International Journal of Engineering & Extended Technologies Research (IJEETR)

|ISSN: 2322-0163| www.ijeetr.com | A Bimonthly, Peer Reviewed, Scholarly Indexed Journal |

| Volume 8, Issue 2, March - April 2026 |

DOI:10.15662/IJEETR.2026.0802391

Adaptive FSS – Based Electromagnetic Shielding using AI Decision Control for Implantable Biotelemetry

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Publication History: Received: 25.02.2026; Revised: 20.03.2026; Accepted: 25.03. 2026; Published: 28.03.2026.

ABSTRACT: This paper presents the design and analysis of an AI-based adaptive Frequency Selective Surface (FSS) for electromagnetic shielding in implantable biotelemetry applications. Implantable medical devices such as pacemakers and biosensors require reliable wireless communication while being protected from unwanted electromagnetic interference. Conventional FSS structures provide fixed frequency filtering characteristics, which may not be sufficient in dynamic electromagnetic environments. To overcome this limitation, the proposed system integrates an artificial intelligence (AI)-based decision control mechanism with the FSS structure to enable adaptive filtering behavior.

The proposed FSS is designed using a square conductive patch printed on a dielectric substrate and is analyzed using Ansys HFSS over a wide frequency range. The structure exhibits both transmission and filtering characteristics, allowing selective control of electromagnetic wave propagation. The AI module is responsible for analyzing incoming electromagnetic signals and determining whether to allow or suppress specific frequency components based on predefined decision logic. This enables dynamic control of the shielding performance depending on the operating conditions.

Simulation results based on S-parameter analysis demonstrate that the proposed FSS provides effective transmission in the desired frequency bands and strong attenuation at unwanted frequencies. Furthermore, the adaptive mechanism enhances the flexibility of the design by allowing real-time tuning of the response. The integration of AI with FSS improves the overall reliability and safety of implantable biotelemetry systems by minimizing the impact of electromagnetic interference. The proposed approach can be extended to advanced applications such as smart healthcare devices, wireless body area networks, and next-generation communication systems. Overall, the developed system offers an efficient and intelligent solution for adaptive electromagnetic shielding in sensitive biomedical environments.

KEYWORDS: Frequency Selective Surface (FSS), Electromagnetic Shielding, Artificial Intelligence (AI), Adaptive Filtering, Implantable Biotelemetry, S-Parameters, Wireless Medical Devices

I. INTRODUCTION

Frequency Selective Surfaces (FSS) have emerged as an important technology in modern electromagnetic and wireless communication systems due to their ability to selectively transmit or reflect electromagnetic waves based on frequency. These structures consist of periodic arrangements of conductive elements printed on dielectric substrates, which act as spatial filters for electromagnetic signals. With the rapid advancement of wireless technologies such as 4G, 5G, and wireless body area networks, the demand for efficient electromagnetic shielding and interference control has increased significantly. In particular, implantable biotelemetry systems, including pacemakers and biosensors, require reliable communication while being protected from unwanted electromagnetic interference.

Implantable medical devices operate in sensitive environments where external electromagnetic signals can disrupt normal functioning or degrade communication performance. Conventional shielding techniques often block a wide range of frequencies, which may also affect the desired communication signals. In contrast, Frequency Selective Surfaces provide a more efficient solution by allowing specific frequency bands to pass while blocking unwanted signals. However, traditional FSS designs offer fixed frequency responses, which may not be suitable for dynamic environments In recent years, the integration of artificial intelligence (AI) in electromagnetic systems has opened new possibilities for dynamic control and optimization. AI-based systems can analyze incoming signals, identify patterns, and make decisions in real time. By combining AI with FSS, it is possible to develop an adaptive system that can modify its response based on the surrounding electromagnetic conditions.

In this work, an AI-based adaptive Frequency Selective Surface is proposed for electromagnetic shielding in implantable biotelemetry applications The performance of the system is evaluated using S-parameter analysis to study transmission and reflection characteristics. In addition, a simple AI-based decision control mechanism is incorporated to dynamically regulate the behavior of the FSS. The results demonstrate that the integration of AI with FSS significantly improves the adaptability and effectiveness of electromagnetic shielding systems.

II. DESIGN METHODOLOGY

2.1 Proposed System Architecture

The overall architecture of the proposed AI-based adaptive Frequency Selective Surface (FSS) system is illustrated in Fig. 1. The system is designed to provide intelligent electromagnetic shielding for implantable biotelemetry applications. Initially, the incoming electromagnetic signal is received from the surrounding environment, which may include both desired communication signals and unwanted interference. This signal is then processed by the AI-based decision control unit, which performs signal analysis and determines whether the incoming frequency component should be allowed or suppressed. The decision-making process is based on predefined logic that classifies signals into safe and harmful categories.

Based on the decision generated by the AI module, the adaptive FSS structure dynamically modifies its transmission and reflection characteristics. The FSS acts as a frequency-selective filter that allows desired signals to pass while blocking unwanted electromagnetic interference. If the signal falls within the acceptable frequency range, it is transmitted through the FSS and reaches the implantable device. Otherwise, the signal is attenuated or reflected, This adaptive mechanism ensures reliable communication and enhances the safety of implantable medical systems. The integration of AI with FSS enables real-time decision-making and improves the overall efficiency of electromagnetic shielding in dynamic environments.

[Incoming RF Signal]
↓
[AI Decision Control]
↓
[Adaptive FSS Surface]
↓ ↓
[Allowed] [Blocked]
↓
[Implantable Device]

Fig 1.Block diagram of AI-based adaptive FSS system

2.2 Proposed FSS Structure

The proposed Frequency Selective Surface (FSS) structure consists of a periodic arrangement of square conductive patches printed on a dielectric substrate, as shown in Fig. 2. The conductive patches are made of copper material, which provides good electrical conductivity and supports the formation of surface currents when excited by an incident electromagnetic wave. The substrate material used in the design is FR4, having a dielectric constant of 4.4 and a thickness of 1.6 mm. A ground plane is placed beneath the substrate to enhance the electromagnetic response and improve the shielding performance of the structure.

The unit cell of the proposed FSS is designed in a square shape, where each conductive patch is uniformly spaced to form a periodic structure. The periodicity ensures that the electromagnetic response is consistent across the entire surface, allowing the structure to behave like an infinite array under proper boundary conditions. The dimension of the patch plays a crucial role in determining the resonance frequency of the structure. In the proposed design, the patch length is selected based on the desired operating frequency range, ensuring effective transmission and filtering characteristics.

When an electromagnetic wave is incident on the FSS surface, it interacts with the conductive patches, inducing surface currents. These currents generate secondary electromagnetic fields, which influence the transmission and reflection behavior of the structure. At frequencies away from resonance, the interaction is weak, and the structure allows the wave to pass through, resulting in high transmission. At resonance frequencies, strong currents are induced on the patch, leading to significant reflection or attenuation of the incident wave. This behavior enables the structure to function as a frequency-selective filter.

The resonance frequency of the square patch can be approximated using the relation:

$$f_r = \frac{c}{2L\sqrt{\varepsilon_{eff}}}$$

where $f_r$is the resonant frequency, cis the speed of light, Lis the length of the patch, and $\varepsilon_{eff}$is the effective dielectric constant of the substrate. This equation indicates that the resonance frequency is inversely proportional to the patch dimension. Therefore, by adjusting the patch size, the operating frequency of the FSS can be controlled.

The proposed structure is simple, compact, and easy to fabricate, making it suitable for practical applications. The design provides a balance between transmission and filtering characteristics, which is essential for electromagnetic shielding in implantable biotelemetry systems. The integration of this structure with an AI-based decision control mechanism further enhances its adaptability, allowing dynamic control of frequency response based on the incoming signal conditions.

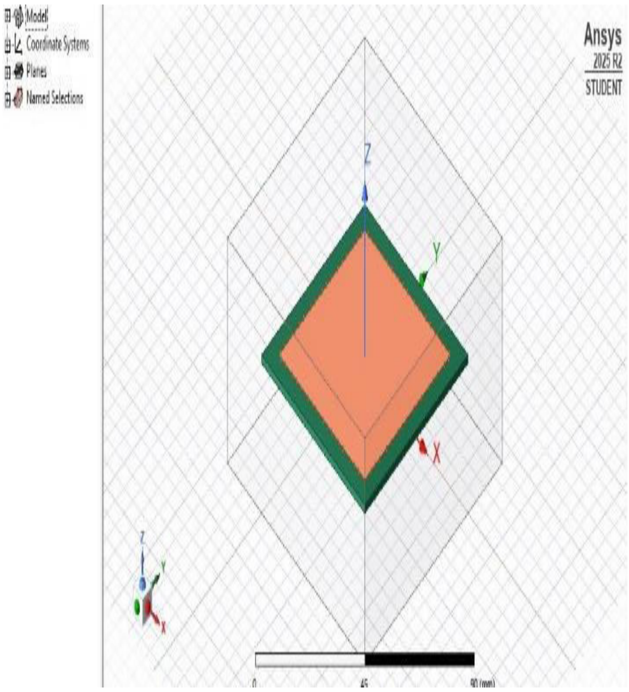

Fig 2. Modified FSS structure with reduced patch dimension

2.3 Modified structure

To further analyze the effect of geometrical variation on the electromagnetic performance, a modified version of the proposed Frequency Selective Surface (FSS) structure is developed, as shown in Fig. 3. In this modified design, the dimension of the square conductive patch is reduced compared to the original structure, while all other parameters such as substrate material, thickness, and unit cell size are kept unchanged. This modification is carried out to study the influence of patch size on the resonance characteristics and overall frequency response of the FSS.

The reduction in patch dimension leads to a decrease in the effective electrical length of the resonant element. According to the fundamental relationship governing microstrip structures, the resonance frequency is inversely proportional to the physical dimension of the patch. This can be expressed as:

$$f_r = \frac{c}{2L\sqrt{\varepsilon_{eff}}}$$

where $f_r$represents the resonant frequency, cis the speed of light, Lis the patch length, and $\varepsilon_{eff}$is the effective dielectric constant. From this equation, it is evident that decreasing the patch length results in an increase in the resonance frequency. Therefore, in the modified structure, the resonance shifts toward higher frequency bands.

When an electromagnetic wave is incident on the modified structure, the induced surface currents are confined within a smaller conductive area. This change in current distribution affects the interaction between the incident wave and the FSS, thereby altering the transmission and reflection characteristics. As a result, the S-parameter response of the modified structure shows a noticeable shift in resonance peaks compared to the original design. The attenuation points move toward higher frequencies, confirming the theoretical prediction.

The modified structure demonstrates that the operating frequency of the FSS can be effectively tuned by adjusting the patch dimensions. This tunability is essential for designing adaptive and multi-band frequency selective surfaces. By comparing the original and modified structures, it is clear that geometrical parameters play a significant role in controlling the electromagnetic behavior of the FSS. Hence, the modified design provides valuable insight into optimizing the structure for different applications.

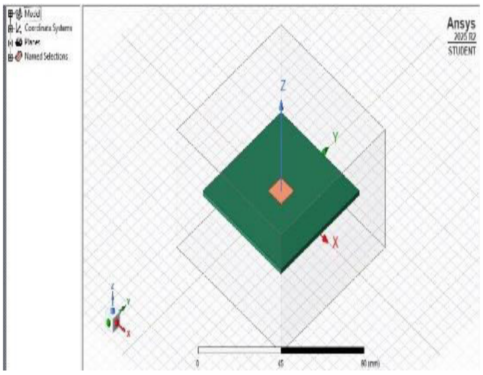

Fig 3.Modified FSS structure with reduced patch size

III. THEORETICAL BACKGROUND

3.1 Frequency Selective Surface Theory

Frequency Selective Surfaces (FSS) are periodic electromagnetic structures that exhibit frequency-dependent transmission and reflection characteristics when interacting with incident electromagnetic waves. These structures are typically composed of an array of conductive elements, such as patches or slots, printed on a dielectric substrate and arranged in a periodic manner. Due to this periodic arrangement, the structure behaves as a spatial filter, allowing certain frequency components of the electromagnetic wave to pass through while blocking or reflecting others. This property makes FSS highly suitable for applications such as electromagnetic shielding, antenna radomes, and frequency filtering systems.

The working principle of an FSS is based on the interaction between the incident electromagnetic wave and the conductive elements of the structure. When an electromagnetic wave impinges on the surface, it induces surface currents on the metallic patches. These currents generate secondary electromagnetic fields, which interfere with the incident wave. Depending on the frequency of the incident signal, this interaction results in either transmission or reflection of the wave. At frequencies where the structure does not resonate, the induced currents are weak, and most of the incident energy passes through the surface, resulting in high transmission. This condition is referred to as the transparent mode of operation.

On the other hand, at specific frequencies known as resonance frequencies, strong currents are induced on the conductive elements. These currents produce significant electromagnetic interaction, leading to either reflection or attenuation of the incident wave. In such cases, the transmitted power is significantly reduced, and the structure behaves as a filter. This condition is known as the filter mode. The resonance behavior is primarily governed by the geometry of the patch, the dielectric properties of the substrate, and the spacing between adjacent unit cells. Among these factors, the dimension of the conductive patch plays a crucial role in determining the resonance frequency.

The resonance phenomenon of an FSS can be understood using the concept of an equivalent LC circuit.

$$f_r = \frac{1}{2\pi\sqrt{LC}}$$

The metallic patch contributes to inductance due to the current flow along its surface, while the gap between adjacent patches introduces capacitance. Together, these elements form a resonant LC circuit, where the resonance frequency is given by:

$$f_r = \frac{c}{2L\sqrt{\varepsilon_{eff}}}$$

This equation indicates that the resonance frequency depends on the inductance (L) and capacitance (C) of the structure. Increasing the patch size increases the effective inductance and capacitance, thereby lowering the resonance frequency. Conversely, reducing the patch dimension decreases these parameters, resulting in a shift of the resonance toward higher frequencies. This theoretical behavior is consistent with the simulation results observed in the proposed design.

Furthermore, the effective dielectric constant of the substrate also influences the propagation of electromagnetic waves through the structure. Since the fields are partially distributed in both air and dielectric material, the effective permittivity determines the actual wave velocity and resonance condition. The periodic nature of the structure ensures uniform response across the surface, making it behave as an infinite array under proper boundary conditions.
Thus, the Frequency Selective Surface operates as a frequency-dependent electromagnetic filter by controlling transmission and reflection characteristics through resonance. The ability to tune the response by modifying structural parameters makes FSS a powerful tool in modern electromagnetic and communication systems. The proposed design utilizes this principle to achieve both transparent and filtering modes, making it suitable for adaptive shielding applications.

3.2 S-Parameter Analysis

The performance of the proposed Frequency Selective Surface (FSS) is evaluated using scattering parameters, commonly known as S-parameters, which describe how an electromagnetic wave behaves when it interacts with a structure. S-parameters are widely used in microwave and RF analysis to represent the transmission and reflection characteristics of a system. In the case of the FSS, the structure can be treated as a two-port network, where the incident wave enters through one port and the transmitted or reflected waves are observed at the output.

The reflection coefficient, denoted as S_{11}, represents the portion of the incident electromagnetic wave that is reflected back from the structure. It is mathematically defined as:

$$S_{11} = \frac{b_1}{a_1}$$

where a_1 is the amplitude of the incident wave and b_1 is the amplitude of the reflected wave at port 1. A lower value of S_{11} indicates that less power is reflected, meaning better transmission through the structure. When S_{11} approaches zero (or becomes highly negative in dB), it implies that most of the incident energy is not reflected.

The transmission coefficient, represented as S_{21}, describes the portion of the electromagnetic wave that passes through the structure from the input port to the output port. It is given by:

$$S_{21} = \frac{b_2}{a_1}$$

where b_2 is the transmitted wave at port 2. A higher value of S_{21} indicates better transmission performance. In FSS analysis, S_{21} is particularly important because it directly represents how effectively the structure allows electromagnetic waves to pass through.

For practical analysis, S-parameters are expressed in decibels (dB) using the relation:

$$S(dB) = 20\log_{10} | S |$$

This logarithmic representation helps in clearly identifying transmission peaks and attenuation dips in the frequency response. In the S-parameter plot, frequency is plotted along the horizontal axis, while the magnitude of S_{11} and S_{21} in dB is plotted along the vertical axis.

The interpretation of the S-parameter graph is crucial for understanding the behavior of the FSS. In the transparent mode, the value of S_{21} remains relatively high across the frequency range, indicating that most of the incident signal is transmitted through the structure. At the same time, S_{11} remains low, showing minimal reflection. This condition corresponds to efficient signal transmission, where the structure behaves like a transparent surface.

In contrast, in the filter mode, the S-parameter plot exhibits deep nulls or dips in the S_{21} curve at specific frequencies. These dips indicate strong attenuation of the transmitted signal, meaning that the structure effectively blocks those frequency components. At these resonance frequencies, the value of S_{11} increases, indicating higher reflection. This behavior confirms that the structure is operating as a frequency-selective filter.

The position of these peaks and dips in the graph corresponds to the resonance frequencies of the structure, which are determined by the patch dimensions and substrate properties. Any change in geometry results in a shift of these resonance points, as observed in the modified structure. Therefore, S-parameter analysis provides a clear understanding of the transmission and filtering characteristics of the FSS and plays a vital role in validating the design through simulation results.

IV. AI-BASED DECISION CONTROL SYSTEM

The proposed system incorporates an AI-based decision control mechanism to enhance the adaptability of the Frequency Selective Surface (FSS) for electromagnetic shielding applications. Unlike conventional FSS structures that operate with fixed frequency characteristics, the proposed approach introduces an intelligent control layer that dynamically regulates the transmission and reflection behavior of the structure based on the characteristics of the incoming electromagnetic signals. This is particularly important in implantable biotelemetry systems, where the surrounding electromagnetic environment is highly dynamic and unpredictable.

The AI decision unit functions as a signal analysis and classification module. It continuously monitors the incoming RF signals and extracts key parameters such as frequency, signal strength, and bandwidth. Based on these parameters, the system applies a predefined decision logic to classify the signals into two categories: desired signals and unwanted interference. Desired signals correspond to the frequency bands required for communication with the implantable device, whereas unwanted signals include noise and external electromagnetic interference that may affect device performance.

The decision-making process is implemented using a rule-based AI approach, which simplifies the system while maintaining effectiveness. The decision logic can be expressed as:

$$\text{If } f \in [f_{\text{allowed}}] \rightarrow \text{Allow Transmission}$$
$$\text{If } f \notin [f_{\text{allowed}}] \rightarrow \text{Block or Attenuate Signal}$$

where f represents the frequency of the incoming signal. This logic enables the system to selectively control electromagnetic wave propagation in real time. The AI unit generates control signals based on this decision, which are then used to adjust the behavior of the FSS structure.

The adaptive nature of the system is achieved by integrating the AI control with the FSS layer. Based on the decision output, the FSS modifies its filtering characteristics to either transmit or suppress specific frequency bands. This dynamic control can be realized conceptually through tunable elements or configurable structural parameters. As a result, the system is capable of responding to varying electromagnetic conditions without requiring manual intervention.

The integration of AI with FSS significantly improves the performance of electromagnetic shielding systems by providing intelligent and adaptive filtering. This approach ensures that only the required signals reach the implantable device, while harmful interference is effectively suppressed. The proposed AI-based decision control system enhances the reliability, safety, and efficiency of implantable biotelemetry systems, making it suitable for advanced healthcare and communication applications.

V. SIMULATION SETUP / PARAMETERS

The simulation of the proposed Frequency Selective Surface (FSS) is carried out using Ansys HFSS, a full-wave electromagnetic solver based on the finite element method. The structure is analyzed to study its transmission and reflection characteristics over a wide frequency range. A single unit cell of the FSS is modeled and periodic boundary conditions are applied along the sides to represent an infinite array structure. This approach ensures accurate analysis while reducing computational complexity.

Floquet ports are used to excite the structure with a plane electromagnetic wave. The incident wave is directed normal to the surface along the Z-axis. The simulation considers both Transverse Electric (TE) and Transverse Magnetic (TM) modes to evaluate the response under different polarization conditions. The frequency sweep is performed over a range of 0 GHz to 12 GHz to observe the behavior of the structure in both transparent and filter modes.

The substrate material is chosen as FR4 with a dielectric constant of 4.4 and a thickness of 1.6 mm. The conductive patch is modeled as a Perfect Electric Conductor (PEC) to ensure ideal conductivity. The mesh is refined near the patch edges to capture the variations in electromagnetic fields accurately. Adaptive meshing is used to achieve convergence and improve the accuracy of the simulation results.

To ensure accurate and reliable simulation of the proposed Frequency Selective Surface (FSS), appropriate parameter selection and setup conditions are essential. The electromagnetic behavior of the structure is highly dependent on the substrate properties, patch dimensions, and excitation conditions. The unit cell configuration, boundary conditions, and port excitation are defined in such a way that the simulated model closely represents an infinite periodic structure. Additionally, The parameters used in the simulation are summarized in Table I.

Table I: Simulation Parameters of Proposed FSS

Parameter	**Value**
Substrate Material	FR4
Dielectric Constant (εr)	4.4
Substrate Thickness (h)	1.6 mm
Patch Material	Perfect Electric Conductor (PEC)
Unit Cell Size	20 mm × 20 mm
Patch Dimension (L)	10 mm (Main), 7 mm (Modified)
Frequency Range	0 – 12 GHz
Boundary Condition	Periodic Boundary
Port Type	Floquet Port
Modes Considered	TE and TM Modes

The parameters listed in Table I define the essential conditions for accurate simulation of the proposed FSS structure. The substrate properties and patch dimensions directly influence the resonance behavior and frequency response of the structure. The use of periodic boundary conditions ensures that the unit cell represents an infinite array, while Floquet ports provide proper excitation of the electromagnetic wave. The selected frequency range allows detailed observation of both transmission and filtering characteristics. Overall, the chosen parameters ensure reliable and efficient analysis of the FSS performance.

VI. RESULT AND DISCUSSION

6.1 Transparent Mode Analysis

The transparent mode response of the proposed Frequency Selective Surface (FSS) is illustrated in Fig. 4. The S-parameter plot shows the variation of transmission and reflection characteristics with respect to frequency. In this mode, the structure is designed to allow electromagnetic waves to pass through with minimal attenuation over a wide frequency range. The transmission coefficient S_{21} remains relatively high across most of the frequency spectrum, indicating that the incident electromagnetic energy is effectively transmitted through the structure. This behavior confirms that the FSS operates as a transparent surface for the desired frequency bands.

The high transmission performance can be explained based on the electromagnetic interaction between the incident wave and the conductive patch. At frequencies away from resonance, the induced surface currents on the patch are weak, resulting in minimal interaction with the incident wave. As a result, the structure does not significantly disturb the propagation of the electromagnetic wave, allowing it to pass through with very low loss. This leads to a higher value of S_{21} and a corresponding low value of the reflection coefficient S_{11}, which indicates efficient transmission and minimal reflection.

However, the S-parameter plot also shows the presence of small dips at certain frequency points. These dips correspond to partial resonance conditions where moderate interaction occurs between the incident wave and the patch structure. At these frequencies, the induced currents increase slightly, leading to partial attenuation of the transmitted signal. Despite this, the overall transmission remains dominant, and the structure continues to exhibit transparent behavior. These minor resonant effects are important as they indicate the frequency-selective nature of the structure.

The observed transparent mode behavior is consistent with the theoretical analysis of FSS structures. According to the resonance principle, strong interaction occurs only at specific frequencies, while at other frequencies, the structure behaves as a non-resonant surface. This results in high transmission outside the resonance bands. The periodic arrangement of the unit cells ensures uniform electromagnetic behavior across the surface, further improving the transmission efficiency.

From the simulation results, it is evident that the proposed FSS structure provides stable and efficient transmission over a wide frequency range. This makes it suitable for applications where uninterrupted signal propagation is required, such as implantable biotelemetry systems and wireless communication devices. The ability of the structure to maintain high transmission while controlling unwanted resonances highlights its effectiveness as a frequency-selective transparent surface.

Furthermore, the transparent mode performance plays a crucial role in ensuring reliable communication for implantable medical devices. In such applications, it is essential to allow only the desired communication signals to pass through without distortion. The proposed FSS achieves this by maintaining high transmission in the required frequency band while minimizing interference from unwanted signals. The integration of the AI-based decision control system further enhances this behavior by dynamically selecting the appropriate operating condition based on the incoming signal characteristics.

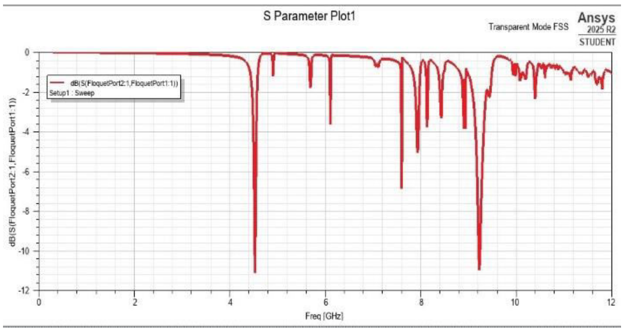

Fig4. Simulated S-parameter response of the FSS in transparent mode

6.2 Filter Mode Analysis

The filter mode response of the proposed Frequency Selective Surface (FSS) is presented in Fig. 5. The S-parameter plot clearly illustrates the attenuation characteristics of the structure over the selected frequency range. In this mode, the structure is designed to suppress unwanted electromagnetic signals by significantly reducing the transmission coefficient S_{21}at specific frequencies. The graph shows distinct deep nulls in the S_{21}curve, indicating strong attenuation of electromagnetic waves at those resonance frequencies.

At these resonance points, the value of S_{21}drops sharply, often reaching very low levels in decibels, which confirms that the structure effectively blocks signal transmission. Simultaneously, the reflection coefficient S_{11} increases, indicating that a large portion of the incident electromagnetic energy is reflected back. This behavior demonstrates that the FSS is operating efficiently as a frequency-selective filter. The presence of multiple deep dips in the S-parameter plot suggests that the structure supports multi-band filtering, which is highly beneficial for applications requiring selective suppression of multiple frequency bands.

The filtering behavior can be explained using the resonance concept discussed in the theoretical analysis. At resonance frequencies, strong surface currents are induced on the conductive patch. These currents generate secondary electromagnetic fields that interfere destructively with the transmitted wave, resulting in significant attenuation. The energy of the incident wave is either reflected or dissipated, preventing it from passing through the structure. This strong interaction is responsible for the deep nulls observed in the S_{21}curve.

The position of these resonance dips is primarily determined by the geometrical parameters of the structure, particularly the patch dimension and substrate properties. As discussed in the modified structure analysis, reducing the patch size shifts the resonance frequency toward higher values. This shift is clearly reflected in the S-parameter response, where the attenuation peaks move to higher frequency regions. This confirms the theoretical relationship between patch dimension and resonance frequency, validating the design approach.

The filter mode performance is crucial for electromagnetic shielding applications, especially in implantable biotelemetry systems. In such environments, unwanted electromagnetic signals can interfere with the operation of medical devices. The proposed FSS effectively suppresses these signals by blocking specific frequency bands while allowing desired signals to pass. This selective filtering enhances the reliability and safety of the system.

Furthermore, the integration of the AI-based decision control mechanism enhances the functionality of the filter mode. The AI system analyzes incoming signals and dynamically determines whether the structure should operate in filtering mode. Based on this decision, the FSS selectively attenuates unwanted frequency components, providing intelligent and adaptive shielding. This combination of resonance-based filtering and AI-driven control makes the proposed system highly effective for modern communication and biomedical applications.

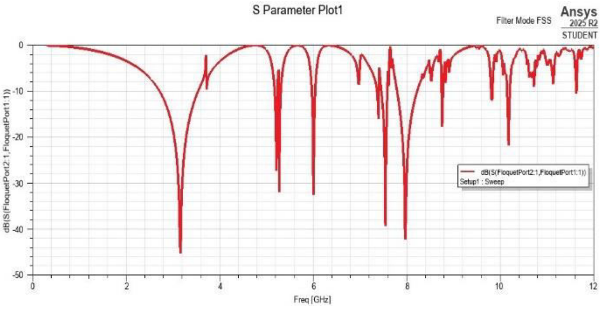

Fig.5. Simulated S-parameter response of the FSS in filter mode

6.3 Performance Discussion

The overall performance of the proposed Frequency Selective Surface (FSS) is evaluated based on its ability to operate effectively in both transparent and filter modes. From the simulation results, it is evident that the structure exhibits clear frequency-selective behavior by allowing electromagnetic waves to pass through at certain frequencies while suppressing them at others. This dual-mode operation demonstrates the capability of the FSS to function as both a transparent surface and a frequency-selective filter, depending on the operating conditions.

In the transparent mode, the structure maintains high transmission across a wide frequency range, ensuring minimal signal loss for desired communication bands. The low reflection observed in this mode further confirms the efficiency of the design in supporting signal propagation. On the other hand, the filter mode exhibits strong attenuation at specific resonance frequencies, as indicated by the deep nulls in the transmission response. This confirms the effectiveness of the structure in blocking unwanted electromagnetic interference.

The comparison between the original and modified structures highlights the impact of geometrical variation on the performance of the FSS. By reducing the patch dimension, the resonance frequency shifts toward higher values, which is consistent with the theoretical relationship between patch size and frequency. This tunability allows the structure to be adapted for different frequency bands, making it suitable for multi-band applications. The ability to control resonance through simple geometrical modifications adds flexibility to the design.

Furthermore, the integration of the AI-based decision control mechanism enhances the overall functionality of the system. The AI module analyzes incoming signals and determines whether the structure should operate in transparent or filter mode. This dynamic control enables the system to respond to changing electromagnetic environments in real time. As a result, the proposed design not only provides passive filtering but also introduces intelligent and adaptive behavior, which is a significant improvement over conventional FSS structures.

From an application perspective, the proposed system is highly suitable for implantable biotelemetry systems, where reliable communication and protection from electromagnetic interference are critical. The structure ensures that only the desired signals reach the implantable device while unwanted signals are effectively suppressed. This improves the safety and performance of medical devices operating in complex electromagnetic environments.

Overall, the simulation results confirm that the proposed FSS structure, combined with AI-based control, provides efficient, flexible, and adaptive electromagnetic shielding performance. The consistency between theoretical analysis and simulation results further validates the reliability of the design. Hence, the proposed system offers a practical and effective solution for advanced frequency-selective applications.

VII . CONCLUSION

In this paper, an AI-based adaptive Frequency Selective Surface (FSS) is designed and analyzed for electromagnetic shielding in implantable biotelemetry applications. The proposed structure, based on a square conductive patch printed on a dielectric substrate, demonstrates effective frequency-selective behavior when interacting with incident electromagnetic waves. The design is evaluated using Ansys HFSS, and the performance is analyzed through S-parameter characteristics over a wide frequency range.

The simulation results confirm that the structure operates efficiently in both transparent and filter modes. In the transparent mode, the FSS allows electromagnetic waves to pass through with minimal attenuation, ensuring reliable communication for desired frequency bands. In contrast, the filter mode exhibits strong attenuation at specific resonance frequencies, effectively suppressing unwanted electromagnetic interference.

The effect of geometrical variation is also investigated by modifying the patch dimension. The results clearly indicate that reducing the patch size shifts the resonance frequency toward higher values, which is consistent with the theoretical analysis. This demonstrates that the operating frequency of the FSS can be easily tuned by adjusting its geometrical parameters. Such flexibility is essential for designing multi-band and adaptive electromagnetic systems.
Furthermore, the integration of an AI-based decision control mechanism significantly enhances the performance of the proposed system. The AI module analyzes incoming signals and dynamically determines whether the structure should operate in transparent or filter mode. This intelligent control enables real-time adaptation to varying electromagnetic environments, which is particularly important in implantable medical applications. By allowing only the desired signals to pass and suppressing harmful interference, the system improves both reliability and safety.

Overall, the proposed AI-based adaptive FSS provides an efficient, flexible, and intelligent solution for electromagnetic shielding. The combination of theoretical analysis, simulation results, and adaptive control demonstrates the effectiveness of the design. The system is well suited for applications such as implantable biotelemetry, wireless body area networks, and advanced communication systems. Hence, the proposed approach offers a promising direction for the development of next-generation frequency-selective and adaptive electromagnetic structures.

VIII. FUTURE SCOPE

The proposed AI-based adaptive Frequency Selective Surface (FSS) provides a strong foundation for further research and development in advanced electromagnetic shielding applications. Although the current design demonstrates effective performance in both transparent and filter modes, several enhancements can be implemented to improve its functionality and applicability in real-world scenarios. One of the primary areas of future work is the development of a fully reconfigurable FSS structure using tunable components such as varactor diodes, PIN diodes, or micro-electromechanical systems (MEMS). By integrating such elements into the FSS, the resonance characteristics can be dynamically adjusted, enabling real-time control of frequency response based on changing environmental conditions.
Another important direction is the implementation of more advanced AI techniques for intelligent decision-making. While the current system uses a rule-based decision control mechanism, future work can incorporate machine learning algorithms to classify signals more accurately and adapt to complex electromagnetic environments. This would enable the system to learn from previous data and improve its performance over time. Additionally, the integration of sensor-based feedback mechanisms can further enhance the adaptability of the system by providing real-time environmental information to the AI module.

The proposed design can also be extended to support multi-band and ultra-wideband operation by modifying the geometry or introducing multi-layered structures. This would allow the FSS to operate effectively across a broader frequency spectrum, making it suitable for next-generation communication systems such as 5G and 6G. Furthermore, the development of polarization-independent FSS structures can ensure consistent performance regardless of the orientation of the incident electromagnetic wave.

From a practical perspective, future work should focus on the fabrication and experimental validation of the proposed design. The structure can be tested using measurement setups such as a Vector Network Analyzer (VNA) and anechoic chamber to verify the simulation results. The use of flexible and transparent substrate materials can also be explored to enable applications in wearable devices, biomedical implants, and smart surfaces. In addition, the integration of the FSS with antenna systems can improve overall system efficiency by combining filtering and radiation functionalities.

Overall, the proposed work opens up new possibilities for the development of intelligent and adaptive electromagnetic systems. The combination of AI and FSS provides a powerful approach for controlling electromagnetic wave propagation in dynamic environments. Future advancements in this area can lead to the development of smart shielding systems for biomedical, defense, and communication applications, making the technology more efficient, reliable, and versatile.

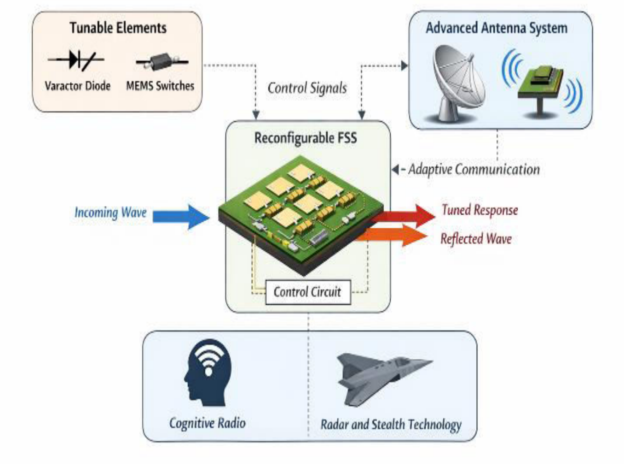

Fig6.future scope of adaptive fss in biotelemetry

IX . ACKNOWLEDGMENT

The authors would like to express their sincere gratitude to the faculty members and the management of their institution for providing continuous support and encouragement throughout the course of this work. Their guidance and valuable suggestions have played a significant role in the successful completion of this project. The authors also extend their heartfelt thanks to their project guide for their constant motivation, technical insights, and constructive feedback, which greatly contributed to the development and improvement of this work.

The authors gratefully acknowledge the facilities and resources provided by the institution, including access to laboratory infrastructure and simulation tools such as Ansys HFSS, which were essential for carrying out the design and analysis of the proposed Frequency Selective Surface. The support received from technical staff and colleagues during various stages of the project is also sincerely appreciated. Finally, the authors would like to thank all individuals who have directly or indirectly contributed to the successful completion of this research work.

The authors would also like to acknowledge the support provided by their department for enabling a conducive research environment. The continuous encouragement received from the teaching and non-teaching staff has been instrumental in completing this work successfully. Special appreciation is extended to the laboratory coordinators for their assistance in providing the required facilities during the project development. The authors are grateful for the academic guidance and resources that helped in improving the quality of the research. The valuable discussions with peers and team members also contributed to refining the ideas presented in this work. The authors further thank their institution for promoting research-oriented activities and innovation. The support extended during the simulation and analysis phase is deeply appreciated. Finally, the authors express their sincere thanks to everyone who supported them throughout the completion of this project, either directly or indirectly.

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