Integration of ultra-wideband elliptical antenna with frequency selective surfaces array for performance improvement in wireless communication

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ABSTRACT

The integration of frequency selective surfaces (FSS) with antennas has gained significant attention due to its ability to enhance key radio frequency (RF) performance parameters such as gain, directivity, and bandwidth, making it highly beneficial for modern wireless communication systems. In this work, we propose and investigate an ultra-wideband (UWB) elliptical antenna operating within the 5.2 to 10 GHz frequency range. To further improve its performance, we integrate the antenna with a 13×13 FSS array. The impact of the FSS on the antenna's characteristics is analyzed, showing a remarkable gain enhancement from 2.6 dBi (without FSS) to 10.05 dBi (with FSS). These results confirm the effectiveness of FSS integration in optimizing UWB antenna performance, making it a promising approach for advanced wireless communication applications.

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1. INTRODUCTION

Ultra-wideband (UWB) antennas that are appropriate for UWB systems must be provided since antennas are essential components of wireless systems. The omnidirectional radiation of the most popular UWB antennas offers the broad coverage area that many traditional UWB applications require. In environments where interference and obstacles are common, directional radiation may be more beneficial than omnidirectional radiation for traditional UWB applications. This is because omnidirectional radiation produces significant interference and power loss in unwanted directions. Consequently, extensive research has been conducted to design planar UWB antennas with unidirectional radiation patterns. The predominant technique for achieving unidirectional radiation is the use of cavity reflectors, which reflect the radiation back towards the antenna, thereby increasing its gain. However, by isolating the antenna from its environment, these reflectors can affect its overall performance. We therefore advocate the use of UWB reflectors in the design of planar UWB antennas with directional radiation patterns. Our research into the development of high-performance UWB reflectors led us to investigate frequency selective surfaces (FSSs), which are versatile structures of significant interest for a wide range of applications, particularly in UWB. This paper provides a comprehensive overview of the key applications of FSSs in antenna engineering, explaining the physical principles that enable their performance optimization. We also present our proposed FSS-based UWB antenna designs. Initially, we designed UWB reflectors using simple FSSs (complementary capacitive and inductive elements) to optimize and stabilize the gain of UWB antennas. Subsequently, we employed a single-layer UWB FSS to achieve the same function. Integrating the FSS with the UWB radiator results in a smaller profile and superior performance.

Any thin, repeating surface designed to reflect, transmit, or absorb electromagnetic (EM) waves in accordance with the incident waves produced by FSS is known as an FSS. FSSs fall into one of two categories: Two types of filters are i) stopband and ii) pass-band. Numerous applications, including randoms, EM absorbers, shielding, wearable technology, meta skin, and reflectors, have made extensive use of these FSS filters [1]–[6]. Stopband-responsive FSSs are capable of successfully blocking the passage of electromagnetic interference. Additionally, FSSs have characteristics that vary with polarization and incidence frequency. FSSs have been widely utilized for shielding purposes in this regard. To produce the notch filter rejection, a small number of metamaterial structures were developed and implemented [7]–[12]. The federal communications commission (FCC) has authorized the use of the 7.5 GHz frequency band (from 3.1 to 10.6 GHz) for UWB applications, provided that it does not interfere with already assigned frequencies. Indeed, UWB technology allows for the generation of low-amplitude signals across a wide range of wavelengths [13]. We use a multi-layer FSS structure to achieve a UWB response with a variable frequency characteristic [14]–[16]. According to the study in [14], a double-conductor FSS layer with dimensions of 12×12×1.6 mm offers a bandwidth of 10.8 GHz (from 5.3 to 16.1 GHz). Furthermore, the study in [15] presents a bidirectional FSS structure covering the C-band for protection purposes, with a frequency range of 8 to 12 GHz. Finally, the authors in [16] used a more complex FSS structure to obtain a stop-band response, covering the frequency range from 3.1 to 13.3 GHz (at -10 dB).

In this work, we propose a UWB elliptical antenna operating in the 5.2 to 10 GHz frequency band. This band is commonly used for wireless communications, radar systems, industrial applications, and satellite communications. In wireless networks, the 5.2 GHz frequency belongs to the UNII-1 band of Wi-Fi (IEEE 802.11a/n/ac/ax), providing a fast Internet connection with less interference compared to 2.4 GHz. This band also covers some intermediate frequencies of 5G, facilitating fixed wireless access (FWA) and mobile broadband services. In the radar domain, automotive short-range radars (SRRs) typically operate around 5.8 and 9 GHz for collision avoidance and adaptive cruise control, while C-band and X-band radars (covering the 4–12 GHz range) are used in air traffic management, weather forecasting, and military surveillance. The 5.8 GHz ISM band is used in industrial heating, RF applications, and medical imaging, while some X-band frequencies (8–12 GHz) facilitate satellite communications, including Earth observation and military satellite links. Overall, this band is essential for high-speed connectivity, precision sensing, and critical infrastructure applications.

The main contributions of this work are:

a. Modeling an ultra-wideband elliptical antenna.
b. Designing an FSS unit structure and FSS array within the same frequency band as the proposed antenna.
c. Studying the improvement of the antenna's RF performance with the FSS array in terms of gain, directivity, and bandwidth.

The remainder of this article is structured as follows: relevant studies are presented in section 2. Section 3 describes the design of the wideband antenna and the FSS structure. Section 4 examines the integration of the FSS structure and the antenna element, along with an analysis of the results. Finally, the conclusions are presented in section 5.

2. RELATED WORKS

To optimize antenna, gain across UWB frequencies, our study examines methods utilizing FSSs, as described in various related research papers. The different FSS methods identified were organized into a taxonomy to determine the most effective strategy for enhancing antenna gain. This research also analyzes the benefits of using an FSS as a reflector to generate directional radiation at UWB frequencies. In the study by [17], the proposed antenna design employs a star-shaped radiating element, offering a wide impedance bandwidth ranging from 3.0 to 11.7 GHz. A higher gain (4 to 5 dB) can be achieved, while maintaining a broad impedance bandwidth, by using a three-layer FSS. The use of an FSS also helps to reduce the antenna's side lobes. This research also presents a broadband antenna with constant gain [18]. The proposed design consists of a coplanar waveguide (CPW) circular disk antenna based on a single-layer FSS. The average gain across the entire UWB band is 9 dB, with a maximum variation of 0.5 dB. The improvement is 2.5 dB at lower frequencies and 7 dB at higher frequencies.

This research introduces a wideband antenna, specifically designed to meet the unique coverage requirements of high-speed applications [19]. It utilizes a suspended ground plane to broaden the bandwidth and employs a FSS reflector to enhance gain. This antenna achieves an impedance bandwidth of 13.4 GHz (from 1.8 to 15.2 GHz). The FSS reflector contributes to increasing the antenna gain in the lower frequency range. The antenna is positioned 1.01λ (36.14 mm) below a novel 5×5 element FSS reflector. The use of the

FSS reflector boosts the antenna gain by 4 to 5 dBi. For UWB applications, a high gain, directional CPW-fed planar antenna with a novel FSS unit cell design is suggested in this study [20]. The Mercedes artistic-shaped planar (MAP) antenna served as the model for the proposed UWB antenna. To increase antenna impedance bandwidth, the antenna was made out of three straight legs placed in a circular ring. Two parallel conductive metallic patches with a circular loop topology were integrated into the simulated FSS. For frequencies between 2.2 and 12.7 GHz, the FSS had a UWB stopband filter response that covered a bandwidth of 10.5 GHz. The proposed FSS architecture consisted of a printed array of 19×19-unit cells, each with dimensions of 5×5×1.6 mm. These unit cells were printed on one side of the FR4 dielectric substrate, which is located between the antenna and the reflector ground plane.

In study [21], the authors introduce a novel circular polarization (CP) UWB antenna system. The antenna has a modified inverted L-shaped radiating patch and is a coplanar waveguide (CPW) feed arrangement. A non-uniform, single-layer FSS, composed of rectangular conducting plates, was designed and implemented with a circularly polarized antenna to enhance its performance and gain. The results show that the antenna with the FSS exhibits a reflection loss of less than 10 dB over a bandwidth ranging from 3.7 to 11.1 GHz. The -3 dB bandwidth ratio is 58.15%, covering the frequency range from 5 to 9.1 GHz. The highest recorded gain is 4 to 9.4 dBi, representing an increase of approximately 3 dBi compared to the antenna without the FSS. In order to improve antenna, gain for UWB applications, this research provides a workable prescription [22]. A thorough investigation was conducted, and a thorough literature review was divided into two groups. Reports were made on the FSS single-layer and multi-layer reflectors. A highly effective technique is proposed to mitigate the effects of the FSS, reducing reflection loss to -10 dB while maintaining a constant gain across the entire UWB frequency range. FSS technology represents an efficient and practical method for enhancing the gain of UWB antennas. Numerous potentials for researchers to close the gaps found are revealed by this systematic review.

This paper describes a high-gain UWB antenna that utilizes a single-layer FSS reflector [23]. This antenna exhibits an impedance bandwidth of 155% (spanning from 1.9 to 15.2 GHz) and a peak gain of 5.9 dBi. The addition of an FSS reflector array further enhances the gain of this UWB antenna. This array, comprising 5×5 elements, consists of circular structures that form the individual FSS components. In the higher frequency range, the UWB antenna with the FSS reflector shows a nearly constant gain, ranging from a maximum average gain of 5.9 to 9.2 dBi. This paper also proposes the design of a broadband, high-gain antenna for wireless UWB applications requiring high gain, incorporating a FSS [24]. An FSS reflector and a monopole make up the antenna. To start, a slot and stub are used to modify a traditional rectangular monopole antenna in order to reduce its size and provide a wide operating bandwidth. With a broad impedance spectrum of 3.6–11.8 GHz, this modified antenna exhibits 50% downsizing in comparison to a primary rectangular monopole. A FSS array is then created by assembling elements with square and circular shapes. This 8×8 cell array, incorporated as a reflector in the antenna, aims to optimize the performance of the proposed compact UWB antenna. The use of this FSS array provides a gain of at least 4 dBi across the entire operating frequency range.

The research [25] proposes a novel compact UWB FSS for electromagnetic shielding applications. The simulated FSS consists of two parallel conducting metal plates with a circular loop structure. Its UWB transmission band spans 10.5 GHz, from 2.2 to 12.7 GHz. The proposed system employs a 19×19 array of printed FSS cells, each cell measuring only 5×5×1.6 mm. An equivalent circuit model (ECC) was used to verify the performance of the FSS cell. Research [26] suggests a novel semi-circular antenna with a very wide bandwidth for high-speed applications. It utilizes a complementary split-ring resonator to extend the frequency band and an FSS reflective surface to enhance gain. First, a wideband antenna with a return loss below -10 dB and a bandwidth of 130.3% (from 3.16 to 15 GHz) is presented. It employs complementary split-ring resonators and two L-shaped resonators. An FSS reflector is added to improve the gain. The coplanar waveguide antenna has dimensions of 35×30×1.6 mm^3, while the antenna with the FSS reflector (a 10×10 array of 17 mm cells) has dimensions of 53.15×53.15×1.6 mm^3. For broadband applications, the average antenna gains increase from 4.9 to 10.9 dB for frequencies of 3.79, 4.44, 7.89, 9.01, and 11.15 GHz.

Ud Din *et al.* [27] introduces a compact, UWB circular monopole antenna, equipped with a FSS to optimize gain. This antenna consists of a circular patch with circular slots along its edges and is fed by a microstrip transmission line. The bottom surface of the UWB antenna is modified with two triangular notches on the sides and a rectangular notch in the center, thus optimizing its radiation characteristics. This antenna was designed on an FR-4 substrate with a thickness of 1.6 mm, a relative permittivity of 4.3, and standard dimensions of 30×30 mm. An FSS, consisting of periodic unit cells of metal printed on the upper layer of a FR-4 substrate with dimensions of 0.11λ×0.11λ at the lowest operational frequency of 3.3 GHz, is meant to increase the gain of the suggested antenna. By positioning the antenna on the FSS, the suggested antenna's gain is raised from 3 to 8.1 dB at 9 GHz. The Table 1 describes the parameters that were used during related works.

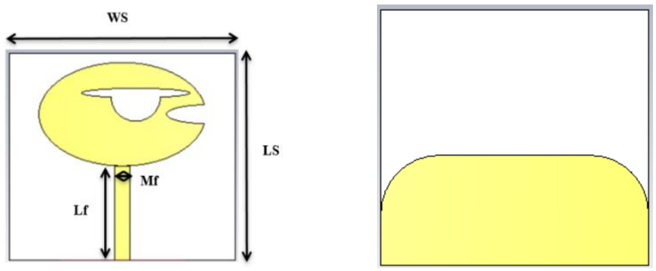
Table 1. Parameters use during related works

Ref	Antenna type	Freq (GHz)	Gain(dB)	FSS structure
[17]	Star-shaped radiation patch	3.0–11.7	+4 to 5	3-layer FSS
[18]	UWB CPW-circular disc	UWB band	9	Single-layer FSS
[19]	UWB with suspended ground	1.8 - 15.2	+4 to 5	FSS (5x5 elements)
[20]	MAP CPW-fed UWB	2.2 - 12.7	11.5	FSS (19x19 cells)
[21]	CP UWB	3.7 - 11.1	9.4	Single-layer FSS
[23]	UWB	1.9 - 15.2	9.2	FSS (5x5 elements)
[24]	Modified monopole	3.6 - 11.8	+4	FSS (8x8 elements)
[25]	UWB FSS (EM shielding)	2.2 - 12.7	NA	19x19 cells
[26]	Semi-circular UWB	3.16 - 15	10.9	FSS (10x10)
[27]	Circular monopole UWB	3.3 - 10.8	8.1	FSS (0.11λ cells)
Work	Elliptical UWB antenna	5.2-10	10.05	FSS (13x13)

3. ANTENNA AND FSS DESIGN

3.1. Single unit cell antenna

An elliptical slotted microstrip patch antenna with truncated ground as shown in Figure 1, is designed. Figures 1(a) and 1(b) shows top view and bottom view. Table 2 summarizes the key parameters of the antenna structure, including their respective values.



(a) (b)

Figure 1. Proposed single unit cell (a) top view (b) bottom view

Table 2. Antenna design dimensions

Parameters	Values (mm)
WS	46
LS	44
Lf	20
Mf	3

3.2. Reflexion parameter (S11) and VSWR

Figure 2 illustrates the S-parameters for an extended frequency range (from 5.2 to 10 GHz), with a center frequency of 7.8 GHz and a reflection loss of -37.8 dB. To ensure efficient antenna performance, the voltage standing wave ratio (VSWR) must be less than 2 dB. Figure 3 demonstrates that the performance of the proposed design is confirmed by its VSWR value of 1.02 at the center frequency.

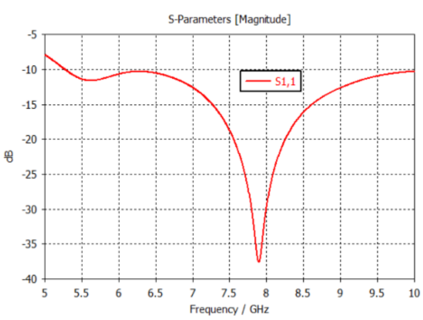


Figure 2. Simulated S11 results

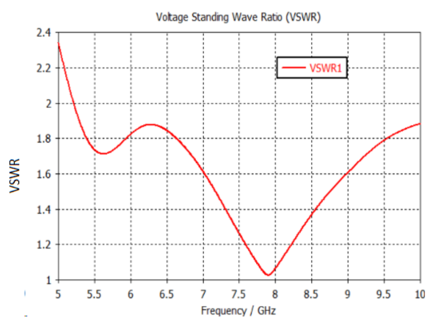
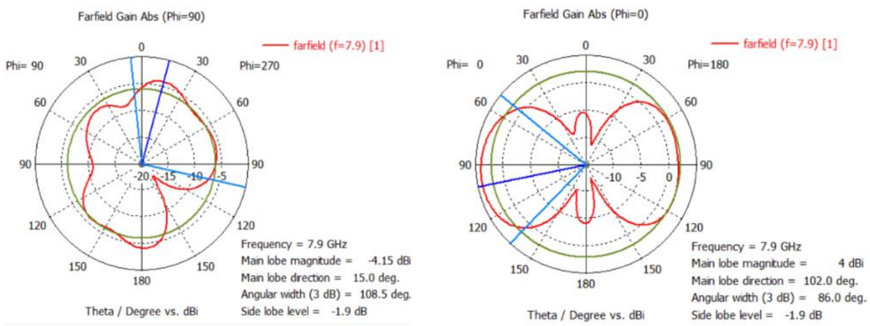


Figure 3. Simulated VSWR of proposed design

3.3. 2D-fields

The 2D e-field and h-field of proposed design are depicted in Figures 4(a) and 4(b). This figure explains gain, main lobes direction and side lobes level.



(a) (b)

Figure 4. 2D far field (a) e-field and (b) H-field

3.4. 3D field

3D far field represents gain of the antenna and direction of main beam. Dark color indicates high current intensity and maximum current while yellow color shows low current. Figure 5 demonstrates that the proposed architecture provides a gain of 5.45 dB at 7.9 GHz.

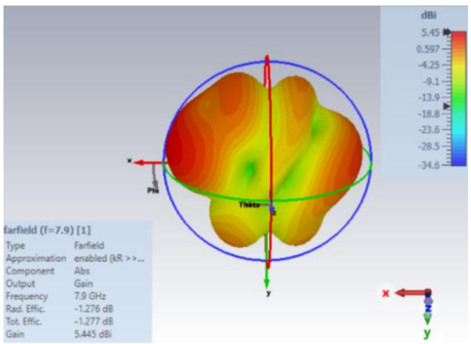


Figure 5. 3D far field radiation pattern

3.5. FSS unit cell

Figure 6 depicts the configuration of the FSS, which consists of a square unit cell with a concentric circle design. The resonant characteristics of this structure are primarily influenced by the inner and outer radii of the circles, as well as other geometric parameters. This type of configuration is designed to operate over a wide frequency range, enhancing its reflection and filtering capabilities. Table 3 lists the main structural parameters of the FSS and their corresponding values.

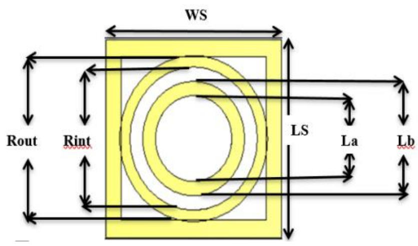
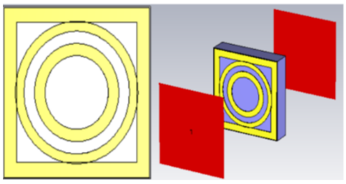


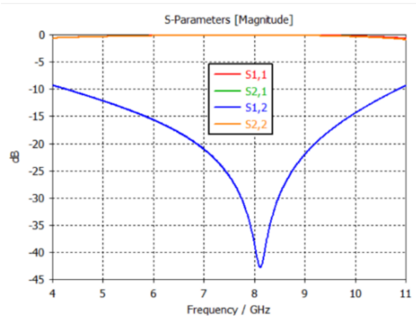
Figure.6. FSS structure

Table 3. FSS design dimensions

Parameters	Values(mm)
WS	7
LS	7
Rout	3
Rint	2.5
La	1.5
Lb	2

The unit cell and the surface of the proposed FSS array, along with its S-parameters, are shown in Figure 7(a). This array is fabricated on a 1.6 mm thick FR4 substrate and measures 7 mm by 7 mm. Figure 7(b) shows the plots of |S11| and |S12| for the proposed FSS array. The array operates over a wide frequency range, from 4.3 to 10.8 GHz.


(a)

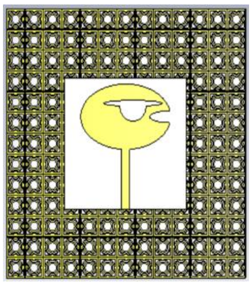


(b)

Figure 7. Proposed FSS design and simulated results (a) FSS design and (b) results

4. INTEGRATION OF FSS WITH ANTENNA AND RESULTS

This section of the document explains the basic principles of using FSS to optimize antenna performance. The proposed FSS is positioned below the antenna, with a 11 mm gap between the two components as shown in Figures 8(a) and 8(b). This distance was chosen to enhance performance. The FSS layer is positioned below the antenna to reflect the radiation emitted from its back surface. Since the antenna's emitted radiation and the reflected waves are in phase, this results in an increase in gain. Figure 9 shows the antenna performance and S-parameters, which serve to confirm the proper functioning of the FSS.


(a)

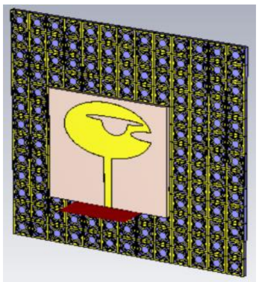

(b)

Figure 8. Proposed design with FSS (a) front view and (b) bottom view

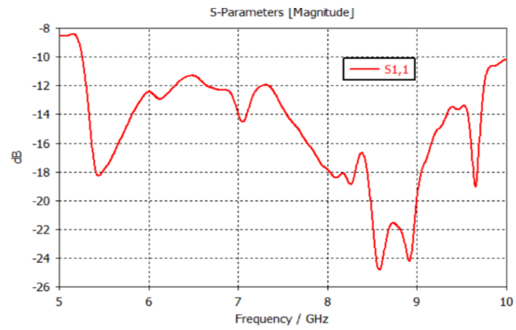


Figure 9. S-parameter of proposed design

As shown in Figure 10, at a frequency of 6.25 GHz, the gain shows a significant increase, rising from 2.6 to 10.05 dBi. Figure 11 illustrates the 3D performance of the proposed system. The proposed system demonstrates the effectiveness of the FSS array, achieving a notable gain of 8.96 dBi at the resonance frequency.

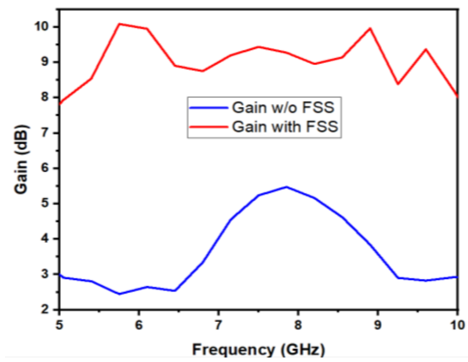


Figure 10. Gain variation vs frequency

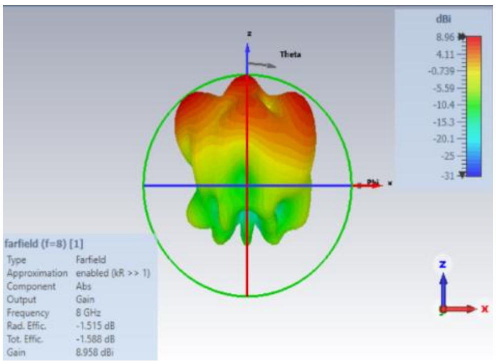


Figure 11. 3D simulated gain of proposed design

5. CONCLUSION

In this study, we designed and investigated an elliptical UWB antenna operating between 5.2 GHz and 10 GHz. To optimize its radio frequency performance, we combined this antenna with a 13×13 array of FSS elements. We then analyzed the impact of this integration on its fundamental characteristics, such as gain, directivity, and bandwidth. The resulting increase in antenna gain, from 2.6 to 10.05 dBi, demonstrates a significant improvement. These findings illustrate the effectiveness of FSS structures in enhancing antenna performance, improving radiation characteristics, and minimizing unwanted interference. In conclusion, UWB antennas incorporating an FSS structure appear to be a viable solution for wireless communication systems requiring high gain and stable performance.

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