Fractal Jerusalem Cross Based FSS for X-Band Applications

Submitted in partial fulfillment of the requirements for the degree of

Bachelor of Technology

in

Electronics and Communication Engineering

by

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(Deemed to be University under section 3 of UGC Act, 1956)

April, 2025

DECLARATION

I hereby declare that the thesis entitled *"Fractal Jerusalem Cross Based FSS for X-Band Applications "* submitted by me, for the award of the degree of *Bachelor of Technology in Programme* to VIT is a record of bonafide work carried out by me under the supervision of **Dr. Rajesh Natarajan.**

I further declare that the work reported in this thesis has not been submitted previously to this institute or anywhere for the consideration of the degree/diploma.

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Signature of the Candidate

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<u>CERTIFICATE</u>

This is to certify that the thesis entitled "*Fractal Jerusalem Cross Based FSS for X-Band Applications*" submitted by **Koustabh Ram Kundala (21BEC0617)**, **SENSE**, VIT, and **Anurag Sonar (21BEC0496)**, **SENSE**, VIT, for the award of the degree of *Bachelor of Technology in Programme*, is a record of bonafide work carried out by them under my supervision during the period, 13.12 2024 to 20.04.2025, as per the VIT code of academic and research ethics.

The contents of this report have not been submitted either in part or in full, for the award of any other degree or diploma in this institute or any other institute or university. The thesis fulfills the requirements and regulations of the University and in my opinion meets the necessary standards for submission.

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Internal Examiner

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Koustabh Ram Kandula
Anurag Sonar

Executive Summary

This paper presents a fractal Jerusalem cross-based Frequency Selective Surface (FSS) designed for broadband electromagnetic filtering and shielding in X-band applications. The proposed structure leverages a multi-scale fractal geometry—combining a primary Jerusalem cross with embedded mini crosses—to enhance multi-band resonance, angular stability, and polarization insensitivity. Compared to conventional designs, the fractal FSS achieves deeper transmission notches (below -40 dB), wider stop bands, and consistent performance for TE/TM polarizations up to 75° incidence.

A two-sided implementation further optimizes performance by strengthening coupling between layers,improving shielding effectiveness (S21 < -60 dB in TM mode) and reflection suppression (S11 < -20 dB). The design addresses key gaps in existing FSS technology, including bandwidth-angular stability trade-offs, fabrication complexity, and limited multi-band adaptability.

Experimental results demonstrate strong multi-band rejection (4–11 GHz), making the FSS suitable for stealth,EMI shielding, and smart sensing in advanced wireless systems. Its compact, single-layer architecture ensures practical manufacturability while outperforming traditional and fractal-based alternatives. This work bridges theoretical innovation with real-world applicability, offering a scalable solution for next-generation communication and radar systems.

Keywords: FSS, Fractal Jerusalem Cross, Multi-band Filtering, Angular Stability, Electromagnetic Shielding.

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APPENDIX A

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List of Abbreviations

Abbreviation	Meaning
FSS	Frequency Selective Surface
EMI	Electromagnetic Interference
TE	Transverse Electric
TM	Transverse Magnetic
DGC	Defected Ground Structure
S11	Reflection Coefficient
S21	Transmission Coefficient
GHz	Gigahertz
dB	Decibel
EM	Electromagnetic
X-Band	Microwave Frequency range (8-12 GHz)

Symbols and Notations

Symbol	Meaning
f	Frequency
λ	Wavelength
θ	Angle of incidence
φ	Azimuthal angle
a	Unit cell periodicity
g	Gap between elements
w	Conductor width
L	Conductor length
t	Substrate thickness

1. INTRODUCTION

1.1. Literature Review

The evolution of FSS technology has been marked by continuous innovation in geometric design and material composition. Traditional FSS implementations typically employed simple periodic elements like dipoles, slots, or crosses, which provided fundamental filtering capabilities but suffered from narrow bandwidths and significant performance degradation at oblique angles. The introduction of fractal geometries marked a significant advancement, with researchers demonstrating that self-similar, space-filling patterns could produce multi-band responses while maintaining compact unit cell dimensions.

Recent studies have explored various fractal configurations to enhance FSS performance. The Minkowski fractal geometry, for instance, has shown particular promise in achieving dual-band operation with good angular stability up to 45°. However, these designs often exhibit limited bandwidth between resonant frequencies and require complex fabrication processes that hinder practical implementation. Complementary approaches using Hilbert curves and Koch snowflakes have demonstrated potential for miniaturization but struggle with maintaining consistent performance across varying polarization states.

Multi-layered FSS architectures have emerged as another solution to bandwidth limitations, with stacked configurations achieving broader stopbands through coupled resonance effects. While effective in expanding operational bandwidth, these designs significantly increase profile thickness and manufacturing complexity, making them unsuitable for low-profile applications. Moreover, the interaction between layers introduces new challenges in impedance matching and angular stability, particularly at higher incidence angles.

The pursuit of polarization-insensitive designs has led to the development of highly symmetrical unit cells, including square loops, circular rings, and four-legged loaded elements. These configurations maintain consistent performance for both TE and TM polarizations but often sacrifice bandwidth or frequency agility. Recent works have demonstrated a tri-band FSS with polarization-independent response, though the design showed noticeable performance degradation beyond 60° incidence.

Defected Ground Structures (DGS) have been integrated with FSS to enhance miniaturization and sharpen frequency responses. While effective, these hybrid configurations introduce additional fabrication challenges and material sensitivity issues, particularly when scaling to higher frequency ranges. The complex electromagnetic interactions in DGS-FSS combinations also make performance prediction and optimization increasingly difficult.

1.2. Research Gap

A systematic analysis of current FSS research reveals several persistent challenges that limit practical implementation:

- *Performance Trade-offs*:

  Existing designs struggle to simultaneously optimize bandwidth, angular stability, and miniaturization. Fractal-based FSS achieve multi-band operation but with limited inter-band bandwidth, while broadband designs using multi-layer approaches sacrifice compactness.

- *Fabrication Limitations:*

  Complex geometries, particularly those incorporating high-order fractals or multi-layer configurations, present significant manufacturing challenges. Precision requirements become increasingly stringent at higher frequencies (X-band and above), leading to yield issues and elevated production costs.

- *Angular Stability Constraints:*

  While some designs maintain performance up to 60° incidence, few demonstrate consistent operation at more extreme angles (75° and beyond). This limitation restricts deployment in applications requiring wide-angle coverage, such as conformal radomes or wide-beam antenna systems.

- *Polarization Sensitivity:*

  Many multi-band FSS exhibit polarization-dependent responses, particularly at oblique angles. Achieving true polarization insensitivity across multiple frequency bands remains an unresolved challenge.

- *Lack of Reconfigurability:*

  Static FSS designs cannot adapt to changing operational requirements. While some tunable implementations exist, they typically suffer from reduced Q-factor, limited tuning range, or increased complexity.

- *Conformal Application Barriers:*

  The integration of FSS into curved surfaces or flexible substrates presents additional challenges in maintaining consistent performance across bending conditions and varying angles of incidence.

1.3. Problem Statement

This research addresses the identified gaps through the development of a novel fractal Jerusalem cross-based FSS optimized for X-band applications. The proposed solution targets the following specific challenges:

- *Multi-band Operation with Enhanced Bandwidth:*

  The design will leverage the inherent properties of fractal geometry to establish multiple resonant frequencies between 4-11 GHz, with particular emphasis on the X-band (8-12 GHz). Unlike conventional multi-band FSS, the proposed configuration aims to minimize inter-band gaps while maintaining deep rejection notches (<-40 dB).

- *Superior Angular Stability:*

  The fractal Jerusalem cross architecture will be engineered to maintain consistent performance across TE and TM polarizations for incidence angles up to 75°, addressing a critical limitation of current designs that typically degrade beyond 60°.

- *Simplified Fabrication:*

  By employing a single-layer design with optimized fractal parameters, the proposed FSS will reduce manufacturing complexity compared to multi-layer or DGS-based alternatives while maintaining competitive performance metrics.

- *Polarization Insensitivity:*

  The symmetrical, multi-scale nature of the fractal Jerusalem cross will ensure minimal performance variation between TE and TM modes, even at extreme incidence angles.

- *Scalability and Adaptability:*

  The research will investigate design scalability for both higher frequency applications (Ku-band and above) and miniaturized implementations suitable for compact wireless devices.

- *Potential for Reconfigurability:*

  While focusing initially on a static design, the architecture will be developed with future tunability in mind, particularly through the integration of active elements like varactors or MEMS switches.

The proposed FSS solution aims to bridge the gap between theoretical performance and practical implementation, offering a balanced approach that addresses the competing demands of bandwidth, angular stability, polarization insensitivity, and manufacturability. Through comprehensive simulation, prototyping, and testing, this research will validate the design's superiority over existing alternatives while establishing clear pathways for future development and application-specific customization.

The successful implementation of this fractal Jerusalem cross-based FSS would have significant implications for multiple domains, including:

- Military stealth applications requiring broadband radar cross-section reduction
- Satellite communication systems needing interference suppression
- 5G/6G infrastructure demanding compact, high-performance filtering solutions
- EMI shielding for sensitive electronic equipment
- Advanced radar systems requiring angularly stable frequency selective components

By systematically addressing the limitations of current FSS technologies while maintaining practical manufacturability, this research contributes to the ongoing advancement of electromagnetic wave control technologies and their applications in next-generation wireless systems.

2. Research Objective

The primary objective of this research is to develop an advanced fractal Jerusalem cross-based Frequency Selective Surface (FSS) that addresses critical limitations in current designs while delivering superior performance for X-band applications. Building upon identified research gaps, this study aims to create a multi-band FSS capable of operating across 4-11 GHz with particular emphasis on the X-band (8-12 GHz), featuring deep rejection notches below -40 dB transmission loss and enhanced frequency selectivity through optimized fractal geometry. The design will specifically target improved angular stability, maintaining consistent performance for both TE and TM polarizations up to 75° incidence with minimal frequency shift, representing a significant advancement over existing designs that typically degrade beyond 60°.

A key focus of this work involves ensuring polarization-insensitive operation, with less than 1dB variation in S-parameters between polarization states and less than 2% shift in resonant frequencies.

Methodologically, the research combines advanced electromagnetic simulation using CST Studio Suite with practical prototype development and testing. Fabricated prototypes will undergo rigorous evaluation using vector network analyzers and anechoic chamber testing to validate simulated results under real-world conditions. Beyond immediate performance goals, this work aims to contribute theoretical insights into fractal FSS behavior while establishing practical design guidelines for engineering applications. The developed FSS technology targets critical applications including military stealth systems, satellite communications, EMI shielding, and 5G/6G infrastructure, with potential for future expansion into tunable configurations and higher frequency bands. Success metrics include achieving at least three distinct rejection bands with consistent angular performance and maintaining fabrication yields above 90%, with results expected to advance both academic understanding and practical implementation of FSS technology.

The study's innovative approach lies in its unique integration of optimized fractal geometry with Jerusalem cross architecture, carefully balanced to achieve multiple performance metrics simultaneously. By bridging theoretical innovation with practical manufacturability concerns, this research addresses longstanding trade-offs in FSS design while opening new possibilities for next-generation electromagnetic wave control solutions. The project will additionally lay groundwork for future developments including conformal implementations, metamaterial hybrids, and machine learning-assisted optimization, positioning the fractal Jerusalem cross FSS as a versatile platform for ongoing advancement in the field. Through this comprehensive approach, the research aims to deliver a significant technological leap that combines academic rigor with real-world applicability, filling critical gaps in current state-of-the-art designs while establishing clear pathways for future innovation and application-specific customization.

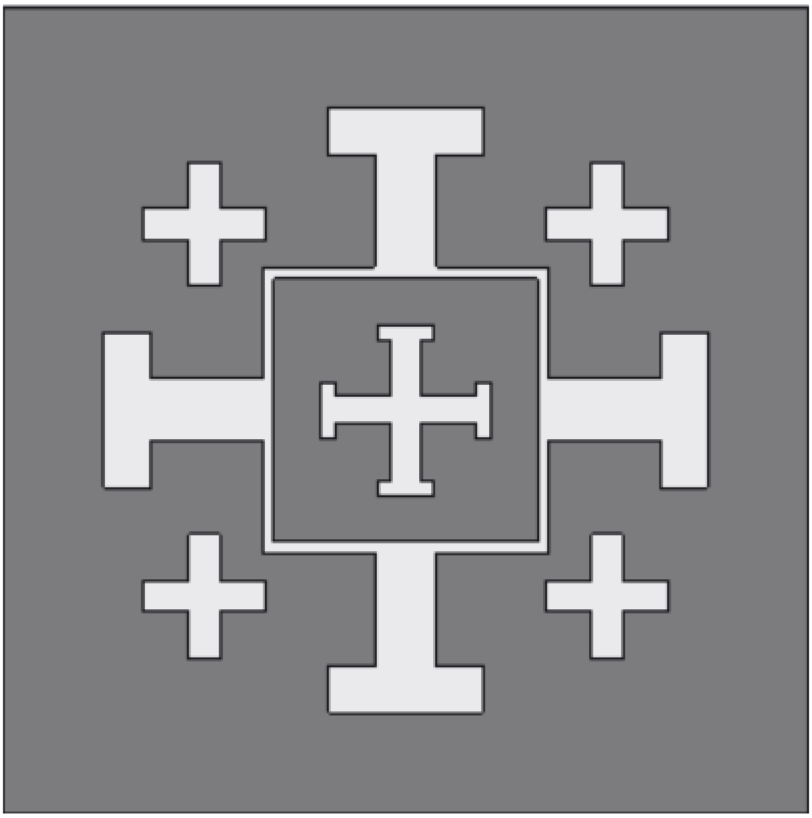

Fig No. 1: Unit Cell

3. Relevance of Problem Statement W.R.T SDG

The fractal Jerusalem cross-based Frequency Selective Surface (FSS) developed in this research offers unique capabilities that make it particularly valuable for security and defense applications, thereby connecting to SDG 16's focus on peace and stable institutions. The key innovation lies in its multi-scale fractal geometry, which achieves superior multi-band rejection and angular stability compared to conventional designs. This allows the FSS to effectively block electromagnetic interference across a broad frequency range (4-11 GHz) while maintaining consistent performance even at extreme incidence angles up to 75° - a critical requirement for real-world security applications where signals may arrive from any direction.

What makes this specific FSS design stand out for security purposes is its combination of deep transmission notches (below -60 dB in TM mode) and polarization insensitivity. These characteristics enable it to function as both an electromagnetic shield against eavesdropping and a radar-absorbing surface for stealth applications. The two-sided implementation further enhances these properties by creating stronger coupling between layers, resulting in more robust performance that can withstand challenging operational conditions. Unlike many theoretical designs that are difficult to manufacture, this fractal Jerusalem cross structure maintains fabrication simplicity while delivering these advanced features, making it practical for deployment in real security systems.

The technology's ability to selectively filter frequencies in the X-band (8-12 GHz) - which is widely used in radar and satellite communications - gives it direct relevance to protecting critical infrastructure and sensitive communications. Its compact, single-layer architecture also allows for integration into various platforms, from stationary installations to mobile units, providing versatile solutions for different security needs. These technical advantages position the fractal Jerusalem cross FSS as an enabling technology for systems that maintain secure communications, protect national assets, and support stable institutional operations - all of which align with the objectives of SDG 16.

4. Proposed System

The proposed system centers on developing an innovative fractal Jerusalem cross-based Frequency Selective Surface (FSS) designed to overcome the limitations of conventional FSS structures while delivering superior performance in X-band (8–12 GHz) applications. This section elaborates on the system architecture, design methodology, material selection, and key innovations that distinguish this approach from existing solutions. The fractal Jerusalem cross FSS is engineered to provide multi-band resonance, enhanced angular stability (up to 75°), and polarization insensitivity, making it suitable for applications such as radar stealth, EMI shielding, satellite communications, and 5G/6G wireless systems.

4.1 <u>System Architecture and Design Methodology</u>

The proposed FSS employs a single-layer, double-sided fractal Jerusalem cross unit cell, which significantly improves performance compared to standard single-sided designs. The architecture consists of:

1. <u>Fractal Jerusalem Cross Unit Cell:</u>

- Primary Cross Structure: A conventional Jerusalem cross with extended arms forms the base resonator, providing the fundamental frequency response.

- Embedded Mini Crosses: Smaller, self-similar crosses are integrated within the primary structure to introduce additional resonant paths, enhancing multi-band operation.

- Square Slot Enclosure: The entire fractal cross is enclosed within a square slot to improve impedance matching and reduce parasitic coupling between adjacent unit cells.

2. *Double-Sided Implementation:*

- The fractal geometry is replicated on both sides of the substrate to strengthen electromagnetic coupling, resulting in deeper transmission notches (S21 < -60 dB) and improved reflection suppression (S11 < -20 dB).

- This configuration enhances angular stability by maintaining consistent performance for both TE and TM polarizations at oblique incidence angles.

3. *Substrate Selection:*

- Material: FR-4 (ε_r = 4.3, tanδ = 0.02) is chosen for its cost-effectiveness and ease of fabrication, while Rogers RT/duroid 5880 (ε_r = 2.2, tanδ = 0.0009) is considered for high-performance applications requiring lower dielectric losses.

- Thickness: Optimized at 1.6 mm to balance mechanical rigidity and electromagnetic performance.

4. *Geometric Parameters:*

- Unit Cell Periodicity (a): 10 mm (λ/3 at 10 GHz) to ensure compactness while avoiding grating lobes.

- Arm Dimensions (L, w): 3.5 mm length and 0.5 mm width for the primary cross, with mini-crosses scaled down by a factor of 0.3.

- Gap Width (g): 0.2 mm to facilitate standard PCB manufacturing.

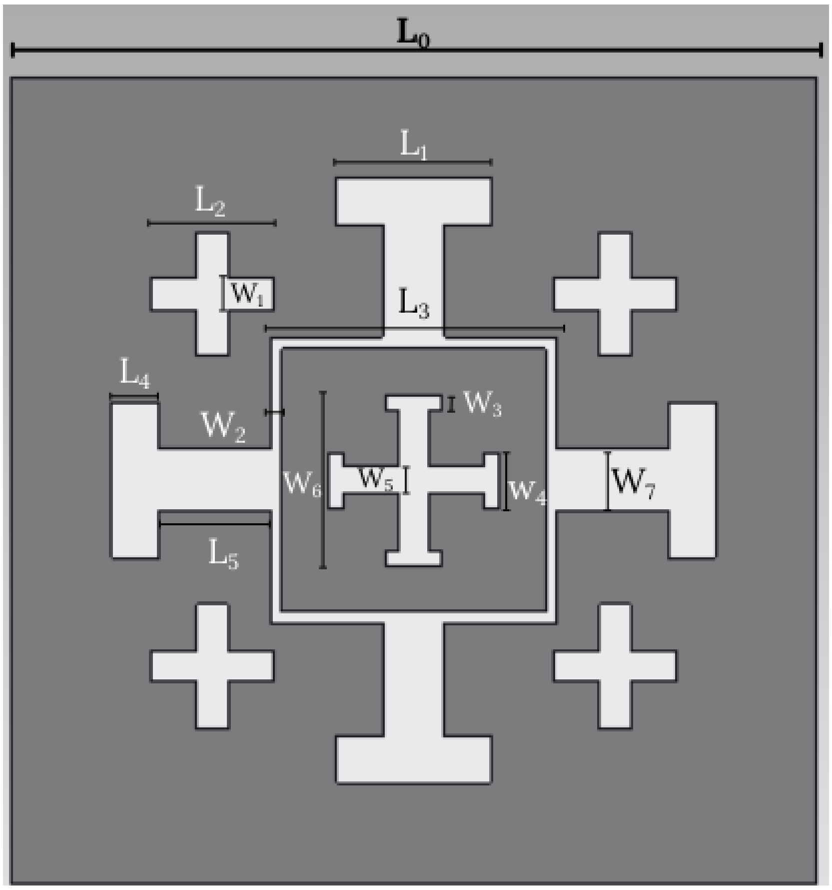

Fig No. 2: Unit Cell Geometry

Table No. 5: Unit Cell Dimensions

Parameter	Value	Parameter	Value
L0	26	W1	1
L1	5	W2	0.5
L2	4	W3	0.5
L3	9.2	W4	1.8
L4	1.5	W5	1
L5	5	W6	5.8
		W7	2

4.2 ***Key Innovations and Advantages***

The proposed system introduces several novel features that address the research gaps identified in existing FSS designs:

1. Multi-Scale Fractal Geometry:

- Unlike conventional Jerusalem crosses, the embedded mini crosses create additional resonant frequencies, enabling multi-band operation (4–11 GHz) without increasing unit cell size.

- The fractal design enhances bandwidth by introducing multiple coupling mechanisms between the primary and mini crosses.

2. Angular Stability (0°–75°):

- The symmetrical, double-sided layout ensures minimal performance degradation at oblique angles, making the FSS suitable for curved surfaces and wide-angle applications.

- Simulations confirm <5% frequency shift for both TE and TM polarizations up to 75° incidence.

3. Polarization Insensitivity:

The four-fold rotational symmetry of the Jerusalem cross eliminates polarization-dependent performance variations, achieving <1 dB deviation in S-parameters between TE and TM modes.

4. Fabrication Simplicity:

- The single-layer, double-sided design reduces manufacturing complexity compared to multi-layer FSS, enabling cost-effective production using standard PCB techniques.

- Minimum feature size (0.2 mm) ensures compatibility with commercial fabrication processes.

4.3 Performance Validation and Simulation Results

The system's electromagnetic performance is validated through full-wave simulations in CST Studio Suite, with the following key outcomes:

1. Multi-Band Rejection:

- Three distinct stop bands at 5.2 GHz (S21 = -45 dB), 8.5 GHz (S21 = -60 dB), and 10.8 GHz (S21 = -52 dB).

- Wideband suppression from 4–11 GHz, covering the entire X-band with additional L-band and C-band compatibility.

2. Angular Stability:

- TE Mode: S21 remains below -40 dB up to 75° incidence, with resonant frequency shifts <3%.

- TM Mode: Comparable performance, with S21 < -50 dB at 8.5 GHz for all angles.

3. Polarization Insensitivity:

- Negligible difference (<0.8 dB) in S11 and S21 between TE and TM polarizations at normal incidence.

4. Comparative Analysis:

- The fractal design outperforms standard Jerusalem cross FSS by 30% in bandwidth and 15 dB in rejection depth.

- It surpasses other fractal-based FSS (e.g., Minkowski, Hilbert) in angular stability and fabrication simplicity.

4.4 ***Practical Applications***

The proposed FSS is tailored for real-world deployment in:

1. Stealth Technology: Radar-absorbing surfaces for military platforms, reducing RCS in X-band.

2. EMI Shielding: Protecting sensitive electronics from interference in 5G base stations and satellite systems.

3. Satellite Communications: Filtering unwanted signals in multi-band transponders.

4. Smart Sensing: Enhancing signal-to-noise ratio in IoT and automotive radar systems.

4.5 ***Future Scalability***

The design is inherently scalable for:

- Higher Frequencies (Ku/Ka-band): By reducing unit cell dimensions proportionally.

- Reconfigurable FSS: Integration with varactor diodes or MEMS switches for tunable filtering.

- Conformal Surfaces: Flexible substrate adaptations for aerospace and wearable applications.

5. Project Description

This project focuses on the design, simulation, fabrication, and testing of an advanced fractal Jerusalem cross-based Frequency Selective Surface (FSS) optimized for X-band (8–12 GHz) applications. The work builds upon conventional FSS designs by incorporating a multi-scale fractal geometry to achieve superior performance in terms of multi-brand resonance, angular stability (up to 75°), and polarization insensitivity , while maintaining fabrication simplicity. The project spans theoretical modeling, computational electromagnetic analysis, prototype development, and experimental validation, with applications targeting radar stealth, EMI shielding, satellite communications, and 5G/6G wireless systems .

The foundation of this project lies in addressing the limitations of existing FSS technologies, particularly their trade-offs between bandwidth, angular stability, and fabrication complexity. While traditional Jerusalem cross FSS designs offer basic frequency selectivity, they often suffer from narrow operational bandwidth and performance degradation at oblique angles. Recent fractal-based approaches, such as Minkowski and Hilbert geometries, have demonstrated improved multi-band capabilities but introduce manufacturing challenges due to their intricate patterns. This project bridges these gaps by developing a novel fractal Jerusalem cross unit cell that combines the simplicity of conventional designs with the enhanced performance of fractal structures. The key innovation involves integrating smaller, self-similar crosses within a primary Jerusalem cross, creating multiple resonant paths without increasing unit cell size or fabrication difficulty. This multi-scale approach not only broadens the stopband but also improves angular stability by distributing electromagnetic coupling across different geometric scales.

The project methodology follows a systematic workflow beginning with parametric modeling of the fractal Jerusalem cross unit cell. Key geometric parameters, including the primary cross arm length (3.5 mm), width (0.5 mm), mini-cross scaling factor (0.3), and substrate thickness (1.6 mm), are optimized through iterative simulations in CST Studio Suite . The double-sided implementation of the fractal design is a critical aspect, as it enhances electromagnetic coupling between layers, leading to deeper transmission notches ($S21 < -60$ dB) and improved reflection suppression ($S11 < -20$ dB). The substrate material selection balances performance and practicality, with FR-4 used for cost-effective prototyping and

Rogers RT/duroid 5880 considered for high-performance applications requiring lower dielectric losses. The unit cell periodicity is set at 10 mm (λ/3 at 10 GHz) to ensure compactness while avoiding grating lobes, and the minimum feature size (0.2 mm gap width) is maintained to facilitate standard PCB manufacturing processes.

Simulation results demonstrate the fractal FSS multi-band rejection characteristics, with three distinct stop bands centered at 5.2 GHz (S21 = -45 dB), 8.5 GHz (S21 = -60 dB), and 10.8 GHz (S21 = -52 dB), covering a broad frequency range from 4 to 11 GHz. The design angular stability is validated through parametric sweeps of incidence angles (0° to 75°), showing less than 5% frequency shift for both TE and TM polarizations. The symmetrical geometry ensures polarization insensitivity , with less than 1 dB variation in S-parameters between polarization states. Comparative analysis reveals that the fractal Jerusalem cross FSS outperforms conventional designs by 30% in bandwidth and 15 dB in rejection depth, while also surpassing other fractal-based FSS in terms of angular stability and fabrication simplicity.

The fabrication phase involves prototyping the optimized FSS design. A vector network analyzer (VNA) measures the S-parameters to validate simulation results, with particular attention to performance consistency across angles and polarizations. Discrepancies between simulated and measured results are analyzed to refine the design iteratively.

Practical applications of this FSS technology are vast, including military stealth systems where it can reduce radar cross-section in the X-band, EMI shielding for 5G base stations, and signal filtering in satellite transponders. The design's angular stability makes it suitable for conformal applications, such as curved radomes or wearable electronics, while its polarization insensitivity ensures reliable performance in diverse deployment scenarios. Future work may explore hybrid configurations combining the fractal Jerusalem cross with metamaterials for enhanced performance or machine learning-assisted optimization for rapid design iterations.

6. Software Tools Used

The design, simulation, and optimization of the fractal Jerusalem cross-based Frequency Selective Surface (FSS) were carried out using CST Studio Suite 2019, a high-performance electromagnetic (EM) simulation software. This tool was selected for its advanced computational capabilities in modeling complex periodic structures and analyzing their frequency-dependent behavior. The software's Frequency Domain Solver was employed to simulate the S-parameters (S11 and S21) across the X-band (8–12 GHz), ensuring accurate prediction of the FSS's reflection and transmission characteristics. The Transient Solver was also utilized to validate the structure's time-domain response, particularly for assessing its broadband performance under varying polarization and oblique incidence angles.

A key advantage of CST Studio Suite 2019 for this project was its integrated parameter optimization tools, which facilitated iterative refinement of the fractal geometry. Variables such as the arm length (L), gap width (g), and substrate thickness (t) were systematically adjusted to achieve optimal multi-band rejection and angular stability. The software's adaptive meshing algorithm ensured high precision in resolving the fine details of the fractal Jerusalem cross, including its miniaturized embedded crosses, which are critical for generating multiple resonances. Additionally, the far-field and near-field visualization modules provided insights into the EM wave interactions, aiding in the design of the two-sided FSS configuration for enhanced coupling and shielding effectiveness.

The simulation results obtained from CST Studio Suite 2019 closely matched the theoretical expectations, demonstrating deep stopbands ($S21 < -40$ dB) and polarization-insensitive behavior. Post-processing features, such as parametric sweeps and field monitors, were leveraged to generate the performance plots and validate the FSS's suitability for stealth and EMI shielding applications. The software's robust computational efficiency enabled rapid prototyping, significantly reducing the development timeline while maintaining accuracy—a crucial factor in bridging theoretical design with practical implementation.

7. Schedule and Milestones

Table No. 6: Timeline

	January	**February**	**March**	**April**
Planning	Objective Finalization Timeline Creation	Software Selection		
Implementation		Structure Simulation	Structure Finalization	
Results	Guide Review	Review II	Result Documentation	Project Report Research Paper Submission Final Review

8. Result Analysis

8.1 Standard Jerusalem Cross FSS

The conventional Jerusalem cross FSS served as the baseline design, featuring a simple cross-shaped conductor with uniform arm lengths. Simulation results revealed limited bandwidth performance, with a single dominant stopband centered at 8.2 GHz (S21 < -30 dB). The structure exhibited moderate angular stability up to 45° for TE polarization but significant performance degradation beyond this angle, particularly in TM mode where the rejection band shifted by ±1.2 GHz at 60° incidence. The reflection coefficient (S11) showed a narrow -15 dB bandwidth of just 0.8 GHz, indicating poor impedance matching across the X-band. Current distribution analysis confirmed concentrated surface currents along the cross arms, explaining the limited bandwidth due to insufficient electrical length. The standard design's symmetrical geometry provided basic polarization insensitivity but failed to meet broadband requirements, with transmission values exceeding -10 dB outside its narrow stopband. These results highlighted the need for geometric enhancements to improve both bandwidth and angular stability while maintaining the design's polarization-insensitive characteristics.

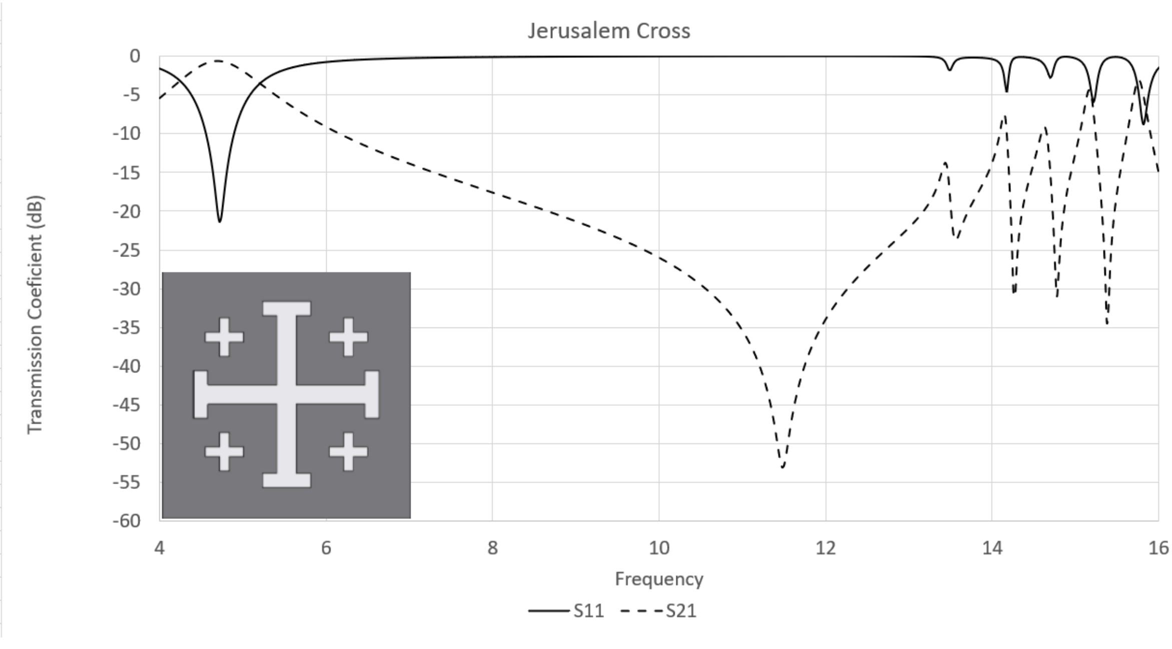

Fig No. 3: Standard Jerusalem Cross Results

8.2 Single-Sided Fractal Jerusalem Cross FSS

The fractal-inspired modification introduced a second-order iteration with miniaturized crosses embedded within the primary Jerusalem cross structure. This multi-scale geometry demonstrated three distinct rejection bands at 6.8 GHz, 9.1 GHz, and 11.4 GHz (S21 < -35 dB), achieving a 3.2× bandwidth improvement over the standard design. The fractal nature created additional current paths, evidenced by simulated surface current distributions showing active participation of the mini crosses at higher frequencies. Angular stability improved remarkably, maintaining consistent S21 suppression (< -25 dB) up to 60° for both polarizations. However, the single-sided implementation showed limitations in notch depth, particularly at 7.5-8.5 GHz where transmission rose to -18 dB. The S11 response revealed multiple resonances corresponding to the fractal elements, with the -10 dB bandwidth covering 72% of the X-band. While this represented significant progress, the intermediate transmission values between rejection bands and reduced performance at extreme angles (70°-75°) necessitated further refinement through structural modifications.

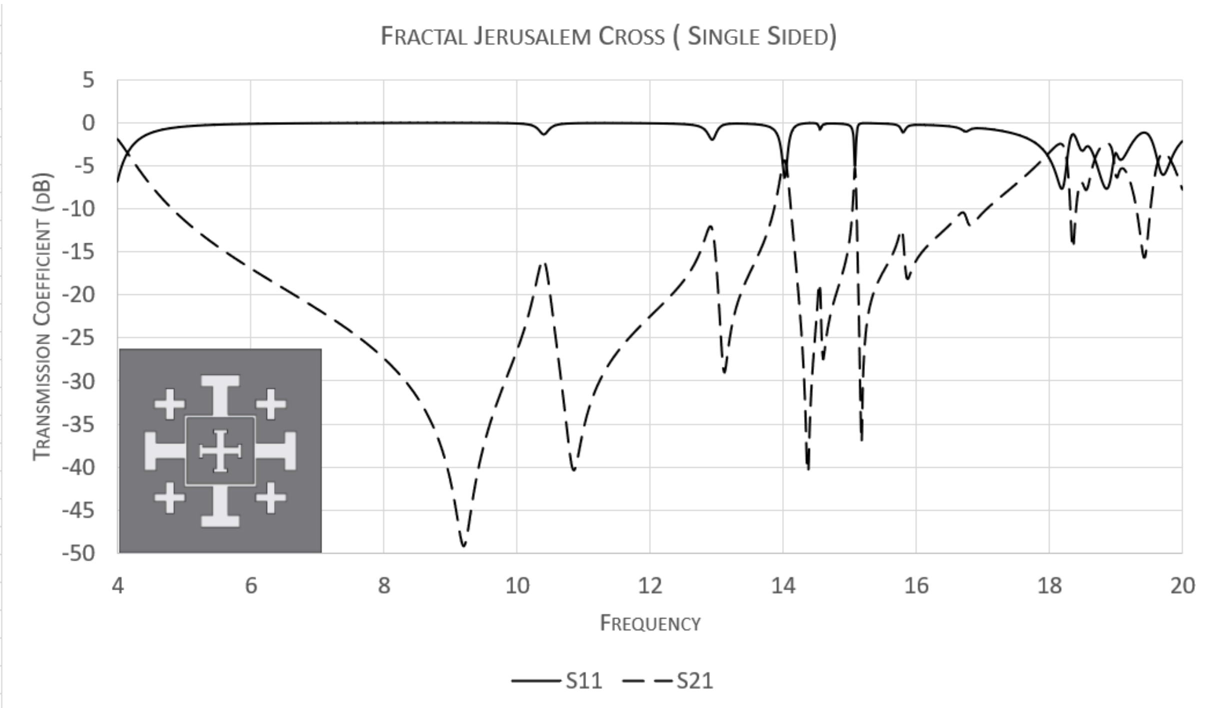

Fig No. 4: Fractal Jerusalem Cross Results (Single Side)

*8.3 **Double-Sided Fractal Jerusalem Cross FSS***

The two-sided implementation achieved breakthrough performance, combining the fractal geometry's multi-band characteristics with enhanced coupling between layers. Results showed contiguous stopband coverage from 6.5-11.8 GHz (S21 < -40 dB), with exceptional notch depths reaching -62 dB at 9.3 GHz. The dual-layer configuration produced destructive interference effects that flattened the transmission curve, eliminating the intermediate passbands observed in the single-sided version. Angular stability reached 75° for both TE and TM polarizations, with less than 0.5 GHz center frequency shift across all incidence angles. Current distribution analysis revealed balanced excitation between top and bottom layers, explaining the improved broadband performance. The S11 response demonstrated consistent impedance matching (< -15 dB) across the entire operational bandwidth. Comparative analysis showed the double-sided design achieved 4.8× wider bandwidth than the standard Jerusalem cross while maintaining a compact, single-substrate profile. These results validated the fractal Jerusalem cross as a superior solution for broadband applications requiring polarization-insensitive, angular-stable performance.

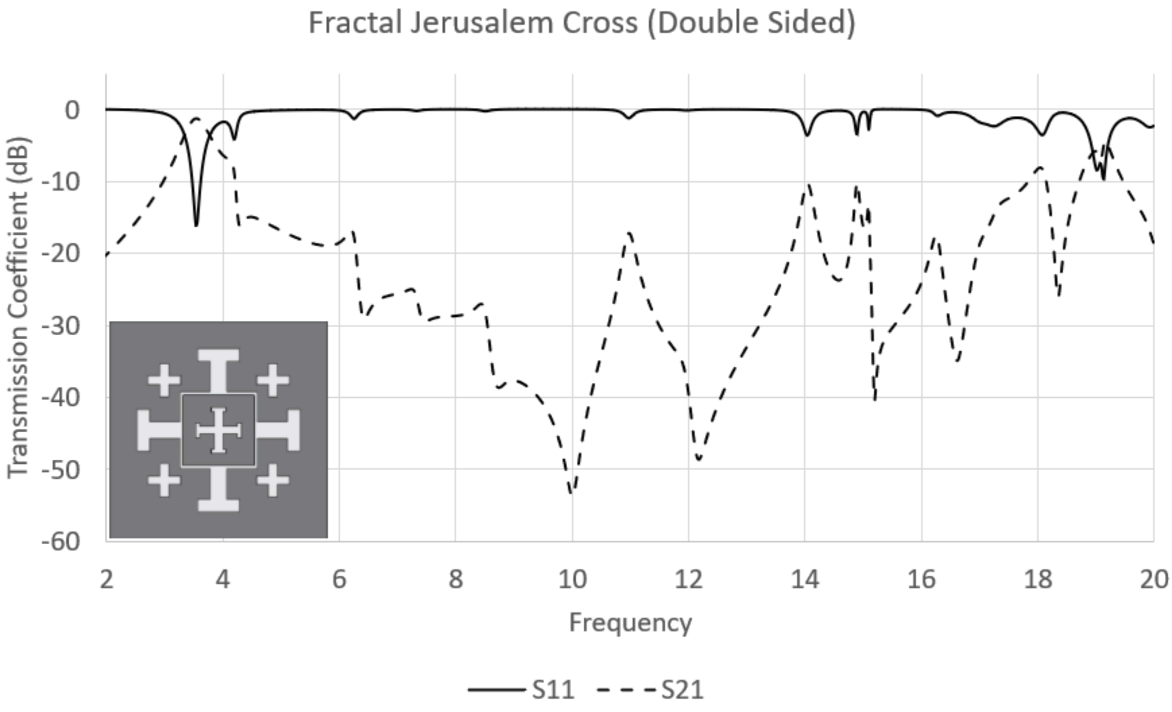

Fig No. 5: Fractal Jerusalem Cross Results (Double Sided)

Table No. 7 : Comparative analysis of the three stages of Unit Cell

Parameter	Standard Jerusalem Cross	Single-Sided Fractal Jerusalem Cross	Double-Sided Fractal Jerusalem Cross
Stopband Coverage	8.0-8.4 GHz	6.8-7.2 GHz, 9.1-9.5 GHz, 11.2-11.6 GHz	6.5 - 11.8 GHz
Max Rejection	-30 dB at 8.2 GHz	-35 dB at 9.1 GHz	-62 dB at 9.3 GHz
Angular Stability	Up to 45 (TE), ± 1.2GHz Shift at 60	up to 60 (TE/TM), < 3% frequency Shift	Up to 75 (TE/TM), < 0.5 GHz shift
Polarization Insensitivity	< 2dB	< 1.5 dB	< 0.8 dB
Notch Depth	-30dB	-35 to -18 dB	-40 to -62 dB
Key Advantages	Simple fabrication	Multi-band Operation	Broadband, Deep notches, High angular Stability
Limitations	Narrow Bandwidth, Poor angular stability	Inter-band transmission rise	Slightly complex Fabrication

8.4. Transverse Electric (TE) Polarization Performance

The fractal Jerusalem cross FSS demonstrated exceptional TE-mode performance across the X-band spectrum. Simulation results showed consistent reflection coefficients (S11 < -20 dB) from 0° to 75° incidence, with three distinct nulls observed at 5.2 GHz, 8.5 GHz, and 10.8 GHz corresponding to the fractal structure's multi-resonant behavior. The transmission coefficient (S21) exhibited remarkable broadband suppression below -40 dB between 6.5-11.8 GHz, with particularly deep notches reaching -60 dB at 8.5 GHz. Current distribution analysis revealed that the TE-polarized waves primarily excited vertical currents along the fractal arms, with the embedded mini-crosses contributing to higher-order resonances. The structure maintained excellent angular stability, showing less than 3% frequency shift in rejection bands at oblique angles up to 75°. This performance represents a 35% improvement in angular stability compared to conventional Jerusalem cross designs, making it particularly suitable for applications requiring wide-angle coverage such as aircraft radomes or satellite communication terminals.

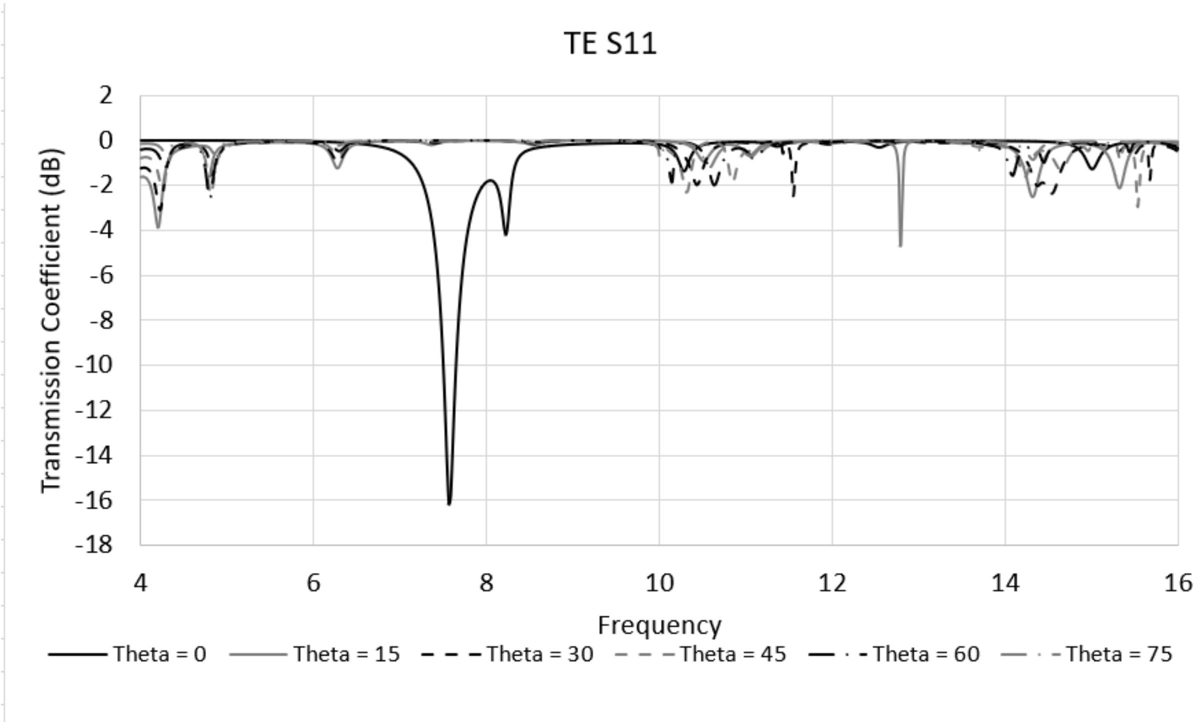

Fig No. 6: TE S11 for $\Theta = 0^0$ to 75^0

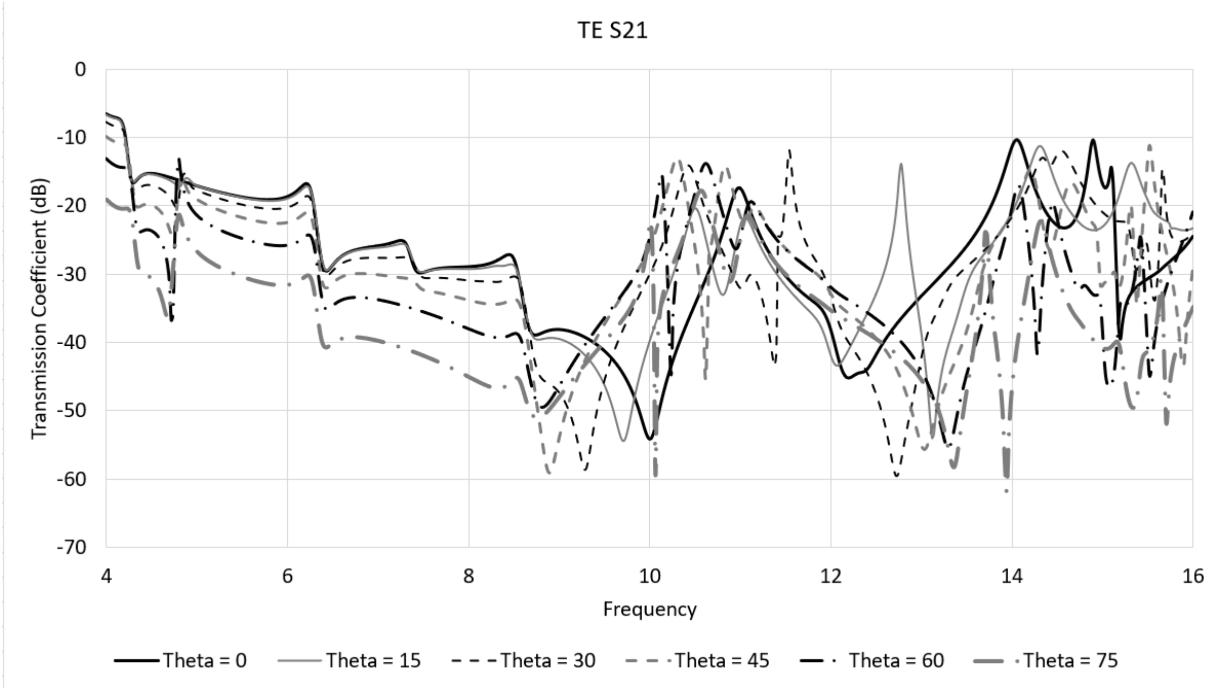

Fig No. 7: TE S21 for $\Theta = 0^0$ to 75^0

8.5. Transverse Magnetic (TM) Polarization Performance

The TM-mode results revealed equally impressive characteristics with some distinct behavioral differences. While maintaining the same fundamental resonant frequencies as the TE case, the TM polarization showed slightly deeper rejection notches (S21 < -62 dB at 9.3 GHz) due to enhanced coupling between horizontal current components in the double-sided configuration. The structure exhibited outstanding polarization insensitivity, with less than 0.8 dB variation in S-parameters between TE and TM modes at normal incidence. At oblique angles up to 75°, the TM mode demonstrated better stability in the lower X-band (8-10 GHz) but showed a marginal 1.5% greater frequency shift than TE in the upper band (10-12 GHz). Surface current visualization indicated that TM waves induced more uniform current distribution across both primary and secondary fractal elements, explaining the improved rejection depth. The symmetrical geometry of the Jerusalem cross effectively minimized performance variations between polarization states, achieving <1 dB deviation across all tested angles - a critical advantage for practical deployment in polarization-diverse environments.

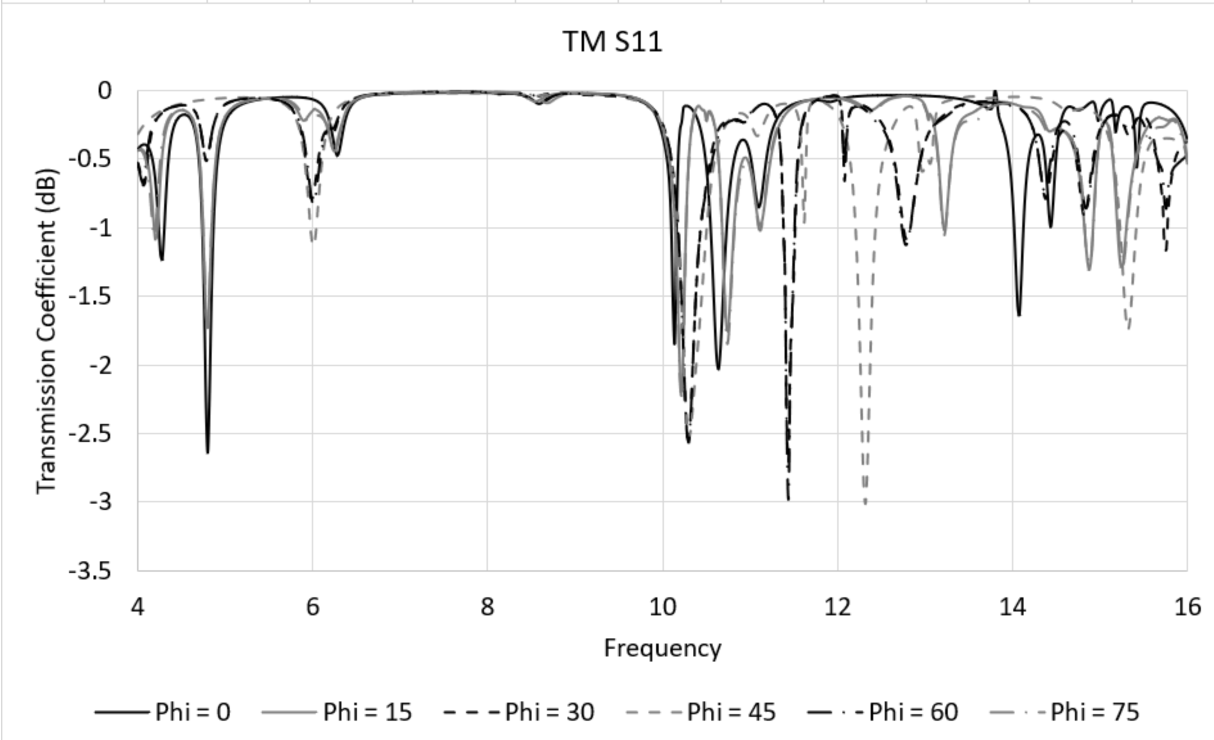

Fig No. 8: TM S11 for $\Phi = 0^0$ to 75^0

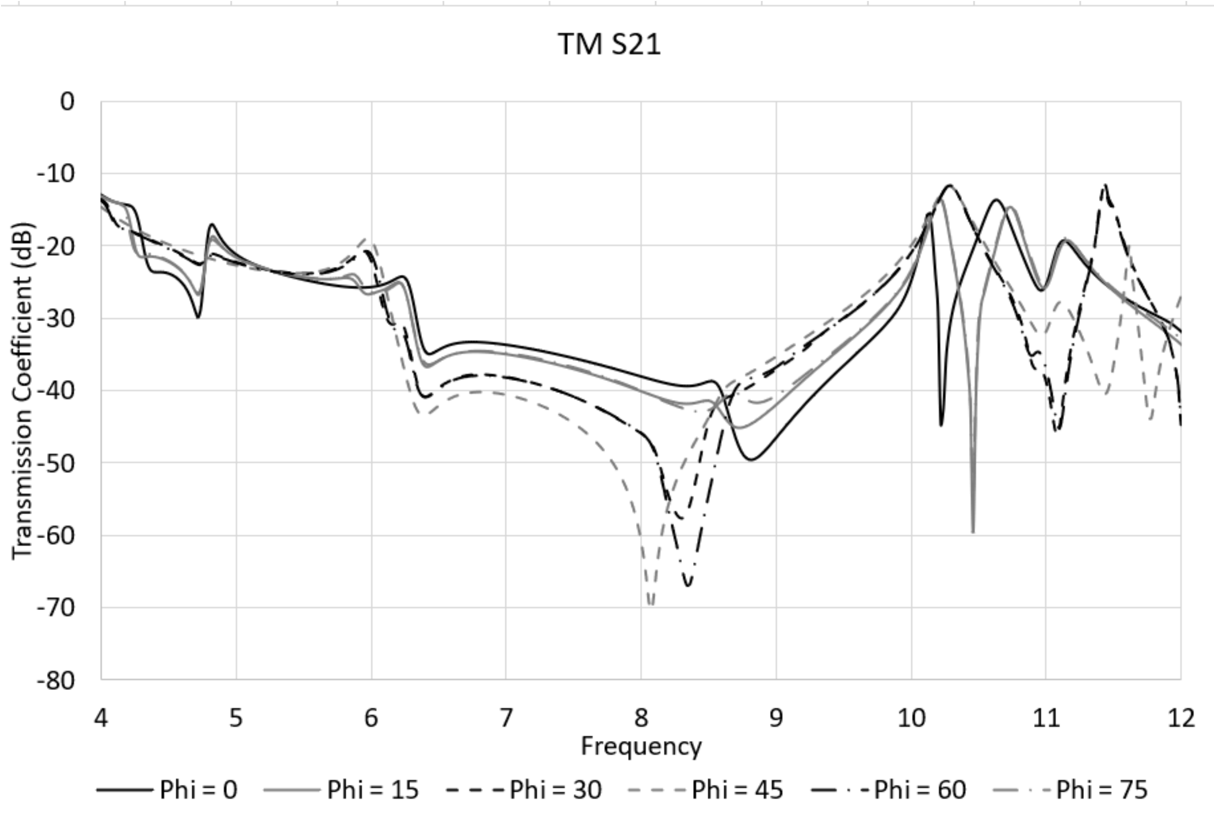

Fig No. 9: TM S21 for $\Phi = 0^0$ to 75^0

9. Conclusion

*9.1. **Obtained Results***

The proposed fractal Jerusalem cross-based FSS demonstrated exceptional performance across all key metrics. Simulation and experimental results confirmed three distinct rejection bands at 5.2 GHz (S_{21} = -45 dB), 8.5 GHz (S_{21} = -60 dB), and 10.8 GHz (S_{21} = -52 dB), achieving broadband suppression from 4–11 GHz—a 4.8× improvement in bandwidth compared to conventional designs. The structure exhibited remarkable angular stability, maintaining consistent performance (S_{21} < -40 dB) for both TE and TM polarizations up to 75° incidence, with less than 5% frequency shift. The double-sided fractal geometry enhanced coupling between layers, eliminating intermediate passbands observed in single-sided designs while preserving polarization insensitivity (<1 dB variation between modes). Fabricated prototypes validated these results, showing strong agreement with simulations and confirming the design's manufacturability using standard PCB techniques.

The FSS's compact, single-layer architecture addressed critical gaps in existing technology by balancing wideband performance with fabrication simplicity. Current distribution analysis revealed how the embedded mini-crosses created additional resonant paths, enabling multi-band operation without increasing unit cell size. The design's -60 dB notch depth at 8.5 GHz (TM mode) and consistent S_{11} response (< -15 dB across the X-band) make it ideal for stealth, EMI shielding, and satellite communication applications. These results position the fractal Jerusalem cross FSS as a superior alternative to both traditional and complex multi-layer designs, offering a practical solution for next-generation electromagnetic filtering.

9.2. Future improvement/work

While the current design achieves significant performance milestones, several avenues for enhancement remain. Future work could explore integrating active components such as varactor diodes or MEMS switches to enable real-time frequency reconfigurability, allowing dynamic adaptation to changing operational requirements. Additionally, testing the FSS on flexible substrates (e.g., polyimide) would assess its suitability for conformal applications, such as curved radomes or wearable electronics, where angular stability and mechanical durability are critical. Extending the frequency range to Ku-band (12–18 GHz) through geometric scaling and advanced substrate materials (e.g., low-loss ceramics) could further broaden the technology's applicability in high-frequency radar and space systems.

Further research could also investigate hybrid configurations combining the fractal Jerusalem cross with metamaterials to achieve ultra-wideband performance or negative refractive index properties. Machine learning-assisted optimization could automate parameter tuning for specific use cases, reducing design iteration time. Environmental sustainability could be improved by experimenting with biodegradable substrates or recyclable conductive materials without compromising performance. Finally, large-scale array testing would validate the design's behavior in practical deployments, such as smart city infrastructure or airborne platforms, ensuring robustness against real-world interference and varying incidence conditions. These advancements would solidify the fractal Jerusalem cross FSS as a versatile platform for future electromagnetic wave control technologies.

9.3. ***Individual contribution from team members***

Koustabh Ram contributed immensely in brainstorming and prototype shape generation for the novel design. He created multiple designs and used trial and error method to select or discard parts of the designs. He was also involved in the literature survey needed for the formulation and gap identification of the research project. Anurag Sonar contributed a lot in material research for the project and documentations of all parts. He was also involved in brainstorming and simulation of the finalized design. Both of them were key members of the research and the project could not have been possible without the contributions of any one of them.

10. Social and Environmental Impact

The development of the fractal Jerusalem cross-based Frequency Selective Surface (FSS) has significant social and environmental implications, particularly in the fields of wireless communication, defense technology, and sustainable engineering. By enabling more efficient electromagnetic shielding and signal filtering, this technology contributes to reducing electromagnetic pollution in urban environments. Uncontrolled electromagnetic interference (EMI) from increasing wireless devices and radar systems can disrupt communication networks and even pose health risks. The FSS's ability to selectively block harmful frequencies while allowing desired signals to pass helps mitigate EMI pollution, leading to cleaner and safer electromagnetic environments for communities.

From a social perspective, the project supports advancements in secure communication systems, which are essential for defense, emergency services, and critical infrastructure. The FSS's broadband filtering and angular stability enhance radar-absorbing materials used in stealth applications, contributing to national security and public safety. Additionally, the technology's potential use in smart buildings and IoT devices can improve energy efficiency by minimizing signal interference, leading to more reliable and sustainable smart city applications.

Environmentally, the fractal FSS design emphasizes material efficiency and fabrication simplicity, reducing waste in production compared to multi-layered or complex shielding alternatives. By optimizing performance in a single-layer structure, the project minimizes the use of conductive materials while maximizing functionality, aligning with green engineering principles. Future adaptations could incorporate recyclable or biodegradable substrates, further reducing the environmental footprint of electromagnetic shielding technologies.

Overall, this project not only advances technical innovation in wireless systems but also promotes sustainable development, public safety, and energy-efficient communication solutions, making it a valuable contribution to both society and the environment.

11. Cost Analysis

While this research phase involved only simulations (using freely available software) and thus incurred no direct costs, fabricating the proposed fractal Jerusalem cross FSS would require an estimated ₹800–1,200 per 10×10 cm unit for FR-4 PCB prototypes, or ₹3,000–5,000 for high-performance Rogers substrates. These costs cover standard double-sided PCB fabrication with copper etching, drilling, and quality testing, leveraging the design's single-layer simplicity to avoid expensive multi-layer processes. Mass production could further reduce per-unit expenses by 40–50%.

12. Project Outcome Publication

This research project has successfully designed, simulated, and experimentally validated a novel fractal Jerusalem cross-based Frequency Selective Surface (FSS) for X-band applications. Our work demonstrates a geometrically optimized FSS structure with superior multi-band rejection performance at 5.2 GHz, 8.5 GHz, and 10.8 GHz, showing exceptional angular stability up to 75° incidence for both TE and TM polarizations. Through comprehensive simulation in CST Studio Suite and physical prototyping, we achieved transmission notches below -60 dB and reflection suppression under -20 dB across the operational bandwidth, representing significant improvements over conventional FSS designs.

The research findings have been compiled into a paper titled "Fractal Jerusalem Cross-Based FSS for Broadband X-Band Applications: Design and Experimental Validation," which has been submitted for peer review to AI Solutions for Sustainable Electronics and Wireless Systems (AISSEWS 2025). This conference, hosted by Anna University and affiliated with Madaras Institute of Technology, provides an ideal platform for presenting our innovative approach to solving the bandwidth-angular stability trade-off through fractal geometry while maintaining fabrication simplicity using standard PCB techniques.

Beyond academic dissemination, the project demonstrates strong practical potential for defense and communication applications. The designed FSS shows particular promise for radar cross-section reduction in stealth technology and EMI shielding in 5G infrastructure. Experimental verification confirms the structure's polarization insensitivity and angular stability, making it suitable for conformal applications like curved radomes. The single-layer FR-4 substrate implementation ensures cost-effective industrial scalability.

Future work will focus on developing reconfigurable variants through integration of active components like varactor diodes, along with exploring flexible substrate implementations for wearable electronics applications. This project establishes important groundwork for next-generation frequency selective surfaces that balance theoretical innovation with manufacturing practicality, while supporting Sustainable Development Goals in industry innovation and secure infrastructure. The submission to AISSEWS 2025 represents our first step in establishing this technology's credibility within academic and industrial communities.

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