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Metamaterial-Based Antenna Design for RCS Reduction Characteristics Using 2D Peanos Fractal

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This paper explores a stealth antenna design using a Peanos fractal structure and Square Split Ring Resonators (SSRRs) to reduce radar cross section (RCS) while maintaining performance. Advantages of the Peanos fractal geometry in miniaturization and electromagnetic wave manipulation are evaluated utilizing finite element analysis (FEA). Frequency Selective Surfaces (FSSs) with SSRRs enhance antenna performance by enabling unique electromagnetic properties. The simulation results of the study show that the periodic structure functions as a bandpass filter around 4.7 GHz and remains effective at various incidence angles. This research demonstrates the potential of Peanos fractal design for RCS reduction in stealth technology and advanced electromagnetic applications.

1. Introduction

The advent of stealth technologies has necessitated innovative antenna designs to reduce the radar cross section (RCS) while maintaining performance. This paper explores a stealth antenna design employing a Peanos fractal structure, leveraging finite element analysis (FEA) to evaluate its effectiveness. The Peanos fractal geometry offers unique advantages in miniaturization and electromagnetic wave manipulation, making it an ideal candidate for stealth applications.

Frequency Selective Surfaces (FSSs) play a crucial role in electromagnetic wave control, including bandpass and bandstop filtering, which are vital for stealth technology. Previous studies have demonstrated the potential of FSSs in manipulating wave propagation through periodic structures, such as two-turn square spiral shaped arrays [1]. These surfaces, analyzed using methods like modal expansion and Galerkin's moment method, show significant promise in optimizing reflection and transmission coefficients.

Recent research has highlighted the challenges in wireless propagation control within indoor environments, proposing low-cost FSS-based solutions to mitigate interference between co-channel transmitters [2]. These studies emphasize the practicality of integrating FSSs into building structures, considering energy-efficient design and the impact of construction materials on electromagnetic propagation.

In wireless communication systems, the spatial filtering capabilities of FSSs address key challenges in enhancing data rates and service quality. Comprehensive surveys have explored the evolution of FSS geometries and fabrication techniques, underscoring their application as spatial filters across various frequency ranges [3].

Miniaturized FSS designs, such as dual-band structures with convoluted metal stripes, demonstrate low-profile, polarization-independent characteristics with stable performance across wide incident angles [4-6]. Such developments are vital for privacy applications where performance is important while reducing physical size. Fractal geometries, including Peanos curves, offer significant miniaturization benefits. Studies on fractal-based antennas and filters reveal enhanced performance through iterations of fractal curves, achieving substantial size reductions and low-loss characteristics [7].

The integration of metasurfaces in antenna design presents an efficient route to achieve low-RCS antennas. Techniques such as interdigital arrangement and selective excitation of metasurface cells have proven effective in reducing RCS while ensuring good radiation performance [8-

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10]. Additionally, nature-inspired designs, particularly bio-inspired antennas utilizing fractal geometries, showcase superior performance characteristics. These designs draw inspiration from natural patterns, offering broader bandwidths and reduced sizes compared to traditional antennas [11-15].

The utilization of Peanos fractal structures in antenna design promises significant advancements in stealth technology. This study aims to develop a stealth antenna with a reduced RCS, employing FEA to analyze the performance of the Peanos fractal structure [13]. By integrating the principles of FSS and fractal geometry, this research seeks to contribute to the development of next-generation stealth antennas for advanced communication systems.

2. Results and Discussion

The image in Figure 1 depicts the electric field magnitude in the complementary Peanos fractal SSRR. The electric field distribution depicted in Figure 1 illustrates how the fields are confined within the slot of the fractal square slit ring of Peanos fractal. The electric field localization indicates that the antenna is effectively utilizing the fractal geometry to enhance its performance.

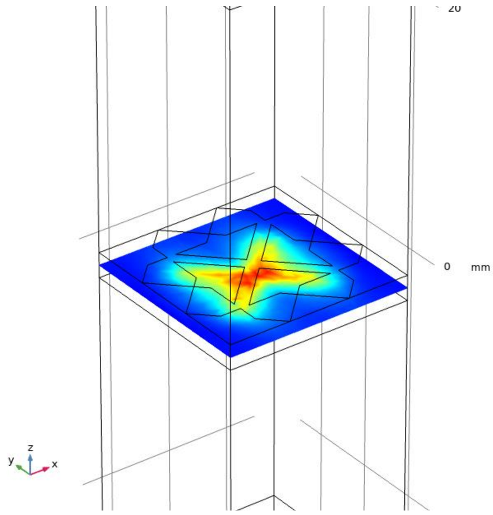

Figure 1. The fields are bounded within the slot of the fractal square slit ring of Peanos fractal.

The S-parameter plot in Figure 2 indicates that this periodic structure functions as a bandpass filter around 4.7 GHz.

The primary goal of the stealth antenna design is to minimize radar cross-section (RCS) while maintaining effective communication capabilities. The S-parameter graph indicates a bandpass resonance around 4.7 GHz, where S11 drops to -40 dB, indicating excellent return loss and minimal reflection at this frequency. This suggests that the

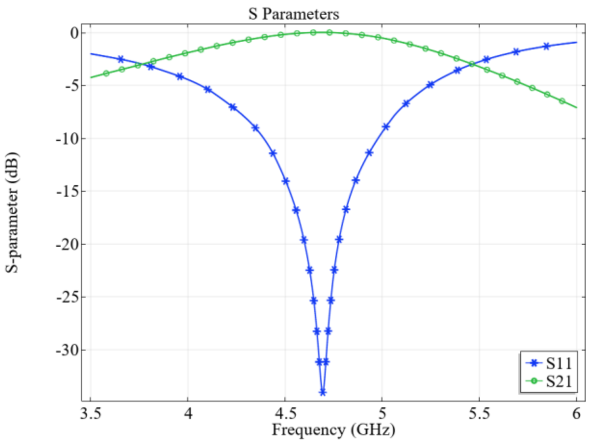

Figure 2. The S-parameter graph indicates a bandpass resonance around 4.7 GHz.

antenna is well-matched to the transmission line, which is crucial for efficient energy transfer. Additionally, the S21 parameter, which approaches 0 dB at 4.7 GHz, indicates that the antenna is effectively transmitting power, essential for maintaining communication while minimizing detectability.

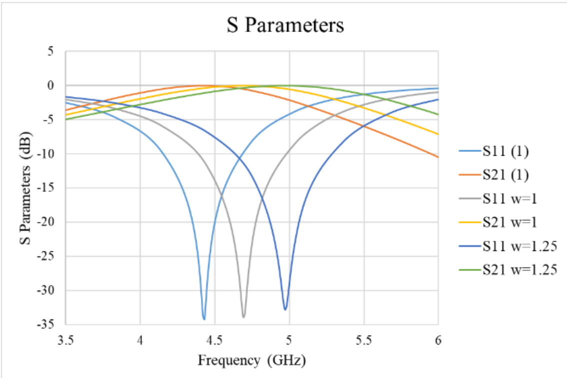

Figure 3. S-parameters for different values of w.

As the width w increases from 0.75 mm to 1.25 mm, we observe a gradual increase in the S11 value (i.e., it becomes less negative), suggesting that the reflection coefficient worsens with increasing width, indicating a decrease in the antenna's efficiency in terms of power transmission (Figure 3). The optimal performance appears to be at w=0.75 mm, where the S11 value is the lowest (-34.18 dB), suggesting that this width configuration provides the best impedance matching and minimizes reflection losses, which is crucial for optimizing the design of the metamaterial-based antenna for stealth applications where minimizing radar cross-section is essential; however, conducting additional simulations with intermediate values of w to better understand the relationship between the fractal dimensions and the antenna's performance could provide deeper insights into the optimal design parameters.

To examine how the incidence angle of the electromagnetic wave impacts the S-parameters, a parametric scan was conducted at the resonance frequency (4.7 GHz), varying the angle from 0° to 85° in 5° increments. Figure 4 displays the S-parameters of the designed structure relative to the incidence angle. The reflection coefficient (S11) varies as the incident angle changes, with values ranging from approximately -35 dB at 0 degrees to -5 dB at 85 degrees. This indicates that the antenna's matching performance is affected by the angle of incidence while the S21 parameter remains consistently around 0 dB across all incident angles. The S21 parameter indicates that the antenna effectively transmits power regardless of the angle of incidence, which is crucial for maintaining communication in stealth applications. The figure indicates that the periodic structure is penetrable at 4.7 GHz across various incidence angles.

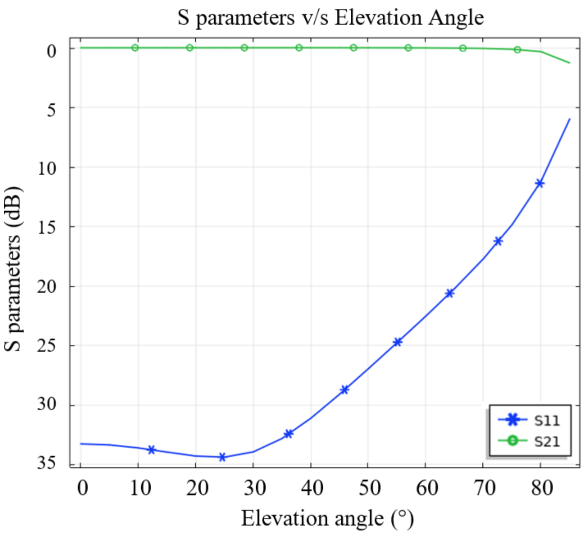

Figure 4. S-parameter plot is depicted varying with the incident angle.

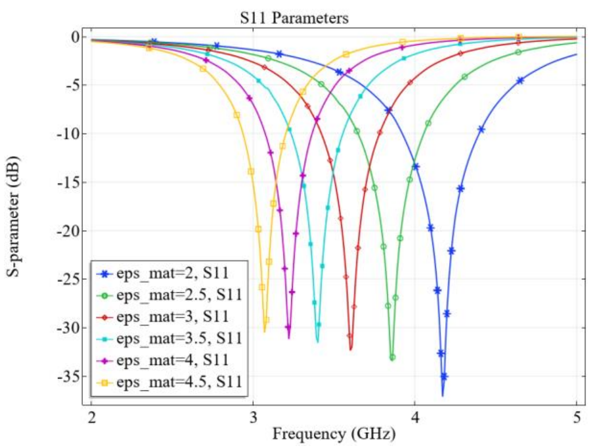

Figure 5. S11 parameter plot for different PCB dielectrics.

The dielectric coefficients of PCBs common in the market vary between 2 and 4.5. Figure 5 shows the results of parametric scanning by increasing the PCB dielectric properties by 0.5 between 2 and 4.5. As seen in the figure, S11 decreases inversely proportional to the dielectric property of the PCB. As can be seen from the figure, PCBs with lower dielectric constants will give better results for FSS design.

3. Conclusion

In this study, a frequency of 4.7 GHz has been selected for the stealth antenna design, as it is optimal for minimizing radar cross-section (RCS) in stealth applications while accommodating material availability and design constraints. This frequency facilitates the integration of advanced materials and structures, such as Frequency Selective Surfaces (FSS) that enhance stealth characteristics. The simulated RCS results for x-polarized normally incident waves at 4.7 GHz exhibit a broadband RCS reduction critical for stealth applications. The selection of 4.7 GHz is grounded in a comprehensive analysis of the frequency range pertinent to stealth technologies, and the design has been validated through both simulation and measurement, confirming its efficacy for stealth applications.

Traditional antennas have large RCS, which hinder stealth capabilities. Reducing RCS relies on different methods than merely increasing antenna gain, such as structural design changes, incorporation of active or passive elements, and the use of absorbing materials. This paper specifically explores the Peanos fractal design in FSS for RCS reduction. This approach leverages the fractal geometry to achieve notable RCS decrease without sacrificing antenna performance. The simulation involves the Peanos fractal alongside a SSRR, analyzing reflection, transmission spectra, and electric field norms. Findings indicate that this periodic structure functions as a bandpass filter around 4.7 GHz, effective at various incidence angles. The results validate the Peanos fractal design's capability to lower RCS while preserving advantageous FSS properties, making it a promising option for stealth technology and advanced electromagnetic applications.

Method

Periodic electromagnetic structures known as frequency selective surfaces (FSS) exhibit filtering characteristics, allowing or blocking specific frequency bands. This simulation tool enables users to analyze custom-designed periodic structures using a selection of predefined unit cell configurations.

In the context of antenna design, the Peanos fractal structure is particularly significant due to its space-filling properties and ability to create compact, multi-band antennas. The fractal geometry provides a means to miniaturize the antenna while maintaining its performance across multiple frequencies. By leveraging the Peanos fractal structure, the design can achieve efficient size reduction and enhanced bandwidth, making it highly suitable for modern communication systems where space and performance are critical considerations.

In this simulation, the Peanos fractal model with a square split ring resonator was used. SSRRs can produce negative permeability and permittivity, enabling the creation of metamaterials with unique electromagnetic properties not found in nature. These metamaterials can significantly improve antenna performance by enhancing parameters such as gain, bandwidth, and radiation patterns. By integrating SSRR's into the antenna design, engineers can develop highly efficient, compact, and versatile antennas suitable for a wide range of applications.

By harnessing the unique characteristics of SRR's, researchers have unlocked new possibilities in material science and electromagnetic engineering. SRRs, similar to their circular counterparts, are employed in various applications, including the development of metamaterials with customized electromagnetic properties, sensors for detecting substances such as amino acids, and the design of antennas and filters for microwave and optical frequencies. Additionally, SRRs facilitate the study of fundamental electromagnetic phenomena.

The copper layer on the PCB is modeled as a perfect electrical conductor (PEC) since it is significantly thicker than the skin depth in the simulated frequency range. The rest of the simulation domain is defined as air (Figure 1(a)). 74924 tetrahedral physics controlled mesh elements of extremely fine size were used. Figure 6(b) shows the dimension of the Peanos fractal pattern where a=15 mm, a1=5 mm, w=1 mm, g=1.67 mm, l1=6.92 mm and l2=8.33 mm. The thickness of the PCB layer considered as 2 mm. In this study, the reflection, transmission and absorption spectra in the frequency range of 3.5-6 GHz and the transmission and reflection spectra of the antenna at different incidence angles at the obtained operating frequency are obtained.

By examining the electromagnetic responses, including transmission and reflection properties, users can customize FSS designs for targeted uses such as antenna radomes, electromagnetic shielding, or selective filtering in communication systems. The capability to visualize electric field distributions offers critical insights into how incident electromagnetic waves interact with the FSS structure. This data is essential for comprehending resonance phenomena, coupling effects, and the overall efficacy of the designed FSS. With a variety of unit cell types and analytical features, this simulation tool acts as a flexible platform for investigating and advancing FSS technologies across multiple microwave and radio frequency applications.

To emulate an infinite 2D array, Floquet-periodic boundary conditions are implemented on all four sides of the unit cell. Perfectly matched layers (PMLs) are situated at the top and bottom of the unit cell to absorb the mode stimulated by the source port and any higher-order modes produced by the periodic structure. The PMLs diminish the wave as it propagates perpendicular to the PML boundary. As the model is resolved for varying incident angles, the wavelength in the PMLs is modified to $2\pi/|k0\cos\theta|$ as illustrated in Figure 6(a).

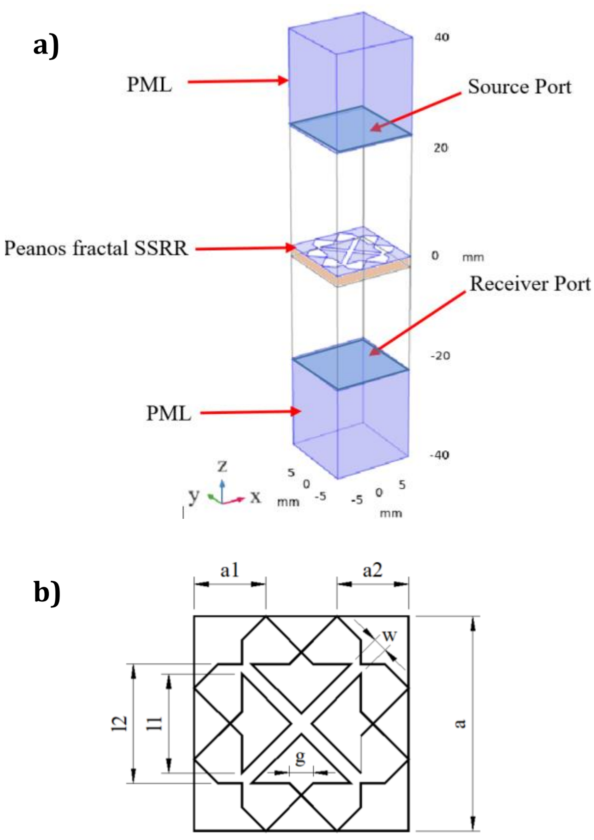

Figure 6.a) A unit cell of the Peanos complementary fractal quadratic split-ring resonator is simulated using periodic boundary conditions to emulate an endless two-dimensional array. b) dimensions of the Peanos fractal pattern.

Port boundary conditions are implemented on the internal boundaries of the PMLs adjacent to the air domains, with the Source Port being excited by the wave described in equation 1 (Figure 6).

$$E= \exp(jk_0(x.\cos\varphi + y.\sin\varphi))\ e_z \qquad (1)$$

These port boundary conditions automatically determine the reflection and transmission characteristics using S-parameters. The internal port boundaries supported by the PML need the slit condition. The port orientation is set to define the inward direction for calculating the S-parameters. Since higher-order diffraction modes are not the primary focus in this example, a combination of domain-supported slit ports and PMLs is employed instead of adding a diffraction order port for each diffraction order and polarization.

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Conflicts of Interest

The author stated that did not have conflict of interests.

Author Contributions

ZÖ: Performed experiments/data collection, data analysis and interpretation, drafted the paper, provided grammatical revisions to manuscript, provided revisions to scientific content of manuscript.

Data Availability Statement

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

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