Simulation of a Fractal Peano Antenna with a Metamaterial Surface

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Abstract— **This paper explores two techniques for miniaturizing antennas: fractal geometry and the use of metamaterials. The Peano fractal antenna is combined with a metamaterial layer, which consists of a periodic array of split-ring resonators. The Peano geometry is applied to a microstrip patch antenna with a base square patch measuring 29.8*29.8 mm^2, and the substrate is made of FR-4. The antenna's performance was simulated using Ansys HFSS software and the Finite Element Method. The research shows that fractal geometry imparts multiband properties of the antenna, while the metamaterial enhances characteristics such as gain and directivity. The results indicate that the proposed antenna can operate on three frequencies 2.1 GHz, 4.0 GHz, 4.6 GHz with a maximum gain of 9.7 dB.**

Keywords—fractal antenna; Peano fractal geometry; metamaterials; split ring resonator; negative refractive index; HFSS.

I. INTRODUCTION

An antenna is a part of a transmitting or receiving system that is designed to radiate or receive electromagnetic waves [1]. With the demand for smaller communication devices, microstrip patch antennas have gained popularity due to their compactness, light weight, and versatility in properties like resonant frequency and radiation pattern. However, despite their advantages, they suffer from drawbacks like low gain and efficiency [2]. To mitigate these issues, techniques such as fractal geometry and metamaterials are explored for miniaturization and performance enhancement.

Fractal shapes have been found to be effective in radiating electromagnetic energy. They possess several properties, such as self-similarity, recursivity, finite structure at a small scale, and space-filling behavior. By incorporating fractals and their unique properties into conventional antenna structures, engineers can achieve significant improvements in antenna performance. The antenna's self-similar property enables it to transmit and receive over a broad frequency range. Additionally, the space-filling property aids in reducing the antenna's size. Fractal geometry allows for the modification of the antenna's shape, resulting in an increase in its electrical length while simultaneously reducing its overall size.

Metamaterials are artificial composite materials composed of microscopic structures that exhibit unusual optical, electromagnetic, or acoustic properties not found in natural materials [3]. These unique properties are primarily determined by the periodic structure of these microscopic elements, which are much smaller than the wavelength. By tuning these structures, the material's permittivity and permeability can be altered, and a negative index of refraction can be achieved. Metamaterials are extensively used in antenna technology, covering frequencies from 100 MHz to 100 GHz. They offer new opportunities for developing compact, highly efficient, and multifunctional antennas. Metamaterials enable improved radiation patterns, compact designs suitable for mobile devices and drones, multi-band operation for versatile communication systems, real-time adaptability to environmental conditions, and enhanced interference suppression for better signal clarity. Their application in antenna systems is a promising and dynamic research area in microwave devices, leading to more efficient and versatile solutions for communication, radar, and other applications. Adding a superstrate layer of metamaterial on top of a microstrip patch antenna has been shown to improve the antenna's radiation efficiency and gain coefficient.

This paper introduces the microstrip fractal antenna that employs Peano curve geometry and split ring resonator meta-cover. The purpose of this work is to study the characteristics of this model of the fractal antenna and determine the optimal configuration to achieve a significant enhancement of gain and directivity.

The objectives of this research are to design an antenna using Giuseppe Peano fractal, analyze and measure it with and without meta-surface. The simulation was conducted using Ansys's HFSS software, which solves S-parameters using the finite element method.

The following paragraph is structured as follows: Section 2 discusses the existing literature on the presented topic. Section 3 briefly describes the methods used in this research. Section 4 presents the obtained and expected results. Finally, Section 5 presents the conclusions.

II. LITERATURE REVIEW

Numerous studies on smart antennas and metamaterials have been published globally, motivating this brief review.

Researchers such as C.A. Balanis [2], S. Verma [4], X. Ren [5], G. Singh [6], B.A. Karibayev [7], and S.A. Kadam [8] have explored fractal geometries for antenna miniaturization and multi-frequency operation. Their results show that fractal antennas can significantly reduce antenna size while maintaining and even improving performance. For example, fractal designs like the Peano curve have been shown to achieve multiband behavior and high aperture efficiency, with practical applications in ultra-wideband and long-distance telecommunications.

Concurrent studies by V.G. Veselago [3], P. Gay-Balmaz [9], H. Attia [10], A.B. Shaalan [11-14], B. Wu [15], and A.A. Yelizarov [16-18] have investigated metamaterials, particularly split-ring resonators, to enhance antenna performance. Their results demonstrate that metamaterials can significantly improve antenna gain, directivity, and efficiency. For instance, placing a metamaterial slab on top of a microstrip patch antenna has been shown to substantially enhance its gain, while the use of split-ring resonators can provide sharp band-gap properties and effective microwave filtering.

The literature shows that fractal geometries and metamaterials are increasingly popular for achieving miniaturization and improved efficiency in antennas. This review focuses on the development and benefits of a Peano fractal antenna covered by split-ring resonators, aiming to enhance antenna characteristics.

III. METHODOLOGY

A Peano curve, shown in Fig. 1, is constructed iteratively by adding new zigzag sections, to a straight line divided into three segments.

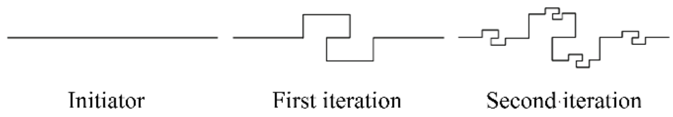

Fig. 1. The recursive procedure of the Giuseppe Peano fractal.

The final fractal shape of the antenna is achieved by applying the generator to each side of the square patch, which has a side length of 29.8 mm, as shown in Fig. 2.

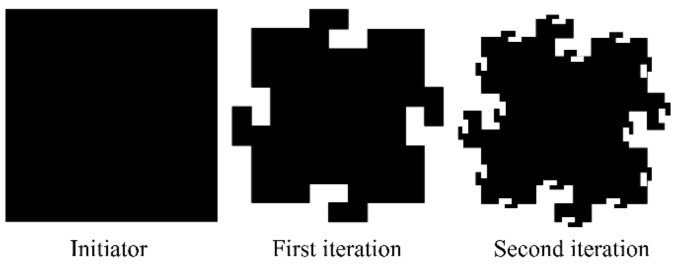

Fig. 2. The generator of Giuseppe Peano fractal patch.

The fractal patch antenna is etched on an FR-4 substrate with a relative permittivity of $\varepsilon_r = 4.4$. Its dimensions are 60 mm*60 mm*1.6 mm (Fig. 3).

The meta-cover is made up of 121 split ring resonators, distributed on an FR-4 substrate ($\varepsilon_r = 4.4$) that is 0.5 mm thick. Each unit cell has a side length of 4 mm, a side width of 0.4 mm and a middle space width of 0.4 mm.

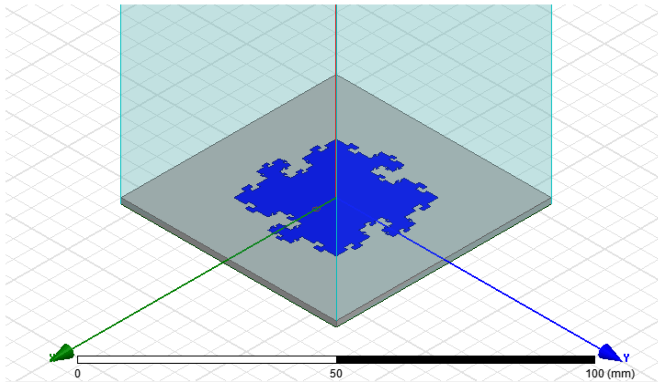

Fig. 3. Fractal Peano antenna model in HFSS.

The distance between cells is 1.4 mm. The meta-cover pattern is illustrated in Fig. 4.

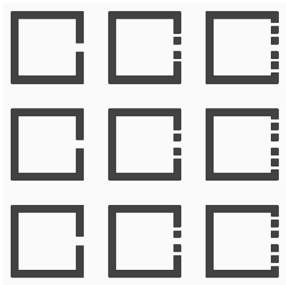

Fig. 4. Meta-cover configuration and unit cell design.

The area above the Peano antenna is covered by the meta-surface as shown in Fig. 5. The distance between antenna patch and metamaterial is 12 mm.

The relative permeability, relative permittivity, and refractive index were determined using the Nicolson-Ross-Weir approach [19].

$$\varepsilon_r = \frac{2}{jkd} * \frac{1-v_1}{1+v_1}, \quad (1)$$

$$\mu_r = \frac{2}{jkd} * \frac{1-v_2}{1+v_2}, \quad (2)$$

$$n = \pm\sqrt{\varepsilon_r \mu_r}, \quad (3)$$

where

$$v_1 = S_{21} + S_{11}, \quad (4)$$

$$v_2 = S_{21} - S_{11}, \quad (5)$$

$$k = \frac{\omega}{c}, \quad (6)$$

where d is substrate thickness, n is the refractive index, and ω is the radian frequency.

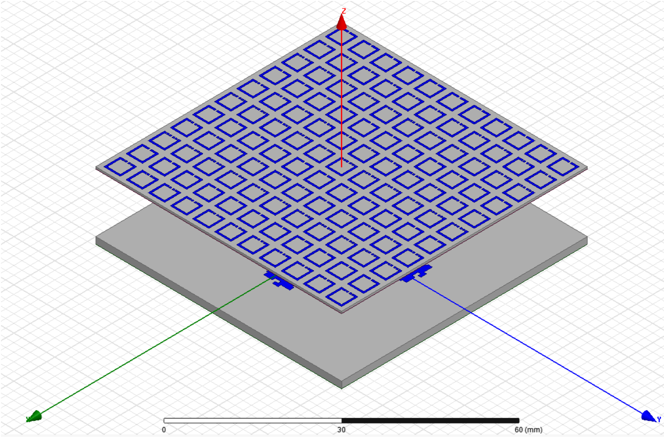

Fig. 5. Fractal Peano antenna with meta-surface configuration in HFSS.

The antenna layout was created using Ansys HFSS and then simulated to obtain S-parameters. The simulations were conducted using the Finite Element Method (FEM). This method subdivides a structure into small tetrahedral elements, called finite elements, which form a mesh. FEM is highly versatile as tetrahedral elements can fit any arbitrary geometry, making them suitable for almost any type of unstructured mesh. The finite element solution produces interconnected fields that satisfy Maxwell's Equations across inter-element boundaries, resulting in a field solution for the entire original structure. The generalized S-matrix solution is determined once the field solution is found [20]. This method provides a high level of uniqueness of numerical algorithms, which are very effective for modeling antennas. The refractive index, permittivity, and permeability can be calculated from S-parameters.

IV. Achieved Results

Based on the simulation results, the second iteration of the Giuseppe Peano fractal antenna has three resonances at frequencies 2.1 GHz, 4.0 GHz and 4.6 GHz (Fig. 6).

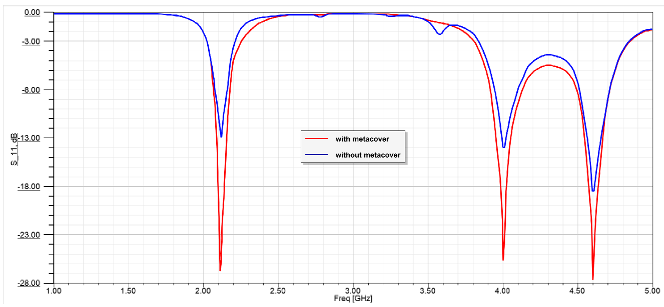

Fig. 6. Resonance frequencies of fractal Peano antenna.

In Table 1, the S_{11}-parameters, gain, directivity and VSWR of the Peano antenna with and without metacover are listed. The radiation pattern shapes are illustrated in Fig. 7.

TABLE I. Fractal Peano antenna parameters.

Frequency (GHz)	S11 (dB)	Gain (dB)	Directivity (dB)	VSWR
without metacover				
2.1	-12.99	4.1	4.3	1.28
4.0	-14.7	5.3	5.1	1.17
4.6	-19.23	6.0	5.9	1.09
with metacover				
2.1	-26.2	8.1	10.2	1.06
4.0	-25.8	8.6	10.5	1.09
4.6	-27.8	9.7	11.9	1.05

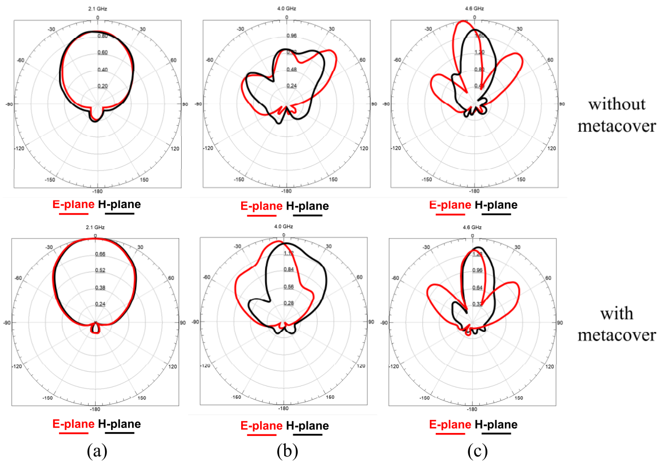

Fig. 7. Radiation patterns of fractal Peano antenna on a frequency (a) 2.1 GHz, (b) 4.0 GHz, (c) 4.6 GHz.

The simulation results show that adding a layer of metamaterial over an antenna, provides an increase in gain and directivity for all three resonant frequencies simultaneously. The gain increase reaches 8.1 dB at 2.1 GHz, 8.6 dB at 4.0 GHz and 9.7 dB at 4.6 GHz.

V. Conclusion

This study modeled a fractal Peano antenna with metasurfaces containing split ring resonators with different slot numbers to evaluate their influence on antenna characteristics. Simulation results show that applying a metamaterial layer positively affects the antenna's directivity and gain, with maximum improvements at 4.6 GHz – gain increases to 9.7 dB and directivity to 11.9 dB. There is also an improvement in antenna matching, indicated by a decrease in the VSWR to 1.05. These effects are observed across all three resonant frequencies, enhancing performance over a wide range.

In summary, the study confirms the effectiveness of the Peano fractal antenna with metasurface, showing improved performance. This combination, along with other similar fractal antennas and metamaterials, holds significant potential for applications in wireless communications, radar, medical technology, and other fields requiring high performance and efficient data transmission. Further research in this area could advance new technologies and techniques in wireless communications and electronics.

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