Çukurova Üniversitesi
Mühendislik Fakültesi Dergisi
Çukurova University
Journal of the Faculty of Engineering
ISSN: 2757-9255 CİLT/VOLUME: 41 SAYI/ISSUE: 1 MART/MARCH 2026

Frequency Selective Surface Used as a Band-Stop Filter in Microwave-Powered Combi System

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Article Info

Received : 05.09.2025
Accepted : 16.12.2025
DOI: 10.21605/cukurovaumfd.1778659

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Keywords

Frekans seçici yüzey
Bant durduran filtre
RF ve mikrodalgalar
S parametreleri

How to cite: *ÜNAL, E., ÖZYURT, F., (2026). Frequency Selective Surface Used as a Band-Stop Filter in Microwave-Powered Combi System. Cukurova University, Journal of the Faculty of Engineering, 41(1), 55-64.*

ABSTRACT

Today, heating systems generally use fossil fuels, which are quite inefficient. These systems not only have high energy costs but also emit carbon dioxide. This study proposes a band-stop filter design that allows the use of microwave energy instead of fossil fuels in heating systems. A frequency-selective surface (FSS) with a band-stop filter operating at 2.45 GHz has been designed to prevent microwaves generated in the magnetron from leaking out of the water tank. The design is implemented using a FIT-based simulation program, samples are produced, and measurements are performed using a vector network analyzer.

Simulations and measurements are conducted in both free space and a water-filled environment. The numerical and measured values of the transmission coefficient (S_{21}) in water are obtained as -17.29 dB and -32.1 dB, respectively. The agreement and consistency between the measured results and the full-wave simulation results confirm the effectiveness of the completely original design in this study.

Mikrodalga Kombi Sisteminde Bant Durduran Filtre Olarak Kullanılan Frekans Seçici Yüzey

Makale Bilgileri

Geliş : 05.09.2025
Kabul : 16.12.2025
DOI: 10.21605/cukurovaumfd.1778659

Sorumlu Yazar

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Anahtar Kelimeler

Frequency selective surface
Band stop filter
RF and microwaves
S parameters

Atıf şekli: *ÜNAL, E., ÖZYURT, F., (2026). Mikrodalga Kombi Sisteminde Bant Durduran Filtre Olarak Kullanılan Frekans Seçici Yüzey. Çukurova Üniversitesi, Mühendislik Fakültesi Dergisi, 41(1), 55-64.*

ÖZ

Günümüzde, ısıtma sistemlerinde, genellikle verimi oldukça düşük olan fosil yakıtlar kullanılmaktadır. Bu sistemler yüksek enerji maliyetinin yanında, dışarıya karbondioksit salımı da yapmaktadır. Bu çalışmada, ısıtma sistemlerinde fosil yakıtlar yerine mikrodalga enerjisinin kullanımına imkan veren bir bant durduran filtre tasarımı önerilmektedir. Magnetronda üretilen mikrodalganın su tankı dışına sızıntısının engellenmesi için 2,45 GHz'de çalışan, bant durduran filtre özellikli frekans seçici yüzey (FSS) tasarlanmıştır. Tasarım FIT tabanlı bir simülasyon programı ile gerçekleştirilmiş, numuneler üretilmiş ve ölçümleri vektör ağ analizörü kullanılarak yapılmıştır.

Simülasyon ve ölçümler hem boşlukta, hem de su dolu ortamda gerçekleştirilmiştir. Su içerisindeki iletim katsayısının (S_{21}) sayısal ve ölçülen değerleri sırasıyla -17,29 dB ve -32,1 dB olarak elde edilmiştir. Ölçülen sonuçlar ile tam dalga simülasyon sonuçları arasında elde edilen uyum ve tutarlılık bu çalışmada, tamamen özgün olan tasarımın etkinliğini doğrulamaktadır.

1. INTRODUCTION

Energy demand is rapidly increasing in parallel with population growth, scientific and technological advancements. This increased demand for energy not only increases energy costs but also leads to environmental problems such as pollution. Recently, numerous studies have been conducted on energy efficiency [1,2] and energy from clean energy sources [3-7]. Reducing the proportion of fossil fuels, which contribute to numerous environmental problems, in energy consumption is as important as increasing energy efficiency.

The energy consumed for residential heating accounts for approximately 70% of total energy consumption in Türkiye and 57% in the European Union, with 25% of this figure reportedly used for hot water production [8]. This energy, which accounts for a significant portion of total energy consumption, requires research into alternative or renewable energy sources and, more importantly, focusing on more efficient systems. In our country, combi boiler systems, commonly used for heating and hot water in homes, generally use natural gas, a fossil fuel, and their efficiency is quite low. In these systems, natural gas is used by burning, and there are side effects such as the release of carbon monoxide gas and its spread into the environment as a result of combustion [9].

Conventional heating systems like natural gas combi boilers, natural gas water heaters, electric water heaters, water heaters, and similar systems use electricity or natural gas to heat water. In these systems, electrical energy is used directly, while natural gas is burned to heat the water. Using microwaves in heating systems can be more energy efficient than other methods. This is because, instead of heating the entire environment, microwave heating focuses energy directly on the substance to be heated, namely the water, and the process is completed in a shorter time.

The purpose of the proposed study is to design a FSS with a band-stop feature that is installed within the water inlet and outlet pipes of the boiler to prevent microwaves from leaking out of the water inlet and outlet pipes while the water is heated using the energy generated by the magnetron in the microwave oven and transferred to the central heating system. Advantages of this design over existing boiler systems include higher efficiency due to the transfer of all 2.45 GHz microwave energy to the water, thus reducing user bills, eliminating the need for wall-mounted installations within the building, and ease of manufacture.

The use of microwaves for water heating is a well-known application [10]. However, microwaves have not been previously used in combi boiler applications. Furthermore, no frequency-selective surface with a band-stop filter designed for this purpose is available in the literature. Therefore, the frequency-selective surface designed to directly heat the combi boiler with microwaves and prevent microwave leakage is a completely original study. The most important original value of this study is the use of FSSs for the first time in the literature in order to prevent microwave energy from leaking out with the water while the water heated by microwave energy is transferred to the system and also to obtain a highly efficient combi boiler.

FSSs with random geometries are generally composed of periodically arranged metallic patches or their complementary geometries [11]. The most important parameters of the FSS structure, such as bandwidth, transfer function, incidence angle dependence and polarization, which determine the overall frequency-dependent response, are controlled by the element type and geometry. substrate parameters, the presence or absence of upper layers and the spacing between elements [12-14]. Due to their frequency-selective capabilities, FSSs are widely used in communication systems to effectively control the reflection and transmission of electromagnetic waves in free space. Furthermore, when plane waves are incident on them at a certain angle, FSSs, being periodic structures, exhibit a band-pass or band-stop filter response through parameters such as bandwidth and attenuation [15]. When it is necessary to attenuate incoming electromagnetic waves within a specific frequency band, a band-stop filter response is necessary. This can also be accomplished with bandpass filters, but when interfering frequencies are particularly strong, special measures must be taken to suppress them. In such cases, it becomes necessary to use band-stop filters to excessively attenuate the unwanted frequency band [16,17]. There is another important point to note here. As is known, single-layer FSSs have low selectivity and narrow bandwidth [18]. Adding multiple layers, including a dielectric intermediate layer, is the most common way to improve the attenuation response and increase the bandwidth [19,20].

FSSs are structures that act as a type of filter; that is, they are two- or three-dimensional structures that reflect or transmit depending on the frequency of the incident electromagnetic wave and have attracted considerable interest in the scientific community in recent years [12-14]. FSSs have potential applications in many areas such as shielding, wireless communication and security of wireless networks. FSSs, consisting of periodically arranged metallic patches or aperture elements, can provide broad-band capacity in specific frequency ranges. When interacting with electromagnetic waves, FSSs exhibit low-pass, high-pass, band-pass or band-stop filters at microwave frequencies and can be used to filter the desired frequencies [21-25]. Due to their wide-band properties, FSSs have recently found potential applications as spatial filters [26-28] and polarization converters [29,30]. In addition, electromagnetic shielding applications are among the most well-known and widely used applications of FSSs [31-33].

Many studies have been conducted on FSSs with band-stop filters. One of these studies has been designed to have band-stop properties in the L and S bands at microwave frequencies [34]. In another study, a band-stopping FSS structure obtained using a glass substrate has been investigated [35]. Murugan et al. have investigated the FSS structure with band-stop feature to prevent the 2.45 GHz 1000 W signals that enable the operation of microwave ovens from leaking out of the oven glass. In this study, the design and simulation results of two different FSS arrays consisting of circular ring-shaped patches are discussed [36].

In this study, an FSS design with band stop feature is proposed to prevent microwave energy from leaking out of the microwave combi boiler together with water during the transfer of water heated by 2.45 GHz microwave energy to the heating system. The following part of the article is organized as follows. The proposed FSS structure is designed and simulated using a FIT-based simulation program in Section II. Furthermore, a parametric evaluation of the band-stopping capability at 2.45 GHz is performed and the dimensions are optimized. In Section III, an FSS structure with band-stop filter properties has been fabricated using optimized dimensions, and experimental measurements have been performed. Furthermore, the integration of the fabricated FSS into the microwave combi system has been realized. Finally, in Section IV, results and discussion, the paper concludes with a comparison of simulation and measurement results.

2. DESIGN AND SIMULATION OF FSS STRUCTURE

Depending on the frequency of the incident electromagnetic wave, an FSS provides reflection or transmission, and also acts as an electromagnetic filter. An FSS can be thought of as a two-port circuit that transmits or reflects the wave depending on the frequency. In other words, it passes waves in the conduction band and reflects waves in the stop band. FSSs consist of periodically arranged patches and cavities; the patches cause a capacitive effect, while the cavities cause an inductive effect [37].

The filtering properties of the FSS structure depend on the electrical properties of the conductor used in the design, the dielectric constant of the material, and the structure, type, and shape of the unit cell. In this context, the designed FSS structure is intended to act as a filter that allows water flow out of the tank but blocks the operating band of the microwave oven. It has been observed that the FSS structure, designed to exhibit band-stop filter properties, can be used in applications where water passes but the operating band of the microwave oven is stopped, unlike known areas of use such as aviation, defense, radar, food, security, telecom and medicine.

2.1. Band-Stop FSS Filter Design

To understand the response of an FSS to incident electromagnetic waves, S-parameters are measured. These measurements typically include reflection (S_{11}) and transmission (S_{21}) coefficients. When determining bandwidth, -10 dB is considered the threshold value; that is, the region where the S-parameters fall below -10 dB is called the FSS bandwidth.

A perspective view of the designed band-stop FSS structure is shown in Figure 1.a. FR4 is used as a dielectric material in the design of the FSS structure because it is easily accessible and low-cost. The FR4 material, coated with 35 µm-thick copper, has a relative dielectric constant of $\varepsilon_r = 4.3$ and a thickness of 1.6 mm.

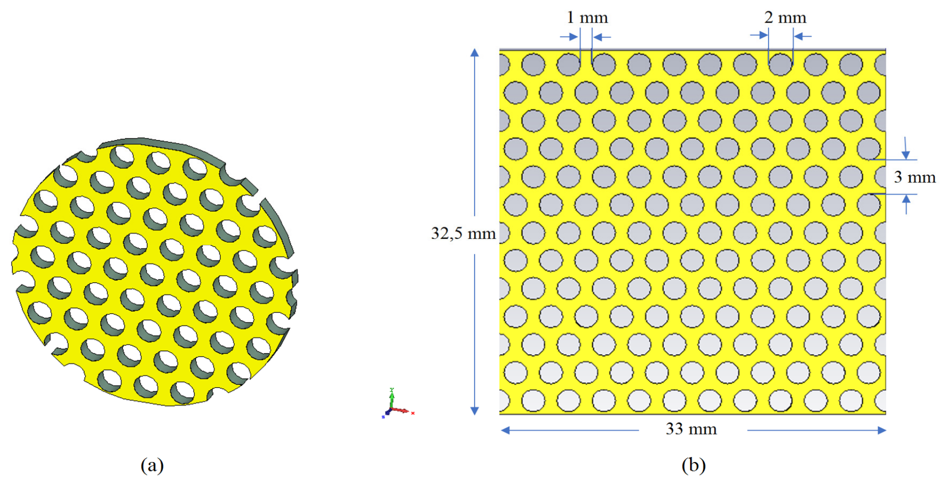

Figure 1. a) FSS perspective view, b) Dimensions of the designed FSS structure

The dimensions of the designed FSS structure are given in Figure 1.b. The periodic slots used in the FSS structure have a diameter of 2 mm, and there is a 1 mm horizontal gap between the slots. Simulation studies have been conducted using a FIT-based simulation program. Simulation studies of the designed structure have been examined in terms of transmission and reflection coefficients in the frequency band covering the desired frequency range (2.45 GHz). The cavity dimensions have also been optimized using genetic algorithm methods in the FIT-based simulation program.

2.2. Simulation Results

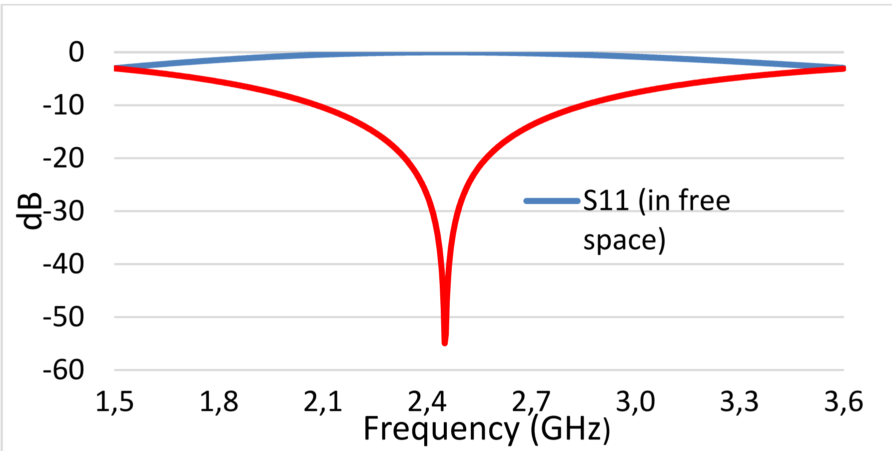

Figure 2. Simulation results when the FSS structure is placed in free space

S_{11} and S_{21} coefficients of the designed FSS structure are shown in Figure 2. It is observed that S_{11} value generally remains below -3dB between 1.5 and 3.5 GHz, which covers the operating band of the microwave oven. Around 2.5 GHz, S_{11} value approaches 0 dB, meaning that almost all of the 2.45 GHz EM wave incident on the FSS is reflected. When S_{21} is examined, it is seen that the designed structure exhibits band-stop filter properties at the 2.5 GHz center frequency. The transmission coefficient value of 54.94 dB obtained at 2.5 GHz means that the entire incoming wave is reflected. Considering the frequency range where S_{21} bandwidth falls below -10 dB, it is understood that the designed FSS structure acts as a band-stop filter in a very wide frequency band of 765 MHz in the range of 2.085-2.85 GHz around 2.45 GHz.
The designed FSS primarily operates in a water-filled environment. Therefore, the FSS structure has been placed inside a water-filled waveguide and the second simulation has been performed accordingly. The results are shown in Figure 3. This simulation has been performed in the 1.5-3.5 GHz range. It is understood that S_{11} value remains below -1 dB in the 1.5-3.5 GHz range and approaches zero around 2.5 GHz, meaning that almost all of the 2.45 GHz EM wave arriving at the FSS is completely reflected. When S_{21} is examined, a relatively high result of -17,29 dB is obtained at 2.45 GHz. Considering the frequency band where the

transmission coefficient falls below the threshold value of -10 dB, it is understood that the designed FSS structure acts as a band-stop filter in a wide bandwidth around 2.45 GHz.

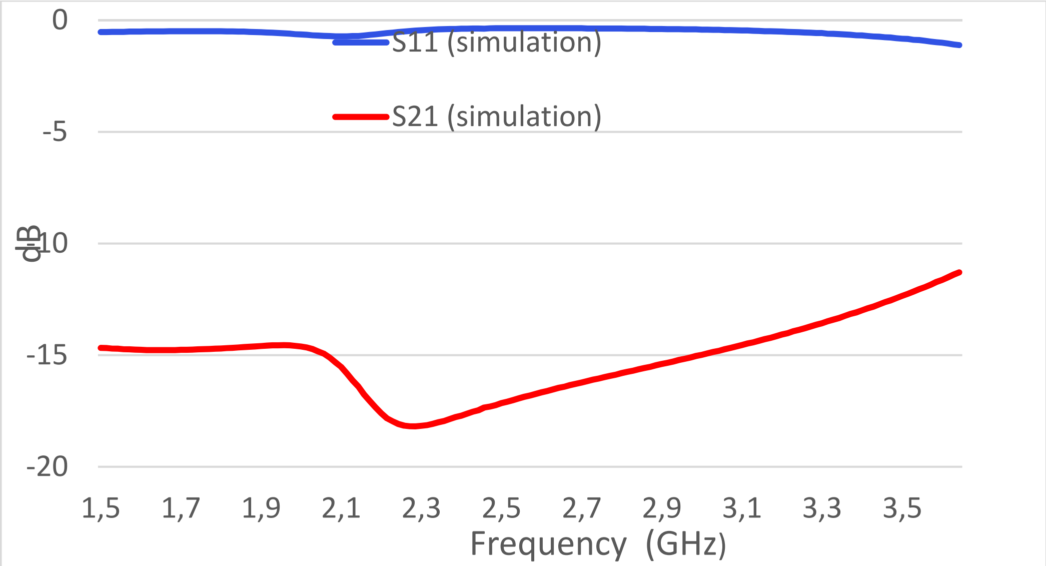

Figure 3. Simulation results when the FSS structure is placed in a water-filled medium

Consequently, two different simulations have been performed to test the designed FSS structure in both a vacuum and a water-filled environment. Both simulations yield highly consistent results for S_{11}. It is understood that especially around 2.5 GHz S_{11} value is below -1 dB, meaning that a very large part of the incident wave is reflected back by the FSS. According to the simulation results in free space, it is observed that the transmission coefficient value has dropped below -54,94 dB at 2.45 GHz frequency, and this value is obtained as -17,29 dB in a water-filled environment. The reason why S_{21} value is lower in water compared to free space is due to losses in the water medium [33]. Thus, considering the threshold value where the transmission coefficient falls below -10 dB, it is understood that the designed FSS structure stops the 2.45 GHz waves, that is, it prevents the waves in the microwave oven from passing to the heating system via water and reflects them back into the boiler.

3. FABRICATION, MEASUREMENT AND INTEGRATION OF FSS

3.1. Fabrication of FSS

The production of the FSS structure, whose design has been completed and dimensions have been optimized, is carried out using LPKF Laser & Electronics AG, Promat E33, i.e., computer numerical control (CNC) and printed circuit board (PCB) device, as seen in Figure 4. Copper-coated FR4 material is used in production. The thickness of the FR4 material, with a dielectric constant of $\varepsilon_r = 4{,}3$ and a loss tangent of 0,025, is 1.6 mm, and the thickness of the copper layer, with a conductivity of $\sigma = 5.8 \times 10^7\ S/m$, is 0.035 mm.

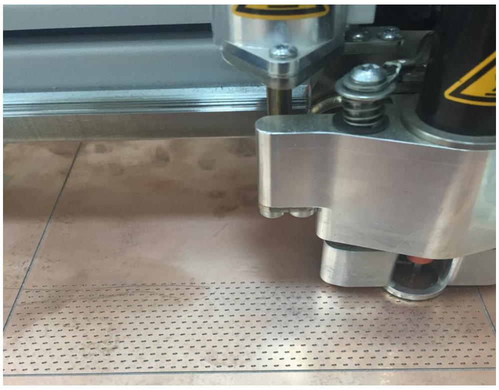

Figure 4. Fabrication of FSS structure using LPKF E-33

3.2. Measurements Made with the Produced FSS

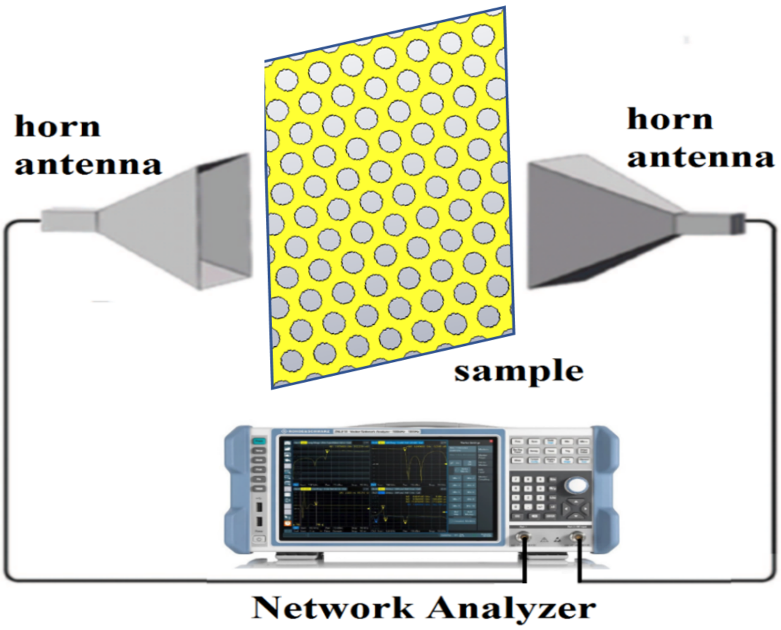

Figure 5. Measurement of S parameters with Microwave Network Analyzer

Experimental results of the manufactured FSS is obtained using the PNA-L Microwave Network Analyzer. Before starting the measurements, the PNA-L Microwave Network Analyzer is calibrated. Two standard gain WR-430 Horn antennas, one receiver and the other transmitter, operating from 1.7 GHz to 2.6 GHz, have been connected to the input and output ports of the calibrated device and measurements have been performed as shown in Figure 5. In the measurements, the distance between the horn antennas is adjusted to meet the far field condition.

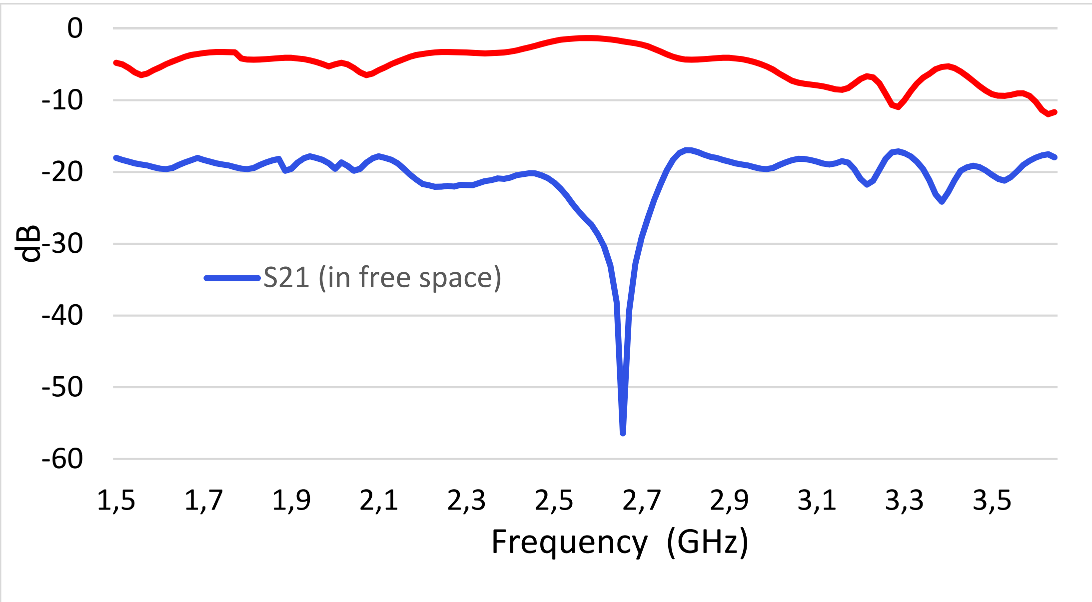

Figure 6. Measurement results when the FSS structure is placed in free space

The first measurement has been performed by placing the designed FSS in the free space between the horn antennas, S_{11} and S_{21} are measured. Figure 6 shows the graph of the measured reflection and transmission coefficients.

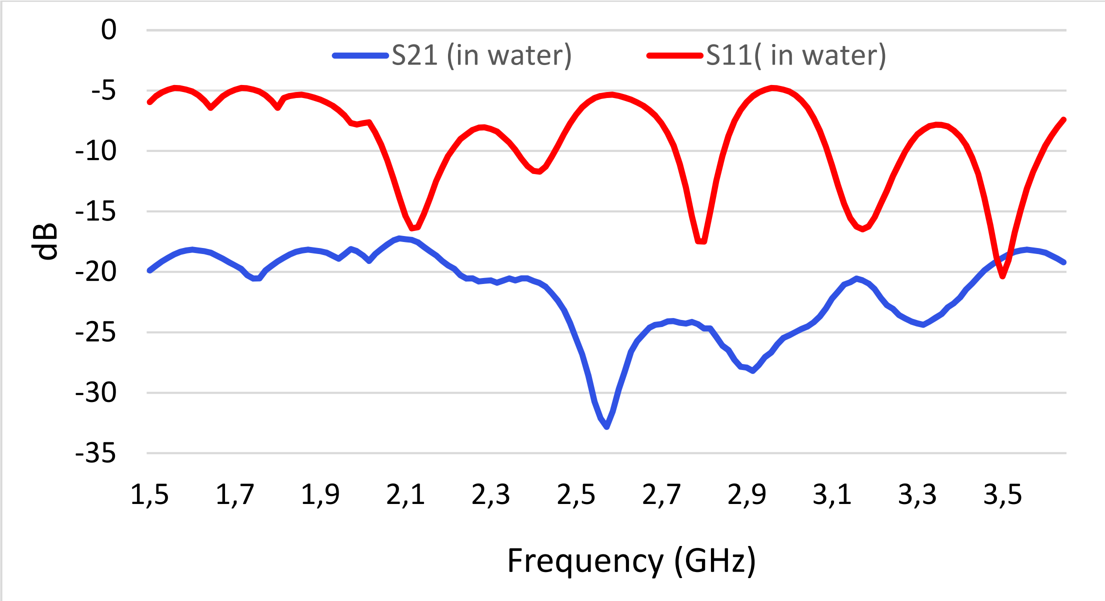

Figure 7. Measurement results when the FSS structure is placed in water

Considering the reflection coefficient given in Figure 6, it has a reflection bandwidth of approximately 350 MHz ($S_{11} > -3\ dB$) between 2.35 GHz and 2.7 GHz and a good band-stop filter property is observed over a fairly wide frequency range. The structure has a maximum insertion loss (IL) of -56.42 dB at 2.63 GHz and a maximum reflection loss (RL) of -1.33 dB at 2.53 GHz. Considering S_{21} response, the selectivity at the center frequency is quite good.

Then, the FSS structure in water is placed between the two antennas to provide the far field condition, S_{11} and S_{21} values are measured again. Considering the reflection coefficient in Figure 7, it is seen that $S_{11} \approx -5$ dB in the 2.45 GHz band. The structure has a maximum IL of -32.1 dB and a maximum RL of -5.4 dB at 2.53 GHz. Considering S_{21} response, the selectivity at the center frequency is quite good.

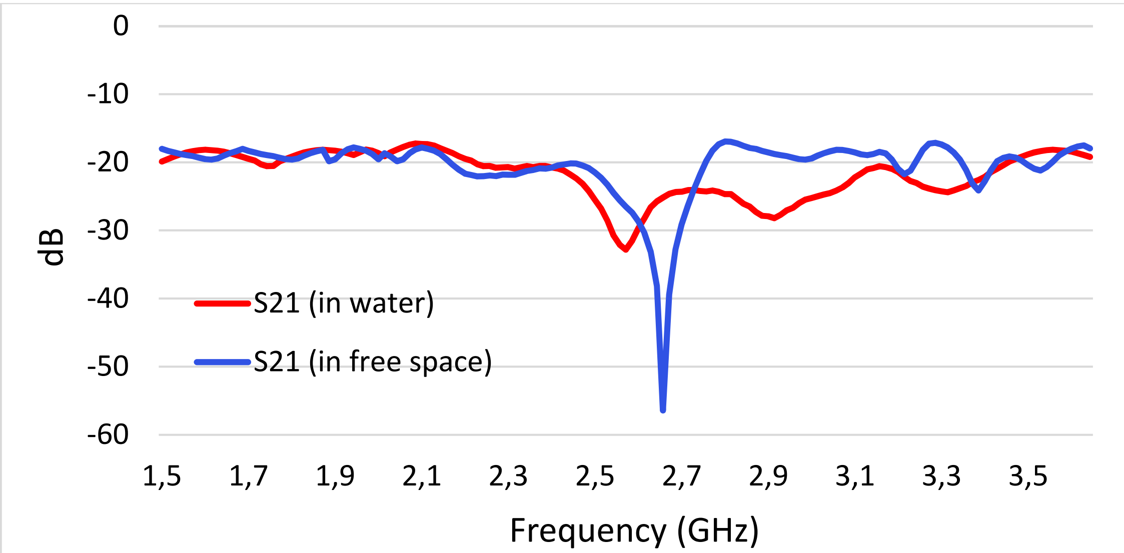

Figure 8. Comparison of S_{21} values measured in free space and in water

The S_{21} values measured in free space and in water are compared and the result is given in Figure 8. A downward shift has been observed in the resonance frequency of S_{21} measured in water, as expected, but it is not at the desired level due to manufacturing and measurement errors. There is an important detail to be noted here; S_{11} and S_{21} of the designed structure do not satisfy the equation $|S_{11}|^2 + |S_{21}|^2 \approx 1$, which shows that the medium, namely water, is lossy [33].

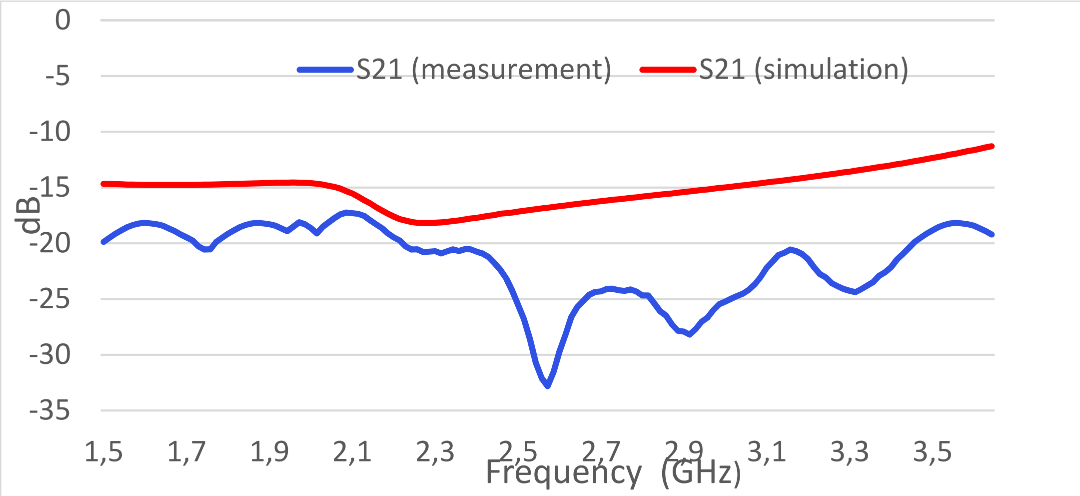

Figure 9. Comparison of measured and simulated S_{21} values in water

The measured and simulated S_{21} values in water are compared, and the results are shown in Figure 9. Both the measured and simulated S_{21} values are observed to be below -10 dB in the 1.5-3.5 GHz range. The measured and simulated results are in good agreement. There is a frequency shift due to manufacturing and measurement errors, and the center frequency is not exactly at 2.45 GHz due to manufacturing and measurement errors. In the production process with LPKF, the line edges are not as smooth as in the simulation and micro edge roughness also occurs. In the simulation, the copper and dielectric surfaces are considered smooth and flat, but after production, the surface usually has a wavy appearance.

In addition, although the measurement results vary between -20 and -30 dB within the desired operating band, the fact that the simulation results are around -15 dB is considered to be due to the difference between the loss tangent of the water used in the simulation and the loss tangent of the water used in the measurement.

3.3. Integration of The Produced FSS Into the Microwave Combi System

The designed microwave combi system is shown in Figure 10. The water tank is designed as a cavity resonator structure filled with water as a dielectric and resonating at 2.45 GHz to transfer microwave energy to the water. Various water-filled structures are tested, and their dimensions are adjusted for maximum efficiency in experimental studies. In practice, the 15x15x30 cm structure has been chosen because it provides the most efficient results, allowing the water temperature in the tank to reach 85 degrees Celsius within two minutes. The pipe diameter is chosen as 4 cm to ensure that the metal pipe does not function as a cylindrical cavity resonator and that the circulation of heated water can be easily ensured within the system. To prevent water from coming into contact with the magnetron, the waveguide that carries energy from the magnetron to the water tank is filled with a suitable dielectric, as shown in the figure, thus preventing water from coming into contact with the magnetron.

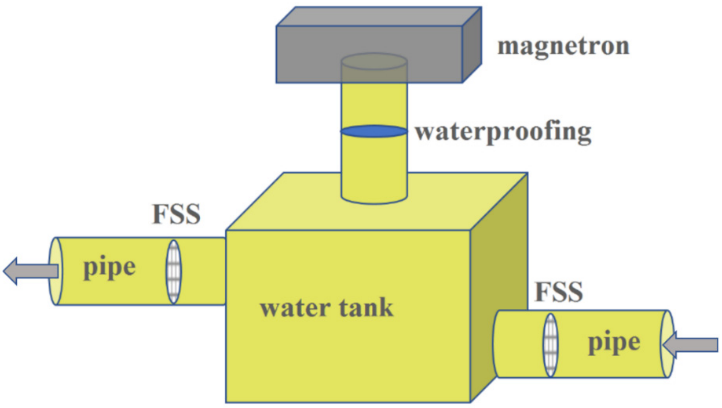

Figure 10. Block diagram of the combi system with FSS

4. RESULTS AND DISCUSSIONS

In this section, the simulation results of the designed FSS structure are compared with the experimental measurement results. Simulation and experimental studies have been conducted in two different environments: the FSS structure in free space and the water-filled environment. Considering that the designed FSS structure operates in water, S_{21} values obtained in the water-filled environment according to the simulation and measurement results have been found to be -17.29 dB and -32.1 dB, respectively. Thus, the measurement and simulation results are in good agreement. The agreement and consistency between the measured and full-wave simulation results confirm the effectiveness of the completely original design strategy implemented in this study.

The FSS structure designed in this study is a unique band-stop filter with a measured S_{21} value of -50 dB, which is consistent with the simulation results. As can be seen from the results, our proposed signal reflector reflects almost all of the 2.45 GHz microwave energy back to the water chamber in a wide bandwidth without obstructing the water flow in closed fluid-mechanical systems.

Consequently, to ensure the reliability and consistency of the results, not only simulations but also measurements are conducted in both free-space and a water-filled environment. Multiple simulations and measurements under two different conditions have confirmed the reproducibility of the data. To further confirm the accuracy and reliability of the results, the experimental findings are cross-validated with simulations [38].

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