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Research Article

# Double-sided bandpass frequency selective surface design for C band WLAN radome applications

**Burak Can KIŞLA[1], Bilge ŞENEL[1,*]**

[1]*Department of Electrical and Electronics Engineering, Süleyman Demirel University, Isparta, 32260, Türkiye*

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## ABSTRACT

Frequency Selective Surfaces (FSSs) are crucial for controlling the transmission and reflection of specific electromagnetic wave frequencies. FSSs play a critical role in various technologies, including wireless communication and radar systems, by targeting specific regions of the electromagnetic spectrum to improve system performance. Integrating FSS on a radome can transmit the wave within the passband while scattering the wave outside the passband. Radomes provide protection for antenna systems from environmental conditions while permitting the transmission of electromagnetic waves. The objective of this study is design, fabrication, and measurement of a 5 GHz bandpass double-sided FSS intended for integration within a radome structure. In the study, aperture, and patch-type FSS structures that provide bandpass filter characteristics were used. The design comprises two distinct shapes, with the front surface patch and the rear shape resulting from the excavation of the copper plate. FR-4 ($\varepsilon_r$ = 4.4) and $t$ = 1.66 $mm$) is used as substrate. For simulations, CST Microwave Studio was employed. After unit cell design and analysis in CST, optimization and sensitivity analysis were performed to meet requirements. Then FSS was fabricated, and transmission loss measurement was performed. According to simulation results -33 $dB$ $S_{11}$ and -0.58 $dB$ $S_{21}$was obtained for optimum aperture and patch sizes. The simulation and measurement results of transmission loss are very close to each other. Therefore, the developed FSS is recommended for use in wireless communication technologies within the 5GHz band.

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## INTRODUCTION

Frequency selective surfaces (FSSs) are a rapidly growing research area in electromagnetic engineering. These surfaces essentially enable wave control by allowing electromagnetic waves to transmission, reflect, or absorb only certain frequencies. FSSs block electromagnetic waves in certain frequency bands while allowing others to pass. They are versatile elements that can be used in many areas such as advanced antenna systems, stealth technologies, radar cross-section reduction, and spectrum control [1].

FSSs are spatial electromagnetic filters. They could be operating as either band-stop or bandpass filters depending on the application area. These structures play a critical

***Corresponding author.**
*E-mail address: bilgeturkel@sdu.edu.tr

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role in radar systems used for target detection and tracking, SAR radars, jamming technologies, signal quality enhancement in MRI devices, and signal filtering in wireless communication systems. Mainly, manipulating and processing electromagnetic waves with FSSs play a vital role in a wide range of applications as mentioned earlier [2-3]. However, FSSs widespread use, especially in military systems, emerged in the mid-1960s, the first known patent in this field was belong to Marconi and Franklin in 1919 [1]. This study aims to design, fabrication, and measurement of a 5 GHz bandpass double-sided FSS intended for integration within a radome structure. The designed FSS is for WLAN applications.

The smallest structural element in FSSs, known as the unit cell, is fundamental to their design and function [4–6]. FSSs consist of various patches and apertures arranged in a periodic pattern. When electromagnetic waves interact with these structures, they exhibit band-pass and band-stop characteristics. The patches and apertures placed on the dielectric create capacitive and inductive effects, which determine the filter's characteristics. [1]. Radomes are dome-like structures used to protect antennas and other sensitive electronic equipment. They are widely used in radar systems. Their primary function is to protect antennas and electronic equipment from adverse weather conditions and other environmental disturbances. Importantly, radomes are engineered to minimize interference with electromagnetic wave performance, thus preserving the functionality and efficiency of the enclosed antenna systems [7]. FSSs and radomes are individually very important elements for military and civilian mobile communication systems. Combining these two structures and designing radomes as FSS will increase mobility especially for air platforms. Because lightness is very important especially for Unmanned Aerial Vehicles (UAVs). The innovative part of our work is that the FSS we designed in this study could be used as a radome on flat air platforms.

The square slotted FSS structure and the gridded square loop FSS structure are widely used in various applications due to their frequency transmission characteristics. However, when analyzing the transmission response of these structures with respect to frequency, a sharp drop is not observed when transitioning to frequencies outside the transmission band. To create a more sharply selective FSS structure for frequencies outside the transmission band, it would be advantageous to implement FSSs on both sides of the dielectric substrate [8], [9]. Because of this reason we have chosen double-sided FSS structure.

Furthermore, FSSs provide significant benefits in antenna design by aiding in directing and focusing the antenna's performance on specific frequency ranges. They can block signals from undesired frequency bands, thereby reducing noise, and can be employed to control the reflection and scattering of electromagnetic waves, effectively expanding the frequency band [10]. In the 4-7 GHz range, Wu and colleagues introduced wideband gridded square FSSs for electromagnetic waves, achieving a stopband using a two-tiered FSS configuration [11]. Additionally, Braz and Campos investigated a simple structure based on fractal geometry [12]. They examined a broad-frequency-tunable FSS in the range of 3.5 GHz to 5.8 GHz for electromagnetic shielding applications [13-16].

There are studies where FSS based filters are used as bandpass filters in 5G applications. Studies targeting wireless communication applications in the 5 GHz band, such as WLAN (Wireless Local Area Network) and WiMAX (Worldwide Interoperability for Microwave Access), are crucial in the context of using FSS as bandpass filters [17]. In Duan's study, a minimum FSS insertion loss of 0.58 dB was observed within the 7.6 to 13.5 GHz range for radomes [18]. Sheng designed a miniaturized conformal wideband FSS for X-band (@ 8.7 GHz resonance frequency) with stable transmission performance [19]. These studies aim to increase the performance of wireless communication technologies and use the electromagnetic spectrum more efficiently. In this study, we are also aimed to design and manufacture a double-sided FSS at 5 GHz for WLAN applications. FSS is manufactured on FR-4 which is cheap and easy to find.

FSS based bandpass filters can isolate or direct the frequencies of wireless communication systems like WLAN and WiMAX in the 5 GHz region [20]. This can assist in reducing interference and collisions between networks. Especially in urban areas or for dense wireless networks, FSSs are indispensable for better connection quality and data transmission rates. Such studies may encompass various factors, including FSS design, material selection, radome geometry, and electromagnetic simulations. Consequently, FSS-based bandpass filters emerge as a significant element in advancing and improving wireless communication technologies. The combination of bandpass filters, which are essential elements for wireless communication systems, and radomes used to protect antennas on aerial platforms, into a single structure increases the importance of our work in terms of mobility and compactness.

The manuscript organization is as follows: FSS design procedure explained elaborately in Section II. Also design process of our work is presented in this section. Investigation of design parameters according to dimensions of patches and apertures is presented in Section III. Production of our FSS and measurement procedure is explained in Section IV. While results and discussions are explained in Section V, the manuscript is concluded with Section VI.

## Frequency Selective Surfaces (FSS) Design

In the introduction, it was mentioned that FSS acquire their electromagnetic wave filtering characteristics based on specific patches and apertures. Generally, information about patches and apertures is provided in Figure 1.

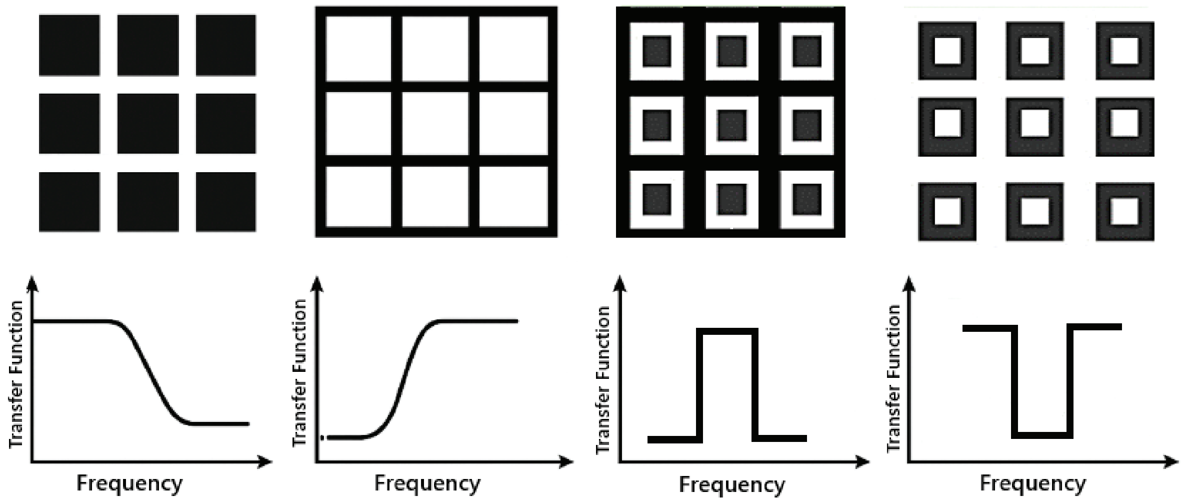


**Figure 1.** FSS types.

In Figure 1, the FSS filter characteristics are presented in the following order: low-pass filter, high-pass filter, bandpass filter, bandstop filter.

Maxwell's equations and the corresponding boundary conditions for electromagnetic boundary value problems support a variety of different field configurations or solutions. These distinct field configurations are often referred to as "modes." The most known modes are transverse electromagnetic (TEM), transverse electric (TE), and transverse magnetic (TM) modes. In TEM mode, both the electric and magnetic field components are perpendicular to the direction of propagation. TE is characterized by electric field components are perpendicular to the direction of propagation, while TM has magnetic field components are perpendicular to the direction of wave propagation. In this study, the simulation has been performed using TE and TM modes.

When examining patch-type FSSs, The current induced by the electromagnetic wave incident on the conductive patch geometry scatters in accordance with the Equation 1. $J_s$ is the induced surface current density on conductive patches. $A$ is the magnetic vector potential resulting from the radiation of the induced current. Equation 1 can be used to calculate the magnetic vector potential created by the current at any point in the medium in which the FSS is located, for cases where the current induced in the conductive patch is known [22].

$$\nabla^2 A + \omega^2 \mu \varepsilon A = -\mu J_s \tag{1}$$

The electric field inside a conductive patch is null. Due to boundary conditions, the tangential components of the electric field are continuous, hence indicating that the tangential component of the electric field on the conductive patch is also zero. The magnitude of the electric field strength ($E_s$) of the scattered wave is provided according to Equation 2 below:

$$E_s = -j\omega\mu A + 1/j\omega\epsilon\, \nabla.(\nabla.A) \tag{2}$$

The duality theorem will be utilized in solving the equations. The solution involves using boundary conditions, ensuring the tangential components of the magnetic field intensity are continuous within the apertures. The current density is expressed as follows according to Equation 3 [22].

$$J(x,y) = \sum\sum J_{mn} e^{j.\left(k_{xg}+\frac{2\pi.m}{a}\right).x+j.\left(k_{yg}+\frac{2\pi.n}{b.\sin(\Omega)}-\frac{2\pi.m}{a}.\cot(\Omega)\right).y} \tag{3}$$

The "Equivalent Circuit Model" in FSSs is a simple and analytical calculation technique. This model emerged through the work of Marcuvitz in modeling periodic grids, with the initial analysis being provided by Anderson [21], [22]. These models are widely employed today due to their assistance in explaining the behavior of FSSs.

In FSS design, the choice of the conductive surface has a direct impact on the equivalent circuit model's resistance, leading to variations in the characteristic structure of the FSS. The resonant frequencies of the structure vary depending on the polarization of the incident wave, and the angle of wave incidence also affects the resonance frequency. The structure's resonance frequency is largely dependent on the dielectric substrate because the dielectric constant provides insights into the material's response to electromagnetic waves.

For simulations, CST Microwave Studio was employed. The design comprises two distinct shapes, with the front surface patch and the rear shape resulting from the excavation of the copper plate. The dielectric plate used has a dielectric constant of 4.4 ($\varepsilon_r$ = 4.4) and a loss tangent ($tan\delta$ = 0.02) of 0.02, and it is made of FR-4 material with a thickness of 1.6 mm ($t$ = 1.6).

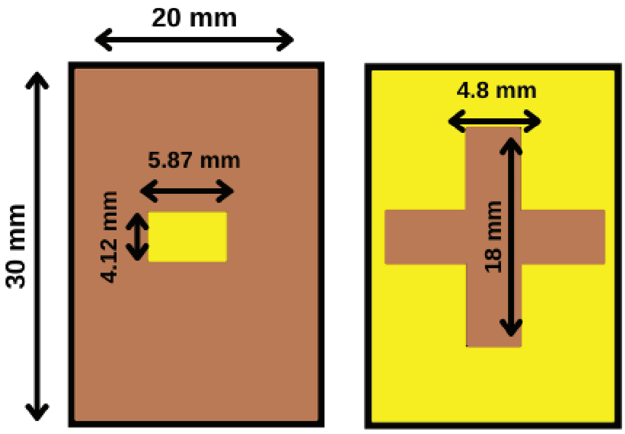


**Figure 2.** The dimensions of front and back surfaces of the proposed double sided FSS.

The dimensions of the proposed double-sided FSS are shown in Figure 2. The dimensions of the patch and apertures are critically important in forming the equivalent circuit model and influencing the behavior of electromagnetic waves. This design has been created through an optimization process, which also includes sensitivity analysis. Further details on this topic will be provided in the upcoming section.

The simulation was conducted in the frequency domain. Two ports were established for unit cell analysis in the z-direction, providing the S-parameters. Reflection and transmission coefficients provide insights into the manipulation of electromagnetic waves. In FSSs, the filter's requirements are determined based on these parameters. The aim of this article is for the proposed FSS to exhibit bandpass characteristics at 5 GHz.

Periodic arrays of conductive patches or apertures placed on a dielectric medium exhibit reflection and transmission properties that vary with frequency. Achieving a reflection coefficient ($S_{11}$) below -10 dB is a targeted parameter. In the proposed FSS in this study, this value is approximately -32.72 dB as shown in Figure 3.

The transmission coefficient is expected to be close to 0 dB to achieve a bandpass filter characteristic. This parameter provides information about electromagnetic wave manipulation like $S_{11}$. Improvement in transmission characteristics

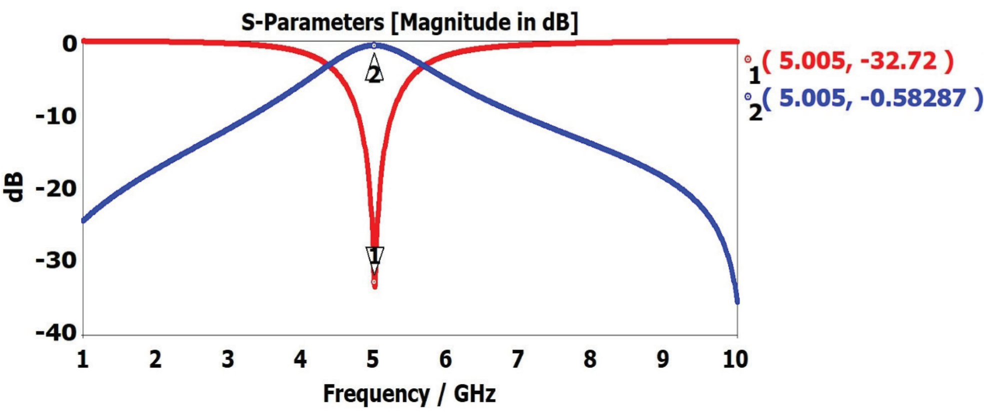


**Figure 3.** Reflection and transmission coefficient of proposed FSS.

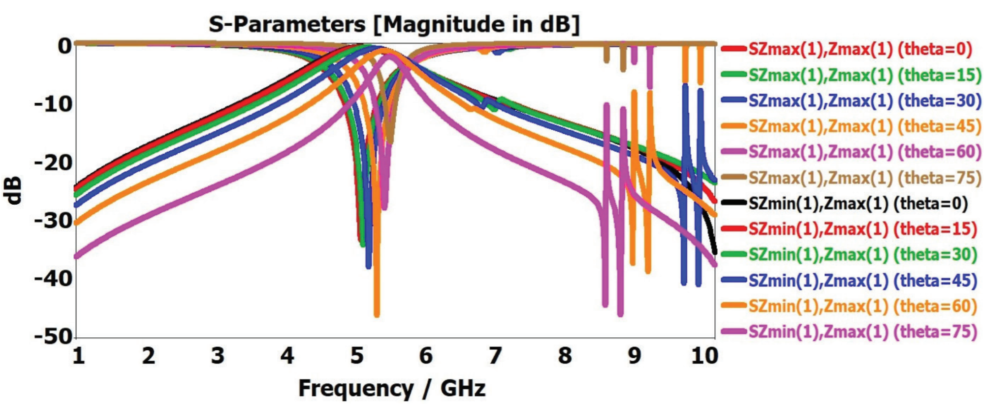


**Figure 4.** Variation of reflection and transmission coefficient according to the $\theta$.

can be achieved by altering the dielectric substrate. In this article, an approximately -0.58 dB transmission coefficient has been obtained, as also shown in Figure 3.

In this study, the parameter theta ($\theta$), which represents the wave incidence angle, has been included in the simulations. Figures 4 depicts the variation of $S_{11}$ and transmission coefficients with respect to the electromagnetic wave's angle of incidence. According to the Figure 4 if $\theta$ increases center frequency ($f_c$) shifts towards right on the x-axis. Also, $S_{11}$ and transmission coefficients of FSS degrades at 5GHz.

## INVESTIGATION OF THE DESIGN PARAMETERS

The dimensions of the patches and apertures have been increased and decreased leading to obtaining an optimal result and subsequently addressing sensitivity. Firstly, the other side was always kept stationary. The increase and decrease in the aperture portion have been made by 10% and patches portion have been made by 20%. Transmission coefficients have been shared for this section. Frequency shift has been observed in the simulation environment, indicating that the FSS is tunable.

This section provides a detailed explanation of the optimization work and sensitivity analysis conducted for the proposed FSS. As a result, it has been revealed that there may be frequency shifts for this

FSS depending on the patch and aperture sizes. If patch and aperture sizes decrease, $f_c$ shifts towards left on the x-axis and if patch and aperture sizes increase, $f_c$ shifts towards right on the x-axis as seen in Figure 5 and 6. We get the best results for dimensions as seen in Figure 2 at center frequency of 5 GHz.

### PCB Fabrication and Measurement of Designed FSS

FSS fabrication and measurement require considerable attention due to factors such as geometric precision, material selection and correct alignment. The challenges of FSS design and measurement extend to the optimization process, which requires fine-tuning to meet specific frequency and angle requirements. Despite these complex processes, what makes FSS technology valuable is its ability to

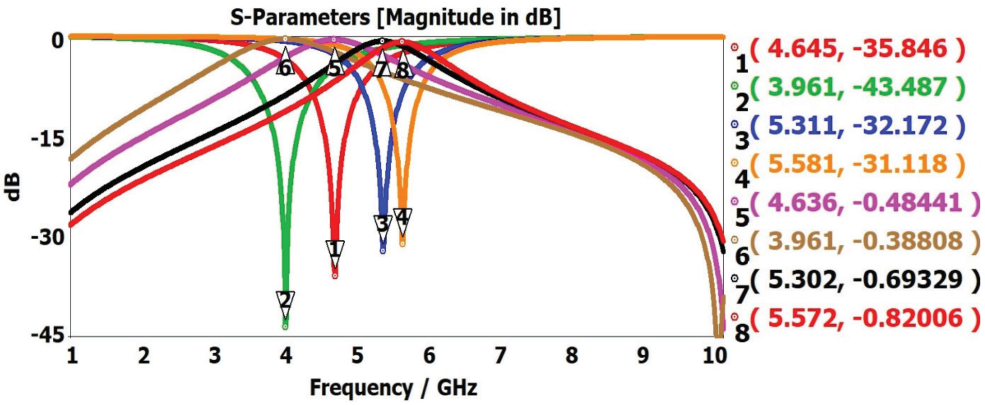


**Figure 5.** Change in reflection and transmission coefficient with 20% patch sizes increase and decrease.

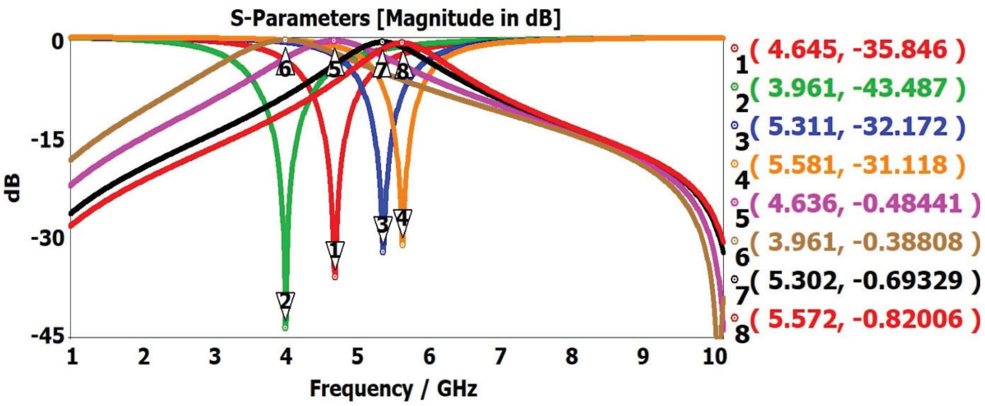


**Figure 6.** Change in reflection and transmission coefficient with 10% aperture sizes increase and decrease.

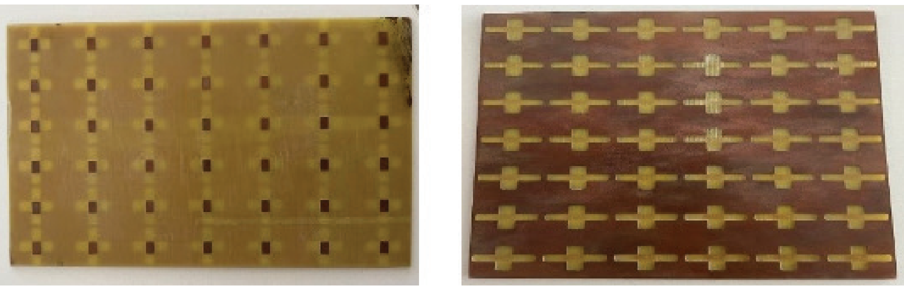

**Figure 7.** Front and back surface of produced double-sided FSS.

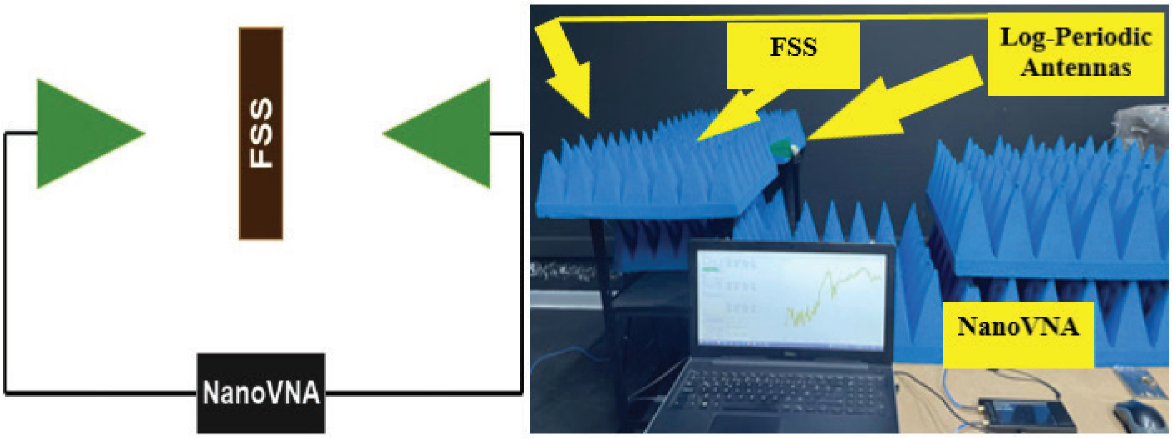


**Figure 8.** Free Space Measurement Setup Schematic and Setup.

configure electromagnetic wave behavior in a desired way. Although free-space measurements are challenging, they help us understand how FSSs work, allowing us to improve their performance and use them in more areas. Although all mentioned complexity the FSSs have the potential radical transformations in electromagnetic engineering and determine the direction of future technological innovations. The proposed FSS is manufactured with Computer Numerical Control (CNC), ensuring precision and consistency in production. CNC technology plays a crucial role in achieving the intricate geometries required for FSS structures [23]. First, the unit cell design of the FSS was developed, and then it was expanded across the plate for manufacturing. Once obtained in plate form, the production was carried out through milling using CNC technology. The produced sample is shown in Figure 7.

The free-space method, as elaborated in this article, has far-reaching implications in the study and development of FSS materials [28]. The rigorous measurement and characterization facilitated by the free-space method foster innovation and progress in these areas, underscoring the collaborative efforts of engineers and academicians in advancing the frontiers of electromagnetic design.

A superficial mechanism was preferred for measurement. The reason for this is that there are studies in the literature that make measurements in this way [29]. The "*D*" length of the antenna is 10 cm. Here, the far field calculation was made as 33 cm according to the far field formula for 5 GHz. For measurements, antennas are adjusted to the far-field distance (33 cm), and Vector Network Analyzer (VNA) calibration is performed. Given the significance of cables and antennas, potential issues in this regard are carefully considered. First, measurements are taken in free space, and then measurements with the sample are carried out, with the difference between them providing the desired measurement result. A NanoVNA 6.3 GHz version previously used in the literature for a broadband complex permittivity measurement was used in the measurement [30]. Figure 8 shows the Free Space Measurement setup and schematic.

In Figure 9, the blue-colored data represents the measurement results, while the red-colored data represents the simulation results.

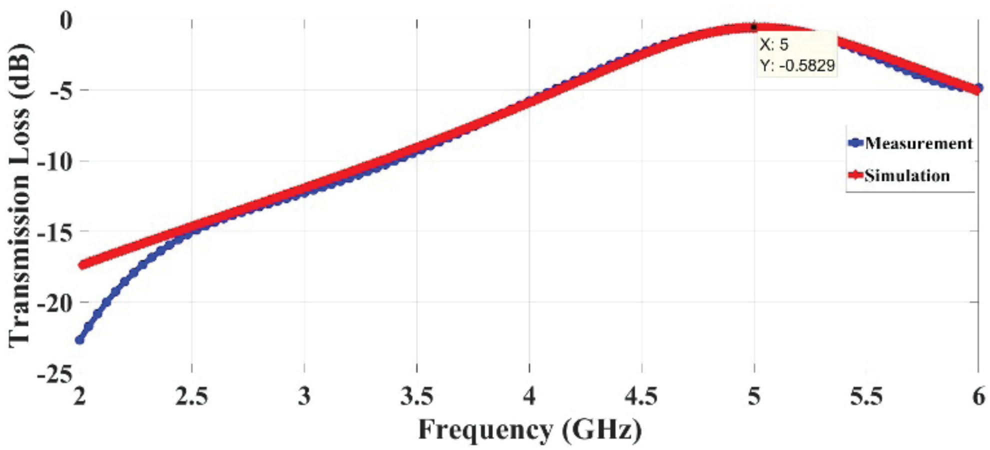


**Figure 9.** Measurement and simulation results up to 6 GHz.

## RESULTS AND DISCUSSION

As mentioned earlier, in this study, low-cost, lightweight a bandpass double-sided FSY is designed for wireless communication systems. It is very important that wireless communication systems, especially those designed for unmanned aerial vehicles, are designed to be cost-effective and lightweight [31]. In CST Studio Suite software, a bandpass frequency selective surface design was created using the frequency domain in the appropriate frequency range. Apertures and patches type were chosen from the literature when creating the unit cell model. Then, a simulation was performed by creating double sides. The reason for choosing the resulting structure is ease of production. For the design, the length values of the patch and aperture were examined parametrically. The simulation was repeated for each length and width value and the best value for electromagnetic transmission was selected as the design. When the literature was examined, it was observed that frequency domain was used for such material designs. The design and optimization process of the proposed FSS in this study is summarized in the flowchart as shown in Figure 10.

We compare our study with the existing literature in Table 1. First, a bandpass FSS designed for WLAN and WiMAX was examined [17]. Second, an FSS antenna radome system was proposed for airborne and ground applications in the X-band [24], where analytical analysis, simulation, and production processes are described. The transmission coefficient for 9.4 GHz to 16 GHz was reported to be between 0.1-0.3 dB. Third, a new metamaterial element with properties across different frequency ranges was presented for radome applications [25]. Fourth, a dual-band sandwich radome was proposed for airborne applications [26]. Lastly, the electromagnetic performance analysis of a radome based on a novel graded dielectric inhomogeneous wall structure was presented [27]. According to Table 1 and the literature, the double-sided FSS proposed in this study is in line with current research and can be effectively used in radome applications.

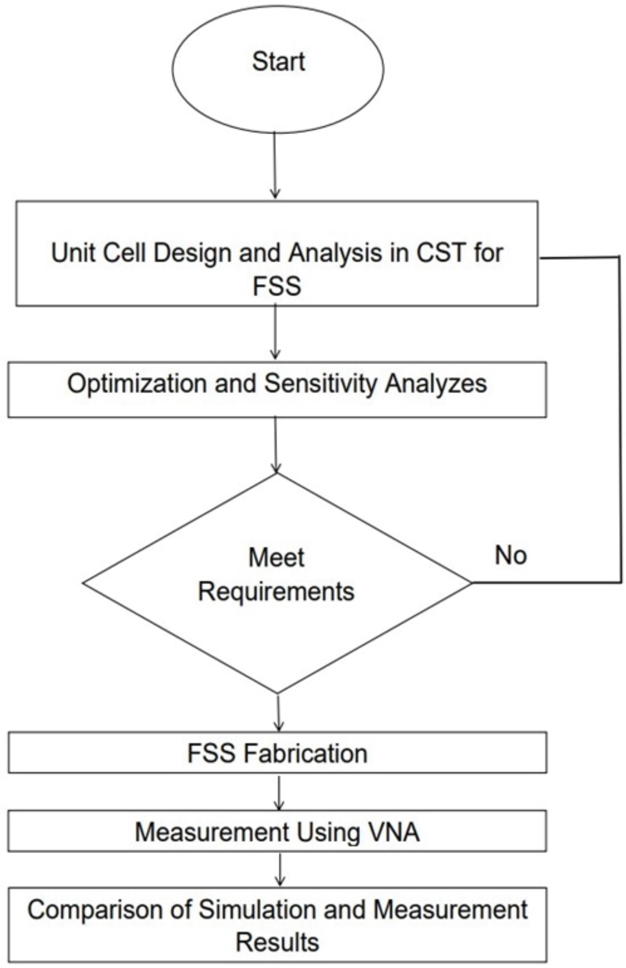


**Figure 10.** FSS design flowchart.

**Table 1.** Frequency selective surfaces comparison table

| Ref. | Frequency | Transmission Coefficient |
|---|---|---|
| [17] | 5 GHz | 0.22 dB |
| [24] | 9.4-16 GHz | 0.1-0.3 dB |
| [25] | 8.5-10.3 GHz | 0.3-0.6 dB |
| [26] | 1.5–1.6 6.49–6.7 GHz | 1.6 dB |
| [27] | 10 GHz | 0.5-0.62 dB |
| This Work | 5 GHz | 0.58 dB |

The integration of FSS within radome structures represents a significant advancement in antenna engineering. Our study offers an advantage for radome applications due to its double-sided structure, which provides a tunable feature thanks to its patches and apertures. This design is aimed to be a reference for future studies in the literature and to provide a practical solution in industrial applications. Double-sided FSSs provide several advantages in radome applications. The double-sided design interacts with electromagnetic waves on both sides, improving the efficiency of the radome and providing strong electromagnetic shielding. This configuration improves signal accuracy and system reliability by reducing signal loss like traditional radomes. These advanced designs offer a counterpoise between electromagnetic performance and structural integrity, particularly in aerospace-defense applications, and represent a significant step forward in antenna technology.

The double-sided FSS structure significantly increases the mechanical robustness of the radome. Precise control of electromagnetic interference in antenna systems increases the reliability and stability of communication systems. For this reason, the double-sided frequency selective surface proposed in the study is highly recommended for WLAN and WiMAX applications.

In conclusion, this article presents the simulation, fabrication, and measurement of the proposed FSS, specifically designed for the 5 GHz band within the C-band. Various studies utilizing different patch and aperture designs were examined in Table 1, and their advantages and disadvantages were carefully considered during the development of the FSS radome design. The rationale for focusing on the 5 GHz range is its relevance to applications such as Wi-Fi and WiMAX. This study follows the existing literature, offering a valuable contribution to antenna and radome engineers.

## CONCLUSION

In this study, the design, analysis, and transmission measurement of a double-sided bandpass FSS were conducted. Based on frequency domain simulations and parametric analyses, the structure that demonstrated the optimal transmission characteristic (-0.58 dB) was selected as the final design. The selected patches and apertures were integrated into the design due to their frequent use in the literature, with an aim to introduce novelty through this integrated approach. Another objective was to achieve ease of fabrication with these shapes. Measurements were carried out using the free-space measurement method, confirming the performance of the working design. The primary goal of this design is to offer a rapidly applicable and adaptable solution for radome and antenna researchers in the academic field. From an industrial perspective, this study is expected to make a significant contribution, particularly given the growing importance of UAVs. In UAVs, weight management is a critical challenge; by embedding this structure into the body of the UAV instead of incorporating a portable wireless communication filter, gains in both weight and payload efficiency can be achieved. This study aims to provide insights and guidance for researchers in both academia and industry. In our future FSY studies, bandpass form patch and aperture type FSYs will be designed with different substrate materials. Conformal FSY designs and printed circuits with the unit cell model in this study will be performed.

## AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

## DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

## CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

## ETHICS

There are no ethical issues with the publication of this manuscript.

## STATEMENT ON THE USE OF ARTIFICIAL INTELLIGENCE

Artificial intelligence was not used in the preparation of the article.

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