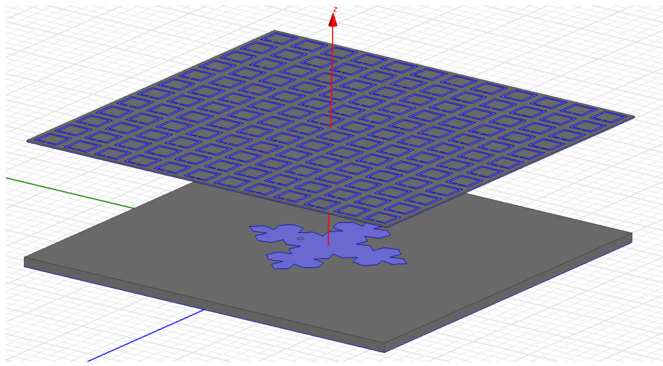
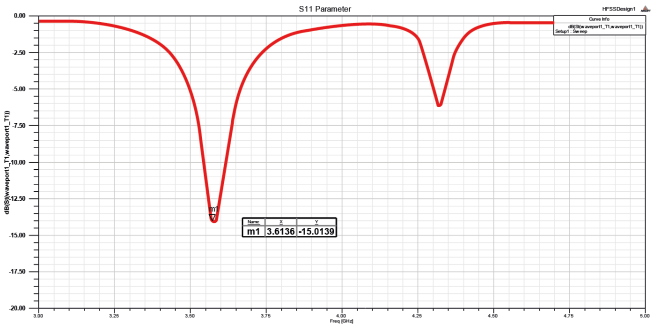


Fig. 4. Fractal Koch antenna with meta-coverage.

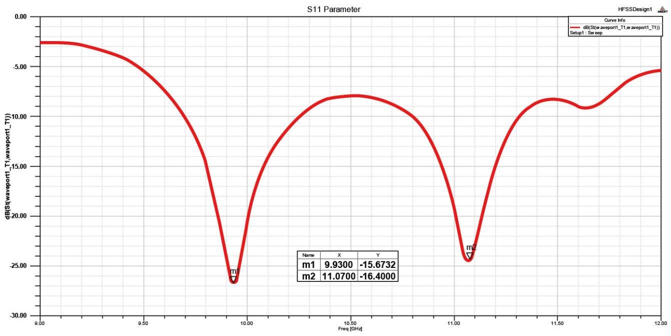
Design and simulation were performed in Ansys HFSS to analyze antennas with metamaterials due to its high precision and computational efficiency, facilitating accurate prediction of electromagnetic behavior. The modelling is an iterative process, so the distance from the radiating patch to the metasurface was varied to obtain better antenna performance. So the best distance at which good performance is achieved is 30 mm.

IV. Results

Calculations of the S-parameters of the fractal antenna show that this model has multi-band properties. It has resonances at 3.6 GHz, 9.9 GHz, and 11.1 GHz, which is shown in Fig. 5.



(a)



(b)

Fig. 5. S-parameters of the fractal antenna in (a) S-band, (b) X-band

Fig. 6 shows the far-field patterns in two planes at different resonant frequencies.

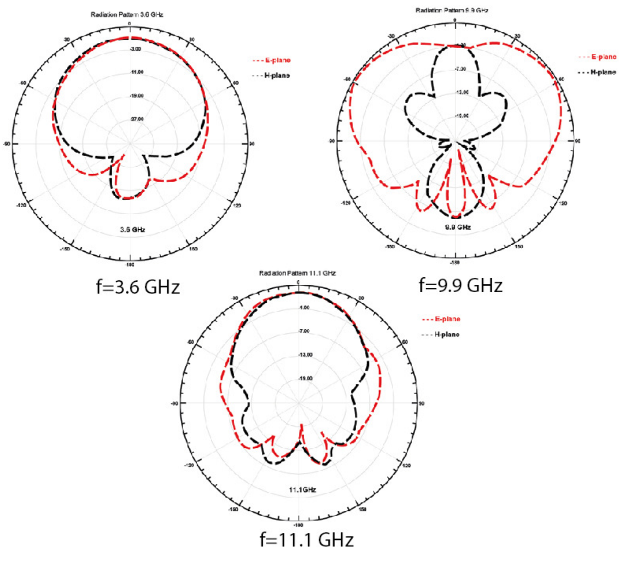


Fig. 6. Directional diagram of the fractal antenna.

After the addition of the meta layer, the gain and directional behaviour at 3.6 GHz remained the same because the metamaterial has a negative refractive index only in the X-band, which is noticeable in the calculation results for frequencies 9.9 GHz and 11.1 GHz. Directional patterns of the antenna after adding the metamaterial also changed at X-band frequencies (Fig. 7). Adding an additional layer to the antenna structure allowed to strengthen the radiation in a certain direction, the main lobe of the radiation became noticeably narrower compared to a conventional fractal antenna without the meta-coating.

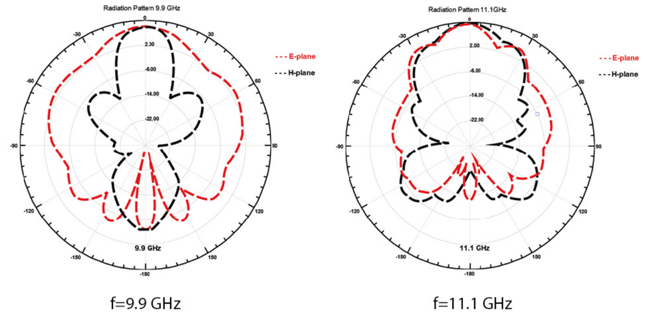


Fig. 7. Directional diagrams of fractal Koch antenna with meta-surface.

After adding the second layer of metamaterial at a distance of 1.5 mm from the first one, a similar situation is observed. The comparison of the main characteristics of the antenna is presented in Table 1.

TABLE I. CHARACTERISTICS OF FRACTAL KOCH ANTENNA DEPENDING ON THE NUMBER OF META-LAYERS

Parameters of Koch fractal antenna without meta-layer				
Frequency (GHz)	S_{11} (dB)	VSWR	Gain (dB)	Directivity (dB)
9.9	-25	1.11	7.2	8.6
11.1	-23	1.13	9.2	10.8
Parameters of fractal Koch antenna with one meta-layer				
9.9	-19.5	1.2	10	11.3
11.1	-17	1.3	11.2	12.7
Parameters of fractal Koch antenna with two meta-layers				
9.9	-19	1.2	12.4	13.7
11.1	-16.5	1.32	13.2	14.8

Thus, the introduction of meta-layers not only enhances the signal transmission, but also but also makes it more directional, i.e. the main lobe emission level increases, while the side lobes decrease.

V. CONCLUSION

In this study, fractal Koch antennas with one and two layers of metamaterial were modelled using Ansys HFSS. The study compared the antenna performance before and after placing the meta-surfaces over the radiating patch. The results showed improvements in antenna parameters, including increases in gain (10 and 11.2 dB) and directivity (11.3 and 12.7 dB) at two resonant frequencies (9.9 and 11.1 GHz) after adding one layer. When a second meta-coating was added, a similar trend was observed in the increase of gain (12.4 and 13.2 dB) and directivity (13.7 and 14.8 dB).

The addition of metamaterial layers improved the antenna performance by narrowing the main lobe width for improved directivity and efficiency. This study demonstrates the potential of combining fractal geometry and metamaterials to improve antenna performance, paving the way for advances in radio technology and communication systems. Further research and experiments can be directed towards extending the functionality and efficiency of such antenna systems in various applications.

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References

[1] C.A. Balanis, Antenna Theory: Analysis and Design. Hoboken, New Jersey: JohnWiley and Sons, Inc., 2005.

[2] K. Xu, "Broadband Microstrip Antenna Overview", Highlights in Science Engineering and Technology, vol. 27, pp. 621 – 629, 2022.

[3] A.K. Kaka, "Applications Fractal Geometry in Wire Antennas Design", Doctoral dissertation, Scientific Research Al – Mustansiriyah University College of Science, 2006.

[4] S. Enoch, G. Tayeb, P. Sabouroux, N. Guerin, and P. Vincent, "A Metamaterialfor Directive Emission", PhysRevLett., vol.89, no.21, pp. 213902-1-213902-4, 2002.

[5] A.A.K. Al-Zabee, S.Q. Jabbar, and D.Wang, "Fractal Antennas (Study and Review)," International Journal of Computer and Technology, vol. 15, no. 13, pp. 7387–7400, Nov. 2016.

[6] Md. Nurujjaman, A. Hossain, and P. Ahmed, "A Review of Fractals Properties: Mathematical Approach," Science Journal of Applied Mathematics and Statistics, vol. 5, no. 3, p. 98, Jan. 2017.

[7] J. He, "The fractal geometry self-similarity principle and its practical applications," Theoretical and Natural Science, vol. 14, no. 1, pp. 143–147, Nov. 2023.

[8] V. Mathur and M. Gupta, "Morphology of Koch fractal antenna," International Journal of Computer and Technology, vol. 13, no. 2, pp. 4157–4163, Apr. 2014.

[9] S.R. Best, "The Koch Fractal Monopole Antenna: The Significance of Fractal Geometry in Determining Antenna Performance. – Proceedings of the 2001 Antenna Applications Symposium. Allerton Park Monticello, Illinois. Sept.19–21, 2000.

[10] S.Malektaji and W.Kinsner, "Simulation of Koch fractal antennas," IEEE Canadian Conference on Electrical and Computer Engineering (CCECE), May 2013.

[11] A.S.Kukharenko, R.V.Shaymardanov, A.A.Elizarov. A Methodology of Metamaterial Effective Permittivity and Permeability Value Measurement // Journal of Materials Science and Engineering A. 2017. No. 7-8. pp. 206-215.

[12] Yelizarov A.A., Kukharenko A.S. Microwave Frequency Selective Devices at Resonant Segments of Electrodynamic Slow-Wave Structures and Metamaterials. M.: HSE Publishing House, 2019. (in Russian).

[13] B.P.O.Boysunov. Integrated antenna on a substrate made of metamaterial based on dielectric and magnetic resonators // Aktyalnye naychnye issledovania v sovremennom mire. 2021. No. 4-2(72). pp. 11-16.

[14] Z. Razi, P. Rezaei, and A. Valizade, "A novel design of Fabry-Perot antenna using metamaterial superstrate for gain and bandwidth enhancement," AEU - International Journal of Electronics and Communications, vol. 69, no. 10, pp. 1525–1532, Oct. 2015.

[15] A.B. Shaalan and A.N. Shareef, "Characteristics of microstrip fractal antenna shape covered by modified split ring resonator," IOSR Journal of Electrical and Electronics Engineering, vol. 9, no. 4, pp. 13–17, Jan. 2014.

[16] Y. Kumar, S. Singh, A Compact Multiband Hybrid Fractal Antenna for Multistandard Mobile Wireless Applications // Wireless Personal Communications 2015. № 1.

[17] J.-H. Shin, A. Akyurtlu, M. D. Deshpande "Comments on 'Design, fabrication, and testing of double negative metamaterials" IEEE Transactions on Antennas and Propagation, vol. 53, no. 2, Feb. 2005. pp.891.