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RESEARCH ARTICLE

Polarization Insensitive and Angularly Stable Adaptive Frequency Selective Surface for Automated and on-Demand Electromagnetic Shielding

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ABSTRACT A new adaptive frequency selective surface (AFSS) has been presented for electromagnetic (EM) shielding applications. Passive EM shields lack reconfigurability which severely limits their application. Moreover, active EM shields involving PIN diodes and other active elements consume power all the time. This paper incorporates a novel adaptive approach with frequency selective surface (FSS) to create a smart environment. The unit cell of the designed FSS has the shape of an octagon loop; each loop includes a pin diode at 180° intervals. An envelope detector has been used to trigger the microcontroller whenever an incident RF signal has been detected. The PIN diodes are switched ON or OFF automatically based on the requirements using a microcontroller to save power. When the PIN diodes are OFF, the FSS is in the shielding mode and when they are ON it is in the transmission mode. A prototype has been built for measurements. A good agreement between theory and experiment has been observed. The proposed AFSS can also be programmed as a time-based event and remote-controlled for on-demand EM wave shielding applications.

INDEX TERMS Frequency selective surface, frequency detector, adaptive shielding.

I. INTRODUCTION

In recent decades the modern environment has been saturated by electromagnetic radiations emitted by different wireless devices around us. This electromagnetic energy has been generated for specific uses, but unfortunately, everyone is exposed to it. High levels of these radiations cause interference and have many other unwanted effects on daily human life if exposed for longer duration, such as tissue damage and, in some worst-case scenarios, cause tumors [1], [2], [3], [4], [5], [6]. In special situations, such as visits of high officials, security operations, intensive care units (ICU), and cardiac care units (CCU) the upper-frequency signals, some frequencies of the IMS band, and useful communication bands such as mobile phones, radio, and television networks have been restricted. Selectively shielding electromagnetic (EM) waves requires the installation of spatial filters.

In corporate offices, the 2.45 GHz spectrum is widely used for WLAN communications to interconnect various systems and workstations. External leakage of sensitive information

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due to the hacking of internal wireless networks is a cause of concern for every such corporation [7]. Security agencies frequently demand Radio Frequency (RF) radiation reduction in zones where data security is paramount. Numerous efforts have been dedicated to enhancing security in controlled environments by reducing electromagnetic radiation and electromagnetic interference (EMI). One common approach involves utilizing metal foils or metallic coatings to shield both the environment and devices [8]. However, conventional shielding methods come with notable drawbacks. They can inadvertently block both desired and undesired signals and are associated with high costs, increased weight, and bulkiness of the shielded devices [8], [9].

Frequency-selective surfaces (FSSs) show promising potential for deployment in critical settings, including military establishments, secure facilities like correctional institutions, and other strategically important locations. This is primarily because of their remarkable capabilities in effectively filtering and suppressing specific frequencies [10], [11], [12]. Different FSSs configurations have been reported in the literature to mitigate EMI for GSM, WLAN/Wi-Fi, and X-band signals in a single- or multi-mode operation [13], [14], [15]. The frequency response of FSSs can be modified using different procedures such as mechanical alterations, tuning of physical properties of the material, biasing of the circuits, and micro-fluidic techniques, as reported in [16]. However, mechanical alterations are challenging to implement due to difficult physical procedures. Similarly, climate conditions such as temperature change and humidity affect the surfaces during material tuning. Electronic reconfiguration of FSS can be achieved through circuit biasing technique implemented by varactor diodes and PIN diodes [9], [13], [14], [17], [18]. The above-mentioned active shielding methods have been used to achieve the desired frequency band as per the end-users needs. However, these active FSSs have major limitations like high power consumption, polarization dependence, and poor performance at different angles of incidence [19], [20], [21].

A tunable FSS based on Jerusalem-cross has been reported by the authors of [21] to filter 900 and 1800 MHz, wherein the lower band tuning has been achieved using varactors. However, the authors have not reported the behavior of FSS for transverse electric (TE) and transverse magnetic (TM) polarization. Moreover, the shielding stability at normal and oblique incidence angles has not been discussed. A metamaterial based tunable FSS has been reported in [22], having a size of 10.5 mm. The varactors have been used on both sides of the substrate, and FSS has been designed to operate from 3 to 3.5 GHz range. Still, polarization independence is a major limitation that makes it unfit for practical applications. In [23], authors presented a reconfigurable FSS operating at 5.8 GHz. A mechanical geometry has been used to adjust the gap between FSS elements to make it reconfigurable. The reported cell size is 15 mm but performance under oblique circumstances has not been discussed. In addition, two techniques based on reconfigurable FSSs have been reported in [24]. The first technique is to alter the current distribution using diodes, and the second is to rotate FSS mechanically. But no prototype has been built to show experimental results, raising many concerns about practical performance.

In [25], a manually employed venetian-blind shutter mechanism-based reconfigurable FSS has been proposed. Similarly, a dual band-stop reconfigurable FSS has been proposed using a liquid crystal polymer [26]. But angular stability and practical realization have not been discussed in detail. In recent literature, different reconfigurable FSS have been reported. The proposed configurations are expensive and complicated. In addition, poor shielding performance has been reported because of coupling between RF and DC currents.

It can be observed from the literature that reconfigurable FSS geometries are bulky. Moreover, it is challenging to achieve polarization independence and angular stability [19], [20], [21], [22], [23]. Additionally, passive FSS lack reconfigurability while active FSS involving PIN diodes and other active elements consume power all the time [27]. In this work, we present an Adaptive Frequency Selective Surface that intelligently responds to ambient 2.45 GHz signals. Unlike traditional Active FSS designs that are either always ON or always OFF, consuming constant power, our adaptive design overcomes this limitation in an intelligent manner. The proposed FSS seamlessly switches its behavior between permitting and blocking 2.45 GHz signals based on real-time detection, thanks to the integration of a microcontroller and a frequency detector. When ambient 2.45 GHz signals are detected, the microcontroller acts intelligently by switching OFF the diodes within the FSS. This action effectively blocks the signals while conserving power. Conversely, in situations where no signals are detected, the microcontroller activates the diodes, allowing uninterrupted signal transmission. This real-time adjustment of the FSS behavior ensures optimal signal isolation when needed and unobstructed transmission when appropriate, making it a smart and efficient solution. The novelty of our work lies in the fusion of adaptive technology with RF shielding, enabled by a microcontroller.

- **Adaptive Shielding FSS**: We introduce a pioneering concept by implementing autonomous control within the FSS context. While FSS designs have been extensively studied, our work stands out for its incorporation of adaptive, real-time control into FSS tailored for WLAN applications. This specific focus is of growing relevance in modern settings, including smart homes, IoT, and wireless communication systems, making our work both original and timely.
- **Power Optimization**: Our approach addresses a crucial issue associated with active FSS designs - constant power consumption. Through adaptive control, we intelligently manage diodes to conserve power when ambient signals are present and enable transmission when necessary. This power optimization is of paramount importance, especially in energy-conscious environments,

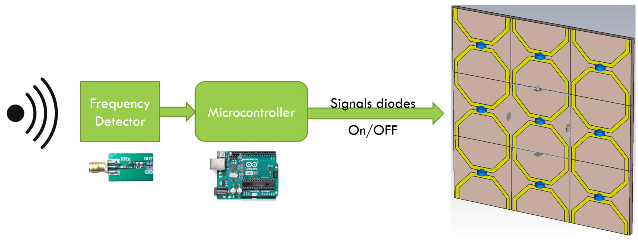


FIGURE 1. Illustration of Adaptive FSS.

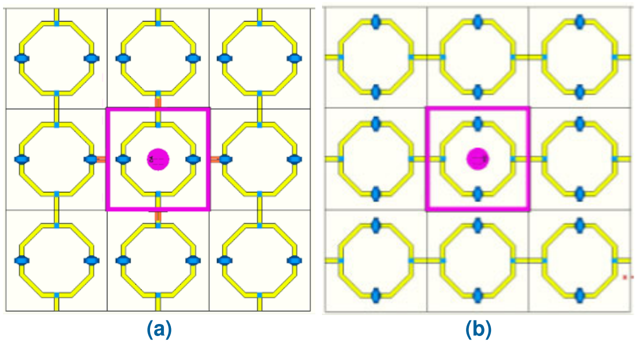


FIGURE 2. Configuration 1: Octagonal loop with 2 diodes in each unit cell. (a) Front view (b) Back view.

setting our work apart in terms of practicality and efficiency.

- **Versatility**: The autonomous control system we propose is highly versatile and can be tailored to accommodate various FSS designs and frequency ranges. This adaptability significantly enhances the versatility of FSS structures, making them suitable for diverse scenarios and applications.

The proposed FSS exhibits stable response in both the TE and TM modes of transmission and has also proved to be effective for the oblique angle of incidence up to 60° with at least −30 dB attenuation. The remainder of the paper is organized as follows: The FSS simulation model has been presented in Section II, followed by Active FSS design, optimization, and adaptive control mechanism. A comparison of the simulated and measured results is shown in Section III, followed by the conclusion in the last section.

II. ACTIVE FSS DESIGN, SIMULATION AND OPTIMIZATION

A novel adaptive FSS energized by a microcontroller and frequency detector has been proposed, as illustrated in Fig. 1.

The transmission properties of the FSS unit cell have been simulated in TE and TM modes using the frequency-domain solver of CST Microwave Studio software. Infinite periodic boundary conditions have been applied on the X and Y-axes, and the Floquet ports are applied on the Z-axis.

This section provides a detailed discussion of the design process of the adaptive FSS, with the performance evaluation of different design configurations, including stable response, angular stability, polarization stability, and low insertion loss. Based on the evaluation, the final design was proposed, chosen from the two different design configurations as shown in Fig. 4, which demonstrated improved results.

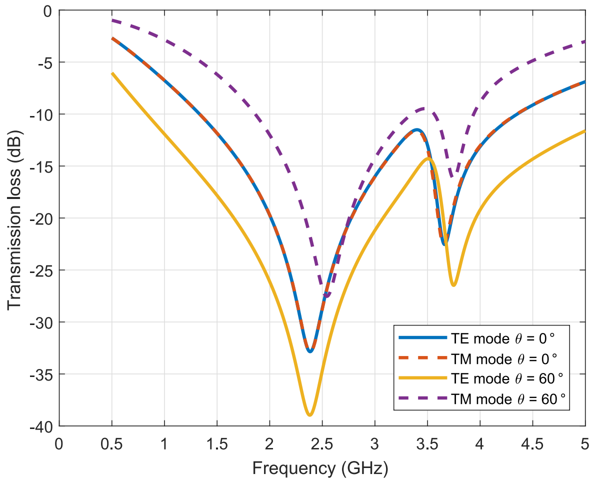
A. CONFIGURATION 1

We present two configurations of octagonal loop FSS with embedded PIN diodes. In configuration 1, the unit cell of the active FSS is an octagonal loop structure loaded with two PIN diodes (BAP65-03) on each side, front and back, as illustrated in Fig. 2. When the PIN diodes are on, the loop behaves as a conducting loop, and when the PIN diodes are off, the loop behaves as an open circuit. Since both diodes are oriented in the same direction, the DC bias voltage is connected at the top and bottom edges of the front side, and at the right and left edges of the bottom side of the FSS. This double-layered structure allows for the design of a dual-polarized FSS. When the control signal is applied to the PIN diodes on one side, the loop structure behaves as a conducting loop for one polarization, while the loop structure on the other side of the substrate behaves as an open circuit for the other polarization. This results in a dual-polarized FSS that can selectively block one polarization while allowing the other polarization to pass through. To make the FSS polarization insensitive, the control signal is applied to both sides.

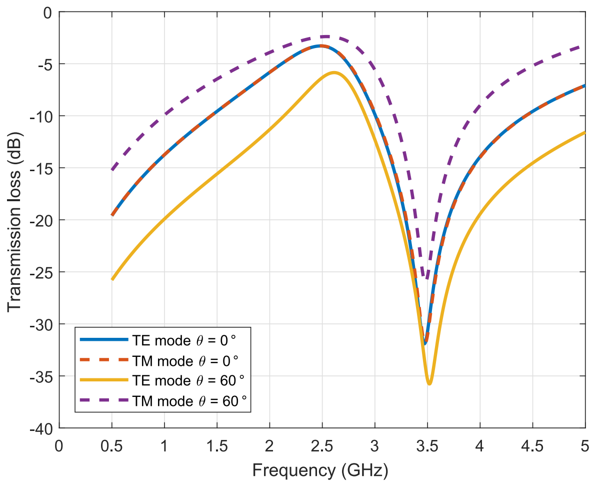
The frequency response of TE and TM mode under oblique conditions at 0° and 60° when the diodes are OFF has been represented in Fig. 3 (a). As observed, the FSS is successfully blocking the signal at 2.45 GHz providing the desired shielding. Moreover, the TE and TM mode response at 0° and 60° when the diodes are ON has been depicted in Fig. 3 (b). As represented, the stable response with reasonable insertion loss has been offered by the designed FSS. But the configuration requires two diodes per unit cell, which makes the fabrication process complex and costly.

B. CONFIGURATION 2

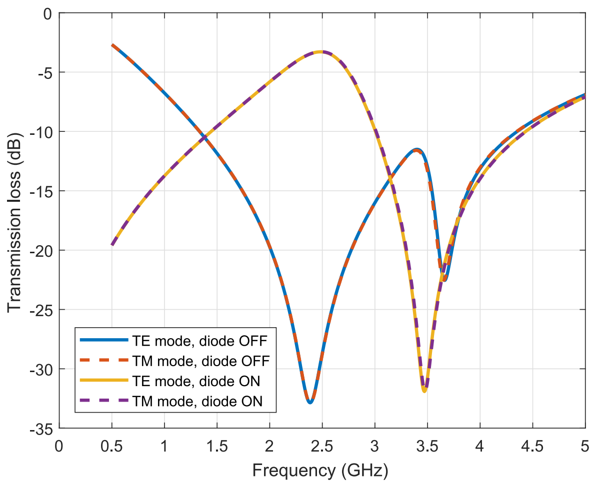
In this configuration, the unit cell of active FSS has been modified by using only one diode on each side of the unit cell only instead of two, as shown in Fig. 4. The switching mechanism alternates between electrically isolating and short-circuiting the two loops. This action induces a shift in the frequency response of the FSS structure, transitioning it between a band-pass and a band-stop configuration. The parameters have been optimized to propose the optimal design that is easy to fabricate and cost-effective. The unit cell FSS is designed as a double-sided octagonal structure on an FR4 substrate. PIN diodes are connected vertically between the unit cells on the top side and horizontally on the bottom side. The dimensions of the proposed unit cell have been depicted in Fig. 5. An iterative design procedure has been adopted to optimize the active FSS. Many simulations with different parameter sweeps have been run to achieve the desired results. The optimized values of the parameters have been drawn in Table 1. The circumference of the octagonal loop is proportional to the guided wavelength at 2.45 GHz as



(a)



(b)

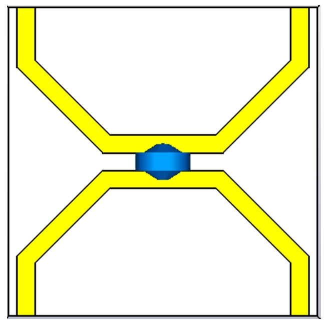


(c)

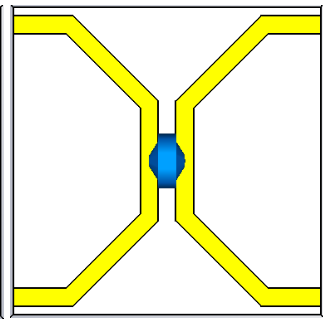
FIGURE 3. Configuration 1: Simulated TE and TM modes at (a) 0° & 60° when the Diodes are OFF (b) 0° & 60° when the Diodes are ON (c) at 0° when the Diodes are OFF vs ON.

given by a simplified equation

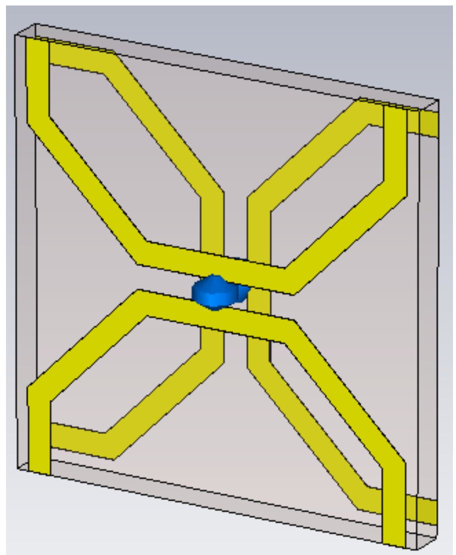
$$\lambda_g = \frac{c}{f\sqrt{\frac{\varepsilon_r+1}{2}}} \tag{1}$$



(a)



(b)



(c)

FIGURE 4. Configuration 2: (a) Front view of the unit cell (b) Back view of the unit cell (c) Perspective view of the FSS unit cell showing the front and back views and diode position.

TABLE 1. Configuration 2: Dimensions of unit cell.

Dimension in mm	
dx	8.91
dy	$dx \times \sin 67.5°$
w	1
g	0.5

where c is the velocity of propagation in free-space in m/s, f is the frequency in Hz and ε_r is the relative permittivity of the dielectric material. The size of the unit cell in terms of the resonant frequency wavelength is $0.14 \times 0.14\ \lambda$.

The frequency responses in TE and TM mode at 0° and 60° when the diodes are OFF have been presented in Fig. 6 (a). Similarly, the frequency response of TE and TM mode at incident angles of 0° and 60° when the diodes are ON have been presented in Fig. 6 (b). A robust response in terms of angular stability and polarization insensitivity has been observed. The designed frequency band, i.e., 2.45 GHz, has been successfully blocked achieving the desired shielding. Moreover, the frequency response when the diode is

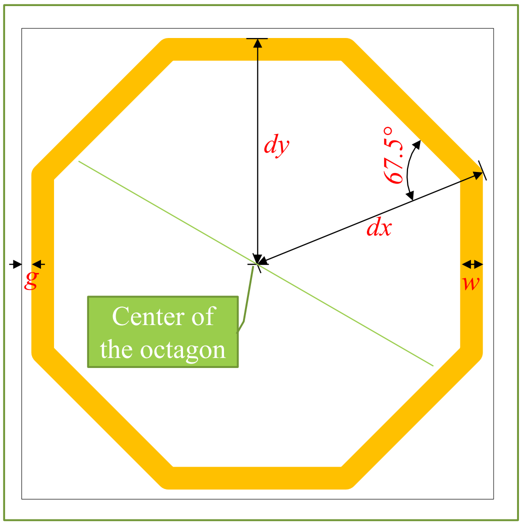


FIGURE 5. Octagonal unit cell with Proposed Dimensions, for both the configurations.

OFF vs ON is shown in Fig. 6 (c). The pass-band response in Fig. 6 (b) shows very low insertion loss. Furthermore, the desired results have been achieved using one diode per unit cell on each side of the structure, which is the standout feature of this research. The active FSS designed in this configuration is the optimized geometry and is further used in designing the proposed adaptive FSS explained in the next section.

C. PROPOSED NEW ADAPTIVE FSS CONFIGURATION

The active FSS designed in configuration 2 has been further utilized in designing the adaptive FSS as shown in Fig. 1. The major limitation of active FSS is that it consumes power all the time when the diodes are switched on. The novelty of this research is to optimize the power consumption by using a frequency detector and automating the switching process of the diodes. The FSS is integrated with a microcontroller which switches the diodes ON and OFF as per the required operation.

The microcontroller circuit schematic has been demonstrated in Fig. 7. For this circuitry, Arduino UNO has been selected because of its ease of programming and cost-effectiveness. An omnidirectional antenna connected to a frequency detector circuit has been used to detect the RF signals. The frequency detection is done using a commercially available module, B09PZFM4R3 [28], which works by envelope detection mechanism. It has a high detection sensitivity of −30 dBm and works in the frequency range of 0.1 MHz to 3.2 GHz. The output voltage ranges between 100 mV to 2 V depending on the power of the source signal.

The pulse generated by the frequency detector is fed as an input to the analog-to-digital converter of the microcontroller. The microcontroller has been programmed to switch ON and OFF the diodes connected on the FSS based on these input pulses. To switch on the diodes, the microcontroller sends a high signal on a digital output pin which supplies the DC

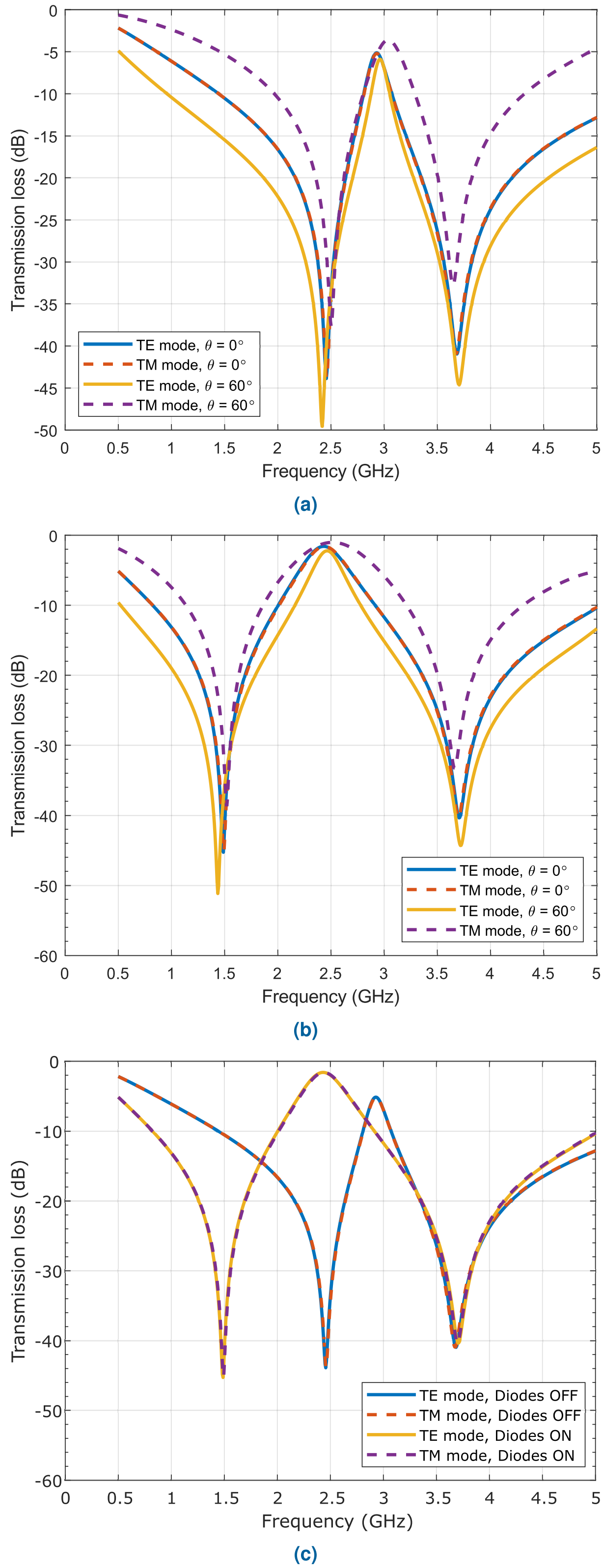


FIGURE 6. Configuration 2: Simulated TE and TM modes at (a) 0° & 60° when the Diode is OFF (b) 0° & 60° when the Diode is ON (c) 0° when the Diodes are OFF vs ON.

bias voltage of 3.3 V. Two 1k ohm resistors are connected in series at the positive and negative bias lines as shown

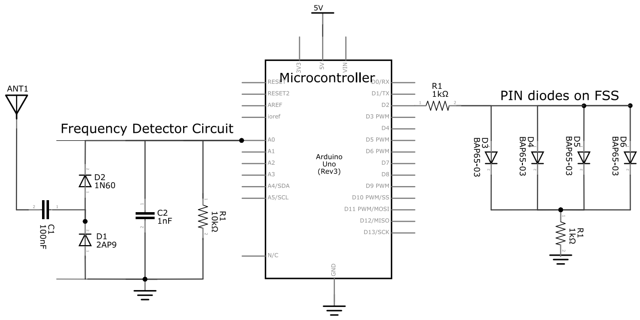


FIGURE 7. Schematic Diagram of the Adaptive Frequency Selective Surface control circuitry.

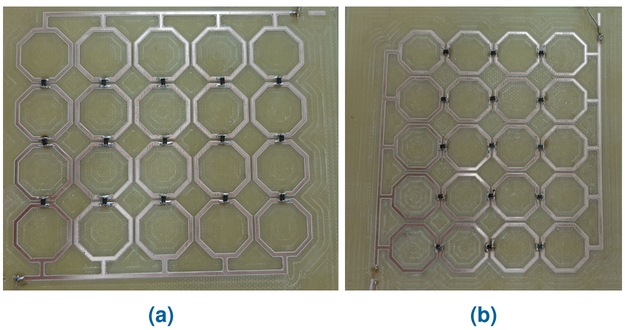


FIGURE 8. Fabricated Adaptive FSS sample (a) Top view (b) Bottom view.

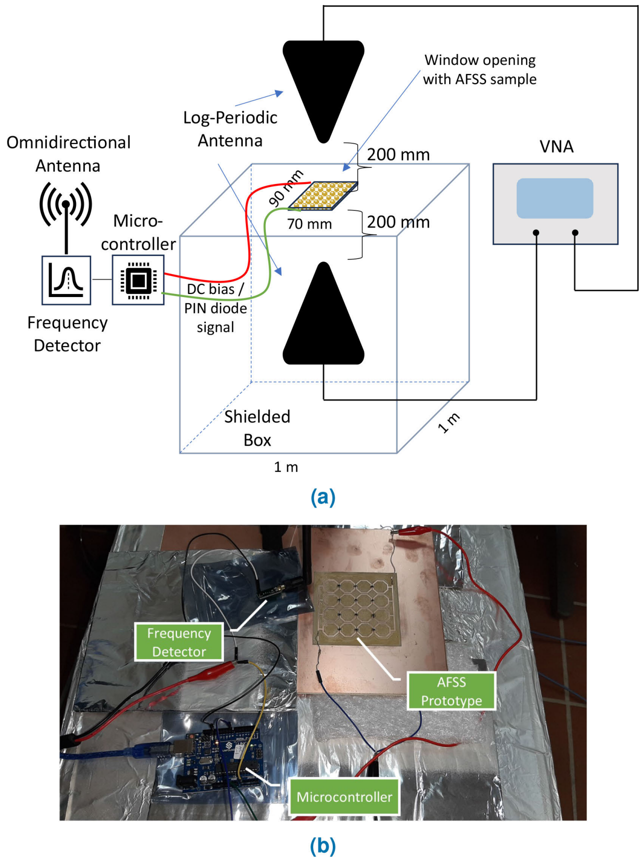


FIGURE 9. (a) Measurement setup illustration (b) AFSS, frequency detector, and the microcontroller used to switch the diodes.

in the schematic diagram in Fig. 7, which limit the current to 1.6 mA. With this mechanism, the WLAN 2.45 GHz shielding has been tested experimentally. The microcontroller programming is flexible and can be done as per requirements, which makes the proposed design effective.

The proposed geometry is bandpass FSS when the diodes are ON but operation can be reversed easily by replacing the loops into patches to make it a bandstop FSS. The FSS can be used in either mode depending on the desired applications. The proposed FSS is designed without any drilling or complicated physical geometry, which makes it useful to be printed on window glass as well. This novel idea of designing adaptive FSS can be utilized with any other FSS designed for blocking different RF bands. The use of a microcontroller for triggering the diodes ON or OFF helps in automating the shielding effect of the FSS. A time-based trigger or a remote trigger is easily achievable thanks to the interrupt capabilities and various interfaces available on a microcontroller.

III. FABRICATION AND MEASUREMENT

A proof-of-concept prototype of the proposed Adaptive FSS has been built for measurements as presented in Fig. 9. The FR−4 is used as the substrate with an $\epsilon_r = 4.8$ and a thickness of 1.5 mm. The PIN diodes (BAP65-03) are soldered by hand at their positions. The photograph of the prototype has been presented in Fig. 8. A 1 m^3 shielded box which acts as a Faraday cage, as illustrated in Fig. 9 (a) with a small opening window of size 70 × 90 mm is used for measurements. The FSS sample of 5 × 4 array of unit cells is placed on the window of the Faraday cage with one of the measurement antennas placed inside the box and the other placed outside the box. Fig. 9 (b) shows a picture of the measurement setup. The far-field region of the AFSS has been carefully considered in the experimental setup. To ensure accurate measurements, the antennas were placed in the far field region calculated using the relation $2D^2/\lambda$, where D represents the dimensions of the antennas. For instance, the dipole radiating at 6 GHz, with a length of 11.8 mm, had a corresponding far-field region of approximately 22.4 mm, while the largest dipole operating at 700 MHz, with a length of 101.9 mm, resulted in a far-field region of about 19.4 cm. To achieve accurate results, the front portion of the antenna operating at 6 GHz was positioned 200 mm away from the AFSS on both sides, as depicted in Fig. 9 (a). Similarly, at a frequency of 0.7 GHz, the longest element of the antenna was positioned 540 mm away from the AFSS surface, considering the antenna's length of 340 mm [29]. Thus, the AFSS sample was appropriately placed within the far-field length of the log periodic antennas at both extreme frequencies.

The transmission properties of the proposed Adaptive FSS are measured using two directional Hyperlog 7060 [29] log-periodic antennas and Keysight's N5225A 2-port network analyzer [30]. Fig. 10 shows the measured results in comparison of simulated results for the switching property of the proposed Adaptive FSS at normal incidence for 2.45 GHz

TABLE 2. Comparison between proposed FSS and other FSS in the literature.

Ref.	Operating Frequencies (GHz)	Angular / Polarization Stability	Design Mechanism	Benefits/ Limitations	Smart Adaptive Control
[16]	12.42	Up to 30°	PIN diodes	Isolation is presented only but no demonstration during ON and OFF states of the diodes I Presented only 1 x 3 geometry array results	NO
[23]	3.5 / 5 / 5.8	Not reported	Changing distance to optimize mechanically	Mechanical arrangement is personalized I Hard to implement on different FSSs I Investigation of Polarization stability is unachievable I Shafts can only be rotated by the motor	NO
[25]	3.2 / 4.75 / 5.2	Up to 60°	Blinds rotated manually	It might not be feasible to rotate blinds to regulate EM waves for FSS I Controlling the FSS structure for frequency reconfigurability is challenging	NO
[31]	3.5 – 5.7	Not Demonstrated	Varactor Diodes	The adopted construction mechanism is expensive	NO
[32]	5.7 – 9.8	Up to 30°	PIN Diodes	A single parallel bias circuit arrangement I Offers limited angular stability	NO
Proposed Work	**2.45 GHz**	**Up to 60°**	**PIN Diodes are controlled by the microcontroller and envelope detector**	**The PIN diodes are switched ON/ OFF automatically to optimize the power consumption I Angular stability I Low insertion loss I Polarization stability**	**YES**

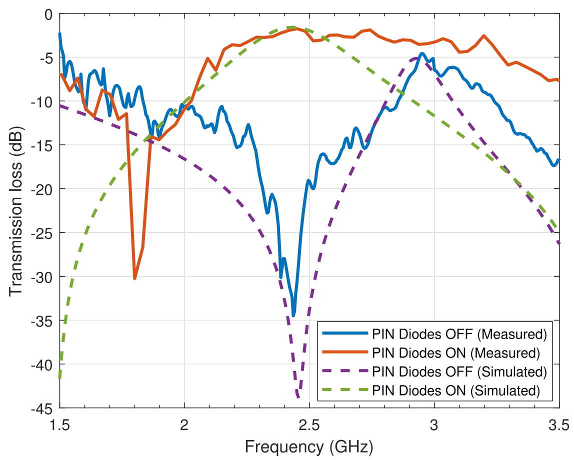


FIGURE 10. Measurement results: Switching between EM Shielding and Transmission at 2.45 GHz with PIN Diodes in OFF and ON States (TE Mode, Normal Incidence).

in TE mode. When the PIN diodes are OFF, we observe a peak suppression of at least −20 dB from 2.31 to 2.51 GHz, and when the diodes are ON, the RF signal passes through the FSS with less than −3 dB insertion loss. The observed −3 dB operational band is between 2.32 to 2.51 GHz. A close comparison between simulated and measured results has revealed minor differences and ripples due to fabrication tolerances and measurement errors, leading to marginal discrepancies at 1.8 GHz in the observed agreement when the diodes are ON; specifically, the mismatch is due to the added inductance of solder at the diode terminals, although it does not impact the operational bandwidth of the Adaptive FSS, which remains between 2.32 to 2.51 GHz. The presence of band suppression at 1.8 GHz and 3.8 GHz is a consequence of the unique characteristics and operational principles of the FSS at higher frequencies, as well as the

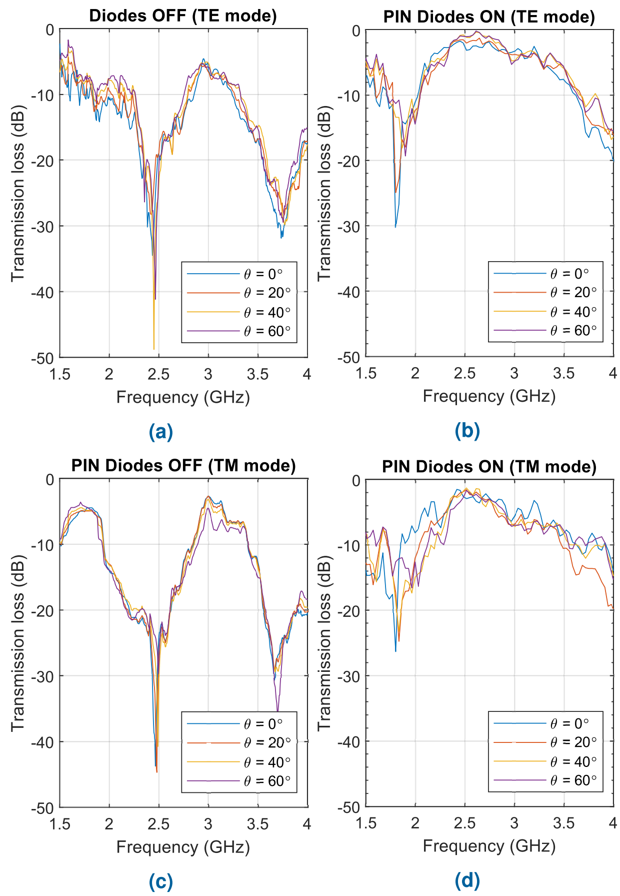


FIGURE 11. Measurement results showing angular and polarization stability in PIN diodes ON and OFF states.

coupling effect between the two FSS layers. While the design optimization primarily targets 2.45 GHz, it is acknowledged that performance at other frequencies may exhibit variability.

The incident angle stability and polarization insensitivity of the proposed Adaptive FSS are substantiated by the measurement results presented in Fig. 11. These results encompass measurements conducted across a range of incident angles from 0° to 60°, encompassing both TE and TM modes, with the diodes in both OFF and ON states. Notably, the proposed FSS design exhibits exceptional stability, demonstrating robust insensitivity to changes in polarization, whether in TE or TM mode.

The comparison of the proposed adaptive FSS with recent literature has been drawn in Table 2. As evident, no adaptive FSS has been found in the literature. The adaptive FSS has been proposed for the first time in this article, which has a clear advantage in optimized power usage. Moreover, the proposed design performs better in terms of angular stability, low insertion loss, and simple design configuration compared to several previously published results for FSS with WLAN shielding applications.

IV. CONCLUSION

An active frequency selective surface with octagonal loop-shaped unit cells has been proposed. The proposed FSS has been integrated with a microcontroller and frequency detector to make smart adaptive operations. Good angular stability up to 60° in both TE and TM modes has been measured, which is a good contribution to those achieved in literature. Moreover, the proposed design has offered low insertion loss and polarization stability. As far as the authors can see, this is the only work featuring an adaptive frequency selective surface for shielding of 2.45 GHz band applications. A good agreement between the simulated and measured results has been observed.

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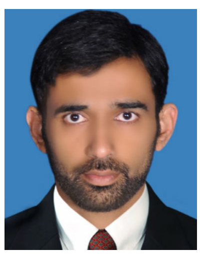

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