Fractal Jerusalem Cross-Based FSS for X-Band Applications

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***Abstract*—This paper presents a fractal Jerusalem cross-based Frequency Selective Surface (FSS) for broadband electromagnetic filtering and shielding. Compared to the standard design, the fractal geometry offers wider stopbands, deeper transmission notches, and improved angular stability. A two-sided implementation further enhances performance across TE and TM polarization for incident angles up to 75°. The structure demonstrates strong multi-band rejection, making it ideal for stealth, EMI shielding, and smart sensing. The design also offers scalability for compact, multilayer applications in advanced wireless systems.**

Keywords: FSS, Fractal Jerusalem Cross, Electromagnetic Shielding, Multi-band, Angular Stability, Stealth, TE/TM

I. Introduction

A. Literature Survey

Frequency Selective Surfaces (FSS) are periodic structures that exhibit unique electromagnetic filtering characteristics, enabling them to selectively transmit or reflect electromagnetic waves at specific frequency bands. Their widespread use in stealth technology, electromagnetic shielding, satellite communications, and antenna systems has driven substantial research into improving their performance characteristics—particularly miniaturization, bandwidth control, angular stability, and polarization insensitivity. Recent advancements in FSS design have explored innovative geometries and materials to meet these growing demands. For instance, the use of complementary Minkowski fractal structures has been shown to achieve dual-band operation in a compact layout with good angular stability [1]. However, these designs often suffer from narrow operational bandwidth and increased fabrication complexity. Another notable contribution employs multi-layered FSS configurations to broaden the stopband characteristics and enhance filtering performance [2]. Although effective in expanding bandwidth, these structures tend to increase the overall thickness and cost, making them less desirable for low-profile applications. Polarization-insensitive and angularly stable designs have also received significant attention. One study utilized symmetrical unit cells to achieve consistent performance for both TE and TM polarizations, even up to 60° incidence [3]. Nevertheless, these designs are often band-limited and not readily adaptable to frequency-agile applications. Furthermore, the integration of defected ground structures (DGS) has proven effective in sharpening stopband responses and reducing unit cell size [4], but the associated complexity and material sensitivity hinder scalability to higher-frequency or large-scale implementations.

B. Gap Identification

From this literature, several gaps emerge. First, while many designs achieve miniaturization, they often compromise bandwidth or angular stability. Second, high-performing geometries like fractals and DGS pose fabrication challenges, especially for higher-frequency regimes. Third, despite improvements in angular stability, multi-band and reconfigurable designs remain underdeveloped, limiting adaptability in dynamic communication systems. Lastly, the lack of conformal, low-profile FSS solutions restricts their deployment in wearable or aerodynamic platforms.

C. Objective Formulation

This paper addresses these gaps by proposing a compact, single-layer FSS design that maintains polarization insensitivity and angular stability, while achieving wideband or multi-band stopband characteristics. The proposed design also emphasizes fabrication simplicity, aiming to bridge the gap between theoretical performance and practical manufacturability.

II. Unit Cell FSS Design

A. Unit Cell

The used structure is a fractal Jerusalem cross (fig1) unit cell designed for Frequency Selective Surfaces (FSS). It features a primary Jerusalem cross with extended arms, and a smaller, self-similar cross embedded at its center, enclosed within a square slot. Four additional mini crosses are symmetrically placed near the corners, enhancing the design's fractal nature. This multi-scale geometry increases the effective electrical length, enabling multi-band resonance and improved frequency selectivity. The symmetrical layout ensures polarization stability, making the structure ideal for monitoring S11 and S21 characteristics across a broad frequency range.

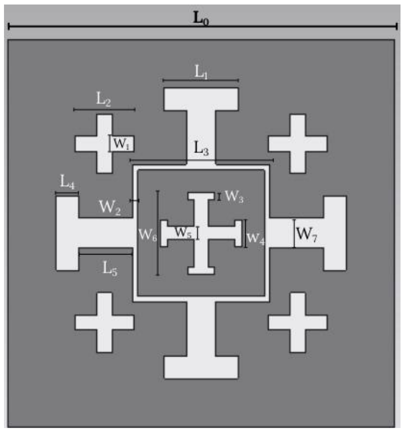


Fig. 1: Proposed fractal Jerusalem FSS Unit cell geometry

TABLE I
Dimensions of the Unit Cell

Parameter	Value	Parameter	Value
l_0	26	w_1	1
l_1	5	w_2	0.5
l_2	4	w_3	0.5
l_3	9.2	w_4	1.8
l_4	1.5	w_5	1
l_5	5	w_6	5.8
		w_7	2

B. Design Evolution

Initially, the standard Jerusalem Cross (refer to fig 2) was implemented as the Frequency Selective Surface (FSS) structure with the expectation of achieving strong frequency rejection and multi-band performance. However, the results, as seen in the corresponding graph(refer to fig 2), showed limited effectiveness. The S11 parameter revealed only a single notable resonance around 11 GHz, and the S21 response indicated poor attenuation outside this narrow band. This narrowband behavior did not meet the desired criteria for broader and more selective frequency control. To overcome these limitations, the design was evolved into a Fractal Jerusalem Cross (refer to fig 3) by introducing self-similar, recursively embedded cross structures. This fractal geometry increased the complexity and the number of resonant paths, leading to a richer interaction with electromagnetic waves. As shown in the updated graph, the fractal version exhibits multiple deep notches in the S21 response and a significantly wider stopband in S11 (refer fig 3), spanning from approximately 6 GHz to over 20 GHz. This enhanced performance justifies the use of the fractal variant, as it provides the desired broadband and multi-resonant characteristics essential for advanced applications like electromagnetic shielding, multi-band filtering, and stealth surfaces. Thus, the fractal Jerusalem Cross proved to be a necessary improvement to meet the design goals unmet by the standard configuration. Although the single-sided Fractal Jerusalem Cross design significantly improved frequency selectivity compared to the standard cross, its performance still showed limitations in terms of stopband depth and transmission suppression. While multiple resonances were achieved, the S21 values in some frequency ranges remained relatively high, indicating incomplete attenuation. To further enhance the electromagnetic response, the same fractal design was implemented in a two-sided Frequency Selective Surface (FSS) configuration. This approach allows both sides of the substrate to contribute to the resonance behavior, increasing the interaction between the incident wave and the structure (refer to fig 4). The two-sided layout effectively strengthens the coupling between layers, leading to deeper notches in the transmission spectrum and more pronounced reflection characteristics. It also enables more precise control of current paths, enhancing the overall rejection bandwidth and making the design more robust to changes in angle of incidence. Thus, applying the fractal design on both sides of the FSS not only builds on its inherent multi-band capabilities but also optimizes its filtering efficiency, making it suitable for more demanding applications like broadband filtering and electromagnetic shielding.

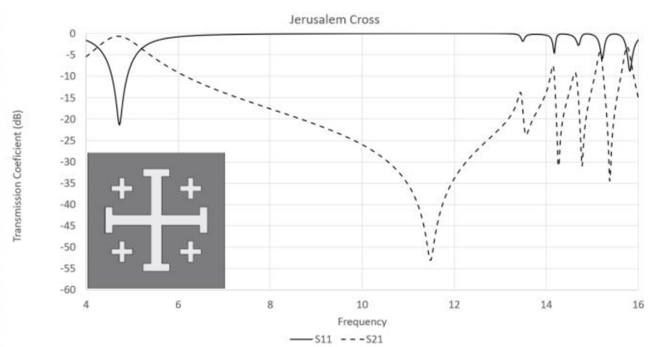


Fig. 2: Standard Jerusalem Cell and it’s results.

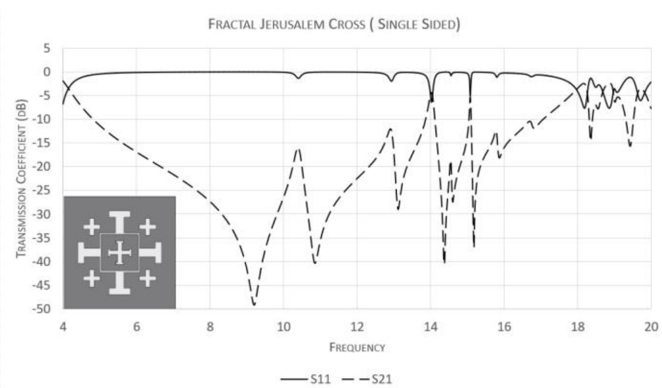


Fig. 3: Fractal Jerusalem Unit Cell (Single Sided)

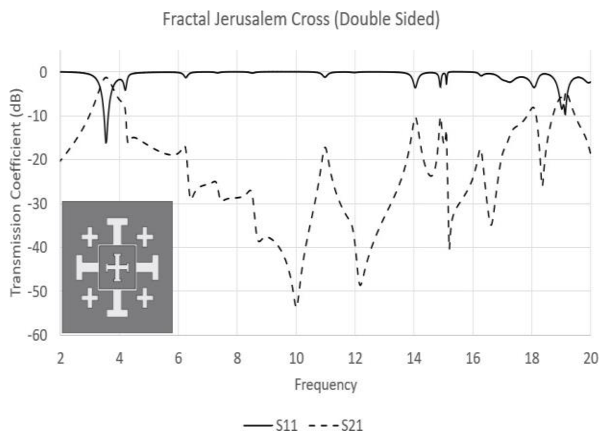
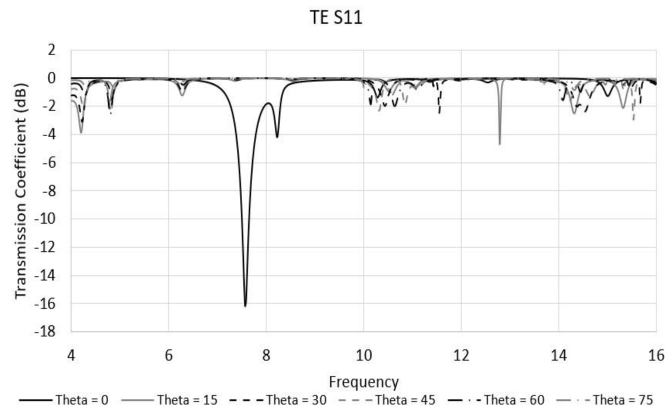


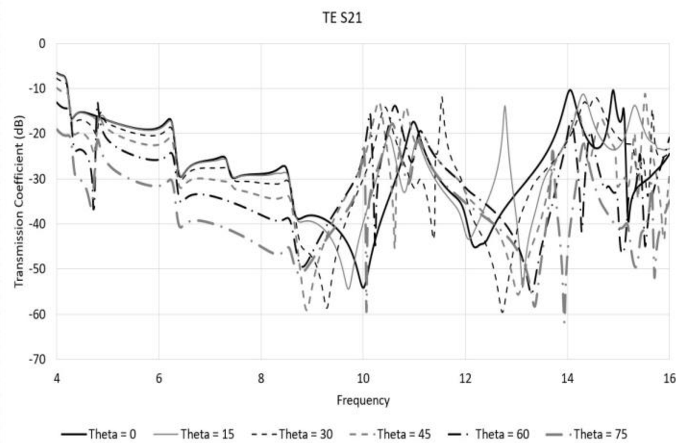
Fig. 4: Fractal Jerusalem Unit Cell (Double Sided)

III. Results and Discussion

The performance of the proposed fractal Jerusalem cross-based FSS design is validated through S-parameter plots for both TE and TM polarizations over a wide range of incident angles (and from 0° to 75°). In the TE S11(fig 5a) plot, consistent deep nulls below –20 dB are observed across multiple frequency bands, with stable response up to = 60°, indicating strong reflection suppression and angle stability. The corresponding TE S21(fig 5b) graph shows transmission levels remaining well below –40 dB, demonstrating effective shielding across the band. Similarly, in the TM mode, the S11(fig 6a) response also exhibits wideband notch characteristics with minimal angular variation, particularly between 4–10 GHz, confirming polarization insensitivity. TM S21(fig 6b) further corroborates this with attenuation often exceeding –60 dB, even at extreme oblique angles. Notably, sharp dips in transmission and reflection near 7–9 GHz and 10–11 GHz highlight strong resonance behavior of the fractal structure. Overall, the fractal Jerusalem cross design achieves broadband filtering and strong angular stability in both polarizations, making it suitable for stealth or shielding applications requiring high isolation and wide-angle performance. The results justify the enhanced electromagnetic response due to the complex multiscale geometry inherent in the fractal design.

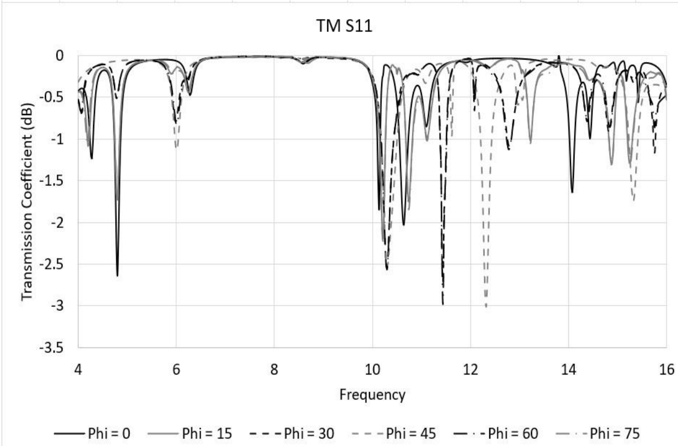


(a) TE S11 for Theta = 0° to 75°

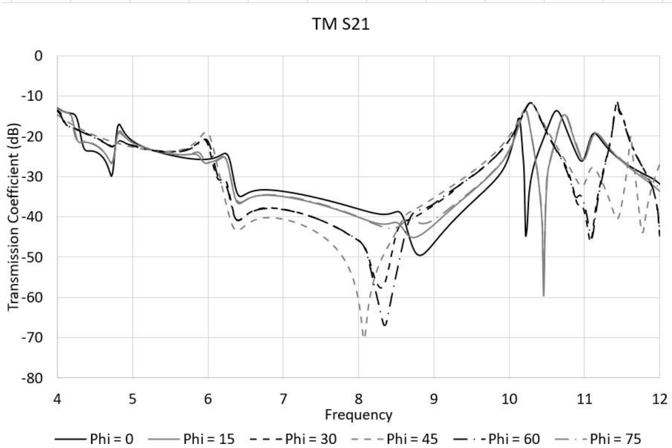


(b) TE S21 for Theta = 0° to 75°

Fig. 5: TE polarization performance of the FSS.



(a) TM S11 for Phi = 0° to 75°



(b) TM S21 for Phi = 0° to 75°

Fig. 6: TM polarization performance of the FSS.

IV. Conclusion

The angular response of the proposed fractal Jerusalem cross FSS array validates its robustness and efficiency in manipulating electromagnetic wave propagation. The results from the S11 and S21 parameter analysis under varied theta and phi angles confirm its suitability for electromagnetic shielding, wave filtering, and multi-band sensing systems. Leveraging the inherent scalability of the fractal design, future upgrades could focus on miniaturization without compromising performance, and on enhancing bandwidth through multilayer or hybrid configurations. This would expand the array's applications to include Internet of Things (IoT) environments, space-borne systems, and next-generation wireless networks requiring compact, low-profile, and multifunctional surfaces.

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