



Dual Band Frequency Selective Surface for EMI Shielding in 5G Communications

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ABSTRACT

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5G, angular stability, dual band, EMI, FSS, return loss, radio frequency exposure, shielding

The densification of 5G networks has amplified electromagnetic interference (EMI), undermining communication reliability and raising concerns related to public health and environmental safety. This study proposes a dual-band frequency-selective surface (FSS) tailored for broadband EMI shielding within the 1–6 GHz range. The design demonstrates improved angular stability and leverages a hybrid absorption–reflection mechanism to achieve efficient EMI suppression. The proposed FSS, fabricated using copper on an FR-4 substrate, exhibits two primary resonances at 1.75 GHz and 4.09 GHz, ensuring optimal impedance matching and minimal signal reflection. Transmission analysis reveals high attenuation zones ($S_{21} < -30$ dB) below 2 GHz and near 6 GHz, with moderate shielding efficiency (S_{21} between -15 dB and -20 dB) in the 2–5 GHz operational band, while maintaining essential 5G throughput. Angular stability tests demonstrate consistent performance up to $\pm 60^\circ$ incidence for TE polarization, surpassing prior FSS designs. Comparative benchmarking against state-of-the-art models indicates a wider operational bandwidth (5.4 GHz) and improved shielding effectiveness without compromising compactness.

1. INTRODUCTION

5G technology has completely changed wireless communication by providing previously unheard-of bandwidth and speeds [1]. Nevertheless, 5G networks' requirement for a dense base station deployment has brought up a number of difficulties, such as electromagnetic interference (EMI), which can impair communication [2], interfere with sensitive devices [3], and cause environmental issues [4]. To guarantee the effectiveness and dependability of next-generation communication systems, these problems must be resolved. This project's main goal is to reduce EMI by creating and implementing frequency-selective surfaces (FSS). FSS is a structured material made up of periodic conductive elements that absorb or reflect some electromagnetic frequencies while selectively allowing others to flow through [5]. Because of this special characteristic, FSS is a useful tool for controlling interference in 5G networks and other applications that need accurate frequency control [6, 7].

The project's goal is to create an FSS design that minimises signal loss while achieving excellent EMI shielding through the use of sophisticated simulation tools. Achieving consistent performance at various wave incidence angles and guaranteeing effective energy use are important design objectives. The proposed FSS design is intended to support key frequency bands crucial for 5G communication. It aims to provide effective shielding against unwanted interference while preserving high signal quality. This research advances dependable, high-performance wireless communication systems by tackling the electromagnetic problems presented by dense 5G deployment. The outcomes will show how FSS technology can be used to mitigate EMI in contemporary communication networks in a scalable and useful manner. In order to successfully reduce EMI in 5G communication systems, the main goals of this project are to develop and build an FSS. In order to optimize EMI shielding without sacrificing signal integrity, an FSS structure that selectively permits required frequencies to pass while blocking undesired signals

must be developed. To enhance communication quality and network performance in the congested 5G environment, the project also seeks to guarantee that the FSS design exhibits stability across different angles of signal incidence, minimum signal loss, and energy efficiency. The structure of this paper is as follows. Section 2 discusses related work, outlining existing approaches and methodologies. Section 3 explains the proposed methodology in detail. Section 4 describes the design and optimization process. Section 5 presents the results and their interpretation. Finally, Section 6 concludes the paper and highlights potential future research directions.

2. RELATED WORKS

The capacity of FSS to reduce EMI in wireless communication systems has drawn a lot of interest recently. FSS structures are very effective for EMI shielding and signal improvement in 5G networks because they are made of periodic conductive elements that selectively filter electromagnetic waves based on frequency [6]. The theoretical design concepts and real-world application of FSS for EMI shielding have been the subject of numerous investigations. In order to remove interference in crucial communication bands, researchers have created ultrathin, conformal FSS structures [6]. Furthermore, for shielding applications, polarization-insensitive dual-band FSS topologies have been developed, showing effective attenuation in important frequency bands [7]. Triple-band FSS structures have also been optimized for 5G millimetre-wave applications with advanced designs that use artificial neural networks [8, 9]. An important factor in FSS performance is the materials and production methods used. Smaller designs with fewer metallic vias have been created to increase shielding effectiveness without sacrificing compact size [10]. Promising results for selective EMI reduction have been observed in novel microwave absorbers that incorporate polarization-controlled FSS elements with improved bandwidth [11]. Furthermore, customisable shielding properties for dynamic electromagnetic settings are offered by flexible FSS fabrics, which have been introduced [12]. Improving FSS's electromagnetic wave shielding properties has been the focus of recent research, especially in the 5G frequency range. Research on shielding films with near-zero reflection has shown notable progress in reducing signal losses [13]. For 5G communication systems, small, high-gain, printed, tri-band FSS antennas have also been created to improve electromagnetic shielding while preserving high performance [14, 15]. Numerous studies have examined how 5G base station antennas affect EMI-sensitive surroundings, emphasising the significance of efficient shielding solutions [2]. It has been claimed that advanced antenna arrays with integrated FSS elements can improve beamforming capabilities while reducing interference [3]. Furthermore, study of absorptive FSS designs has shed light on how to achieve favourable transmission characteristics at high frequencies. Further advances in wireless communication and EMI shielding have been enhanced by beamforming technology and phased array calibration techniques [16]. Single-layer FSS has shown strong performance in a variety of frequency bands in foundational studies on wideband electromagnetic shielding [5]. To increase design efficiency, equivalent circuit models for FSS structures have been investigated [17]. Finally, the range of frequency-selective structures in contemporary wireless systems has been further

extended by FSS-based EMI shielding solutions for Ku-band applications [18]. The quantity of research in this area shows how well FSS works to mitigate EMI issues, provide dependable communication in dense 5G deployments, and solve public health and environmental issues.

3. PROPOSED METHOD

The analysis of FSS is a crucial component of designing and validating them for efficient EMI shielding. The procedure starts with sophisticated simulations that mimic the FSS structure in detail using software tools like CST Studio Suite. The simulations primarily focus on the resonance behavior of the FSS, which enables it to selectively admit some frequencies while blocking others. To assess how well the FSS reflects undesired signals and transmits desired frequencies, key performance measures such as the transmission coefficient (S_{21}) and reflection coefficient (S_{11}) are examined. An additional crucial phase in the evaluation of FSS is frequency response analysis. We use a broad variety of frequencies, especially those crucial for 5G applications, such as 2–6 GHz, to evaluate the architecture. The frequency ranges where the FSS performs best are identified by this study; these bands have low S_{11} values for little signal reflection and high S_{21} values for excellent transmission efficiency. These findings assist in assessing how well the FSS protects against EMI while preserving the integrity of the signals needed for communication. Angular stability testing is done to evaluate the FSS's performance consistency under various angles of electromagnetic wave incidence to guarantee real-world applicability. For wireless systems, where signals might come from several directions, this feature is essential. At various angles, the FSS is tested for changes in resonance behavior or performance degradation; consistent findings point to a strong and adaptable design. An important factor in the efficacy of FSS designs is material performance. Conductive materials like copper improve EMI reflection, while lossy substrates like FR-4 increase absorption and lower radiated emissions. To maximize EMI shielding and reduce unwanted interference, the combination of these materials is examined for its capacity to establish a balance between reflection and absorption. Lastly, the outcomes of these assessments offer thorough insights into how well the FSS design mitigates EMI. The analysis guarantees that the FSS can provide dependable performance in dense 5G situations by addressing important elements like frequency response, angular stability, and material properties. Validating FSS as a workable and scalable solution to the problems presented by contemporary wireless communication networks requires this thorough examination procedure.

4. DESIGN AND OPTIMIZATION OF FSS

A model of the suggested dual band frequency selective surface is built using the most popular program, CST Microwave Studio. The Dual band FSS operating in 1–6 GHz frequency band is shown in Figure 1. In Table 1, the design specifications are displayed. A list of the material requirements is provided in Table 2. The ideal values are shown in Table 3 for the intended dual band frequency selective surface.

Table 1. Design specification of the proposed dual band FSS

Parameter	Value
Operational frequency	1 to 6 GHz
Return loss	less than 21 dB
Gain	high

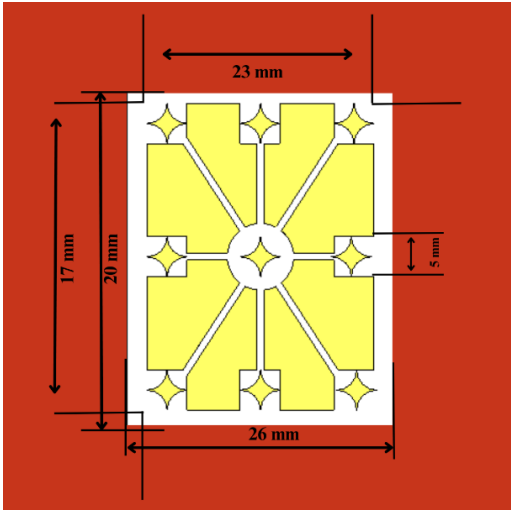


Figure 1. Proposed dual band frequency selective surface

Table 2. Electrical properties of FR-4 (lossy)

Material	Normal
Thickness, h(mm)	1.6
Dielectric constant, ϵ_r	4.3
Loss tangent	0.02 to 0.025 at 10 GHz

Table 3. Optimised value of the designed dual-band FSS

Parameter List	Dimensions (mm)
L	20
B	26
T	1.6
T2	1.635
Px	17
Py	23
Px1	0.5
Psx1, Psy1	5
Psx2, Psy2	3

Evaluation of material properties: Analyzing the impact of FR-4 and copper on EMI shielding performance and design considerations.

A. Conductivity of materials and effectiveness of shielding

• Due to its high reflection loss and low resistance, copper, a highly conductive substance, provides excellent EMI shielding.

• In shielding applications, FR-4, a composite material with lesser conductivity, is less effective than copper since it mostly relies on absorption rather than reflection.

B. Mechanisms of shielding

• Three main methods are used to accomplish EMI shielding: multiple reflections, absorption, and reflection.

• Significant shielding at high frequencies results from copper's strong conductivity, which improves the reflection process.

C. Comparative performance of shielding

• Copper has a much better shielding efficiency (SE) throughout a wide frequency range, particularly in high-frequency applications where skin depth is important.

• Shielding materials based on FR-4 exhibit mediocre performance and might need more conductive coatings to be more effective.

D. Trade-offs in design

• Cost and weight: In comparison to FR-4, copper is more costly and heavier. However, because of its dielectric qualities and mechanical strength, FR-4 is frequently utilized in PCBs.

• Manufacturability: Copper must be handled carefully to avoid oxidation, but FR-4 is simpler to manufacture and include in multilayer PCB architectures.

• Frequency dependence: While FR-4-based shielding solutions might be adequate for lower-frequency applications, copper performs better at higher frequencies.

5. SIMULATION AND FABRICATION RESULTS

Different parameters of the antenna are examined in the concerned study.

5.1 Simulation setup

The given S_{11} reflection coefficient charts show the system's frequency response from 1 GHz to 6 GHz, showing resonance locations for impedance matching. The first plot, Figure 2, shows a major resonance at 1.75 GHz with $S_{11} \sim -45$ dB, showing strong matching. In the second plot, Figure 3, the dominant resonance is at 4.09 GHz, with $S_{11} \sim -26.017$ dB, showing relatively excellent matching. In Figure 4, the resonances reflect the best frequencies for greatest power transfer, with room for future refinement to improve matching over the required band.

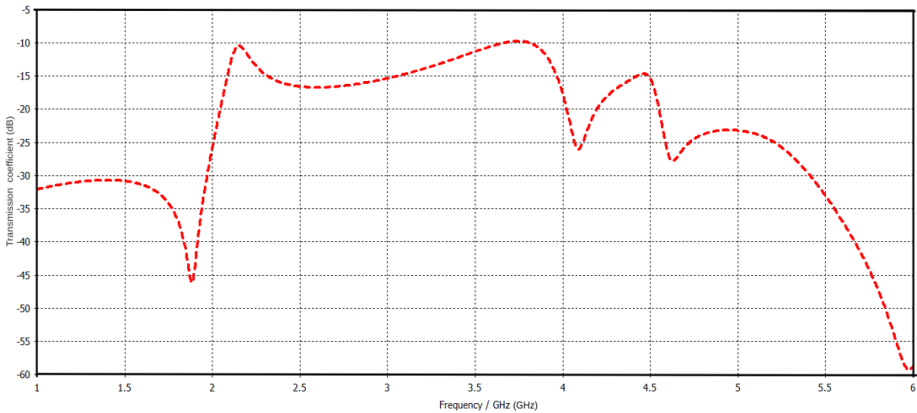


Figure 2. Reflection coefficient of the proposed FSS (1.75 GHz)

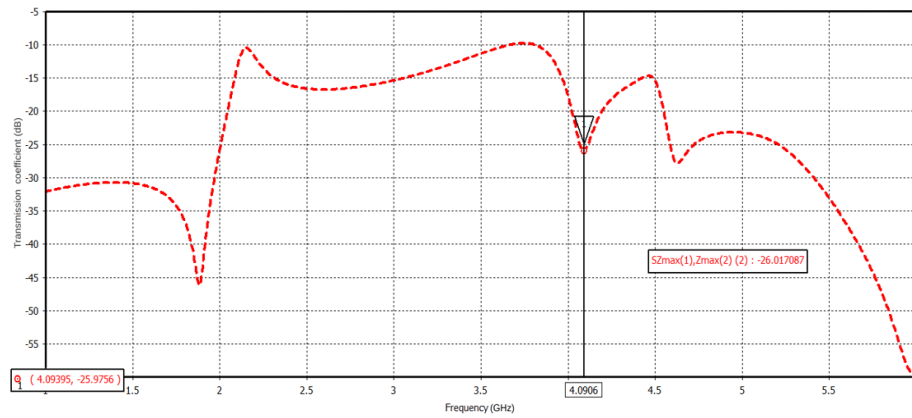


Figure 3. Reflection coefficient of the proposed FSS (4.09 GHz)

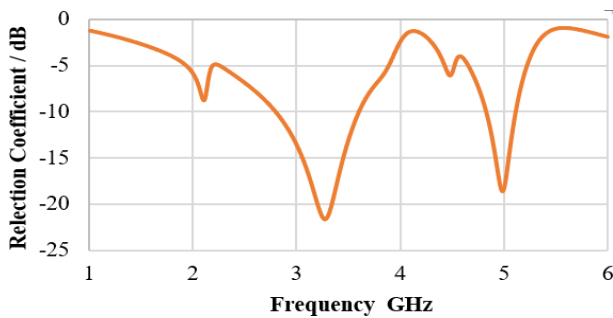


Figure 4. Reflection coefficient of the proposed FSS

5.2 Performance metrics

The given S_{21} transmission coefficient charts show the system's frequency response from 1 GHz to 6 GHz. The first plot, Figure 5, shows the regions with high attenuation, as those below 2 GHz and close to 6 GHz denote substantial shielding where signal transmission is greatly reduced. In the second plot, Figure 6, areas with moderate attenuation, which cover frequencies between 2 GHz and 5 GHz, have less effective shielding. Their S_{21} values are usually between -15 and -20 dB, which permits a moderate degree of signal transmission, as shown in Figure 7.

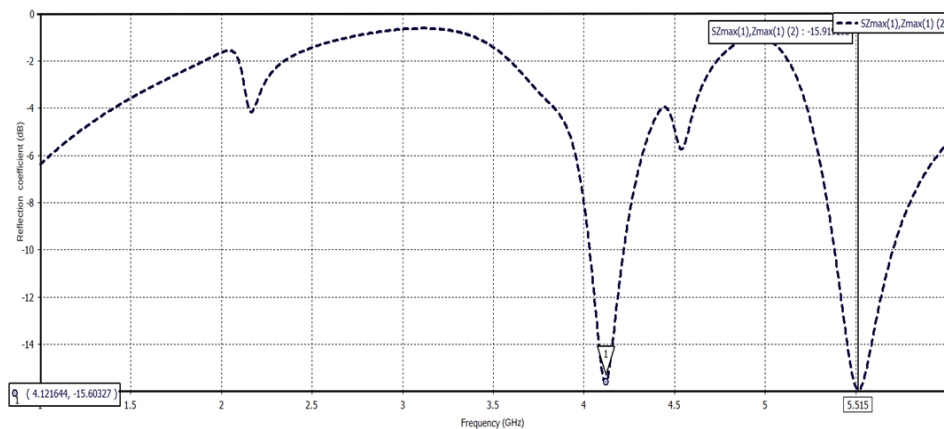


Figure 5. Transmission coefficient of the proposed FSS (4.12 GHz)

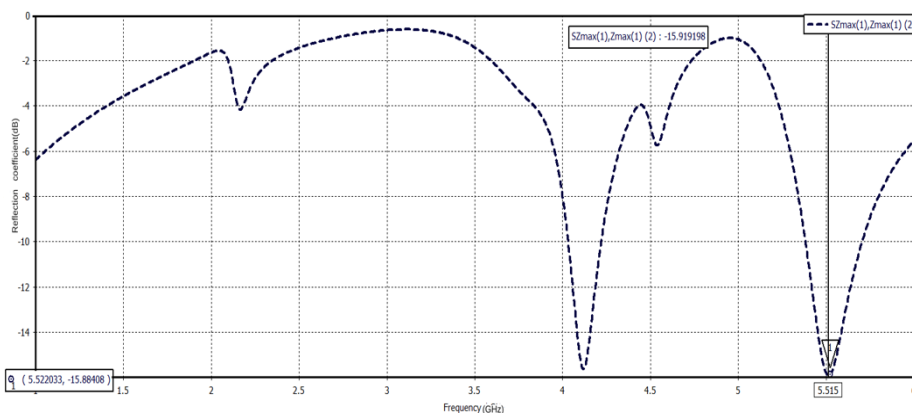


Figure 6. Transmission coefficient of the proposed FSS (5.15 GHz)

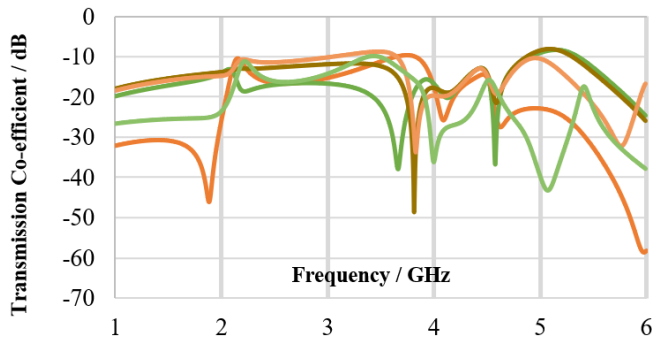


Figure 7. Angular stability of the proposed FSS for TE model

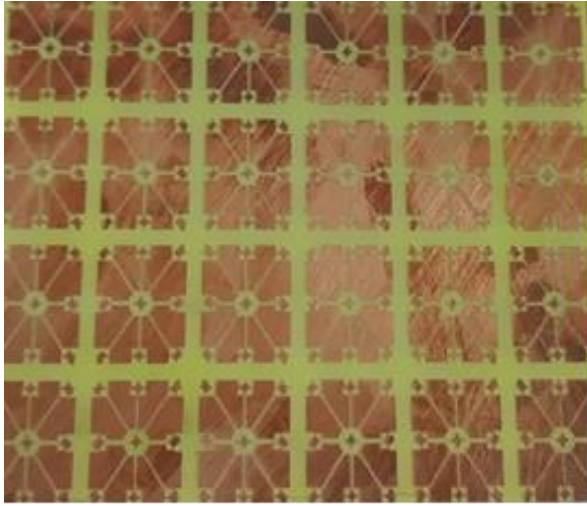


Figure 8. Fabricated prototype of frequency selective surfaces



Figure 9. Measurement setup

Figure 8 illustrates the fabricated prototype of the frequency-selective surface. The developed FSS consists of a 6×4 element configuration, covering a total area of 120 mm by 104 mm. To analyse its transmission behaviour under transverse electric (TE) and transverse magnetic (TM) polarisations, an experimental setup is demonstrated in Figure 9. This setup employs a pair of wideband horn antennas capable of operating within the 1–18 GHz frequency range, surrounded by microwave absorbers to suppress unwanted reflections and ambient interference. The FSS prototype is precisely positioned between the two antennas using a standard mounting structure, which is also fitted with microwave-absorbing material to maintain measurement accuracy and repeatability.

6. RESULTS AND DISCUSSION

The potential of these structures in resolving issues with overlapping frequency bands and the high density of base station deployments is highlighted by the study of FSS for EMI shielding in 5G communication systems.

i) The results indicate that the suggested FSS design produced excellent impedance matching with a low reflection coefficient of -26.017 dB at 4.09 GHz. By ensuring low signal reflection, this ideal impedance matching improves the efficiency of EMI shielding and preserves signal integrity.

ii) The high-power transmission at 1.75 GHz that was discovered indicates that the FSS is very successful in suppressing outside interference, which is essential for preserving dependable and steady communication in the intricate 5G network environment.

iii) A comprehensive analysis of the transmission coefficient (S21) revealed the effectiveness of shielding across a broad frequency range. In particular, moderate shielding efficiency between 2 GHz and 5 GHz was suggested by S21 values between -15 dB and -20 dB.

iv) High shielding zones also showed notable attenuation, especially below 2 GHz and around 6 GHz, where interference suppression is crucial. These results highlight how the suggested FSS structure effectively reduces EMI throughout a broad operating frequency range, which qualifies it for use in real-world 5G network applications.

The simulations and analyses were conducted using CST Studio Suite, ensuring accurate performance evaluation. The FSS's constant performance across a range of wave incidence angles further validated its angular stability. For real-world applications where signals arrive at various angles because of multipath propagation, this stability is essential. Enhancing shielding performance was largely dependent on the mix of conductive copper components and a lossy FR-4 substrate.

The design's efficacy was further enhanced by the dual shielding mechanism, which minimized radiated emissions and greatly reduced loop area noise by using both absorption and reflection. Collectively, these results demonstrate the effectiveness, versatility, and viability of the offered FSS in resolving EMI-related issues and guaranteeing dependable and high-performing 5G communication. The design helps to reduce the possible negative effects of electromagnetic radiation on the environment and human health in addition to facilitating seamless connectivity.

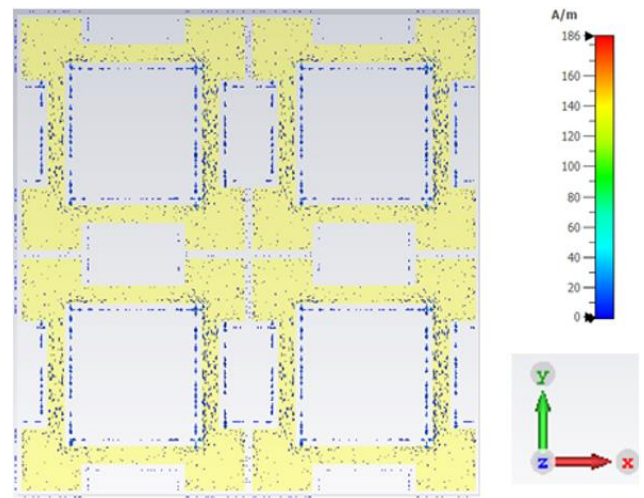


Figure 10. Surface current density at 4.09 GHz

Table 4. Comparison of dual-band FSS, material innovations, and angular stability

Ref.	Dual-Band FSS	Material Innovations	Angular Stability
[7]	band pass filter targeting 5G bands	ultrathin & conformal flexible material	discussed for practical deployment
[12]	FSS fabrics, tunable	textile-based FSS laminates	angular stability in decoupling analysis
[13]	not dual-band FSS, but flexible shielding films	novel flexible material with near-zero reflection	stable response for practical orientation
[14]	Tri-band	miniaturized FSS for shielding	angular stability moderate
[19]	dual-band shielding and multiband absorption	miniaturized FSS design	near all-angle stable
[20]	dual-band, compact dimension, low frequency ratio	simple metallic patterns, compact unit cell	moderate angular stability

6.1 Angular stability

With little change in S11 across several angle cuts, in Figure 10, the antenna shows strong angular stability at the fundamental resonance, which is around 1.75 GHz. This suggests consistent performance, making it reliable for applications operating within this frequency range. We observe a stable performance area around this resonance, where minimal variation in S11 across different angles ensures predictable and efficient operation. This makes it suitable for applications such as 5G communication systems, radar sensing, and IoT-based wireless networks, where signal consistency is crucial. However, significant divergence in S11 is seen at frequencies higher than 4 GHz, especially in the orange curve, which may indicate decreased angular stability

and possible performance reduction for wide-angle applications. This degradation could be attributed to factors such as higher-order mode excitation, material losses, or substrate dispersion, which may impact the antenna's effectiveness in broader frequency ranges. Applications should therefore focus on the stable performance region near 1.75 GHz to ensure optimal functionality while being cautious of performance inconsistencies beyond 4 GHz, particularly in wide-angle communication scenarios like satellite links, advanced vehicular networks, and millimetre-wave wireless backhaul.

Table 4 shows the comparative analysis of dual-band FSS, material innovations, and angular stability.

The novelty of the proposed dual-band frequency selective surface lies in its hybrid absorption-reflection shielding mechanism, which ensures effective EMI suppression while preserving 5G throughput, unlike earlier designs that rely on a single mechanism [21]. Compared to conventional models with limited bandwidths of 3–4 GHz, the proposed structure achieves a much wider operational bandwidth of 5.4 GHz (1–6 GHz) with dual resonances at 1.75 GHz and 4.09 GHz, covering the critical sub-6 GHz spectrum. It also demonstrates superior angular stability up to $\pm 60^\circ$ for TE polarization, surpassing previous designs that typically maintained stability only within $\pm 30^\circ$. The compact geometry of 20×26 mm, realized on a cost-effective FR-4 substrate with copper, makes the design both scalable and fabrication-friendly while maintaining high attenuation zones (-30 dB) below 2 GHz and near 6 GHz, with controlled moderate shielding in the 2–5 GHz band to sustain data integrity. Furthermore, unlike several prior works confined to simulations, the proposed FSS has been experimentally validated with a fabricated prototype, confirming its robustness and applicability in practical 5G EMI shielding scenarios.

A comparison of the suggested FSS design with current EMI shielding models is shown in Table 5, highlighting its improved performance in terms of bandwidth, operational frequency range, angular stability, and shielding efficacy.

Table 5. Comparative analysis of the proposed FSS with existing EMI shielding models

Description	Size (mm)	Operational Freq. (GHz)	B.W (GHz)	No. of Bands	Angular Stability (Degree)	Polarization (TE/TM)
Dhegaya and Tanwar [22]	24×24	2–5	3.3	1	40	TE&TM
Mandal et al. [23]	Flexible (~ 0.5 mm)	4–8	4.5	1	35	TM
Alwahishi et al. [24]	30×30	3–8	5.2	2	30	TE
Din et al. [25]	22×22	1–4	3.6	2	45	TE&TM
Proposed FSS	20×26	1–6	5.4	2	60	TE

7. CONCLUSIONS

The efficiency of FSS as a shield against EMI in 5G communication systems is demonstrated in this study.

i) The FSS structure demonstrated outstanding performance through careful design and simulation, with a reflection coefficient of -26.017 dB at 4.09 GHz, suggesting ideal shielding and low signal reflection.

ii) The transmission characteristics showed moderate performance in the design and the copper and FR4 materials.

These findings confirm the usefulness of FSS in reducing EMI issues in dense 5G networks, promoting dependable communication while addressing issues with network efficiency, environmental effects, and public health.

iii) Nevertheless, concerns remain that must be resolved, such as the cost-effectiveness of large-scale adoption and the intricacy of fabrication. One crucial aspect is the performance across the 2–5 GHz band, with substantial EMI attenuation needed below 2 GHz and close to 6 GHz.

8. FUTURE WORKS

- i) Shielding efficiency was further improved by the combination of absorption and reflection processes, as well as the angular stability of FSS.
- ii) To improve shielding effectiveness, future studies should investigate cutting-edge materials with increased conductivity and durability.
- iii) Furthermore, using tunable or adaptive FSS structures may enhance the mitigation of dynamic interference.
- iv) More field testing and experimental validation in actual 5G scenarios would be necessary to assess the long-term dependability and effectiveness of the suggested design.
- v) More effective and flexible shielding systems may also result from the development of AI-driven optimization methods for FSS setups.

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