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A Compact SWB Monopole Antenna and FSS for Gain Enhancement

Imran Khan
School of Information and Communication, Guilin University of Electronic Technology Guilin, China
imrannchu@outlook.com
Hongbing Qiu
Cognitive Radio and Information Processing Key Laboratory Authorized by China's Ministry of Education Foundation, Guilin University of Electronic Technology, Guilin, China,
qiuhb@guet.edu.cn
Saeed Ur Rahman
School of Electronic Engineering, Xidian University, Xi'an, Shaanxi, China
saeed@xidian.edu.cn
Habib Ullah
College of Electronics and Information Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing, China
habibtelecom209@gmail.com

ABSTRACT

In this research, a compact super-wideband monopole antenna is introduced. The antenna's electrical dimensions are 0.228λ × 0.144λ × 0.009λ, the λ represents the wavelength of the lowest operating frequency. The suggested antenna achieves a single operating band 10 dB between 2.8 and 40 GHz, a percentage bandwidth of 173.83%, and a BW ratio greater than 10:1. The suggested super wideband antenna has a large BDR of 5432.18 and a maximum gain of 6.6 dB. The antenna features a U-shaped radiating element and a rectangular, chamfered-cornered partial ground plane to attain super wideband characteristics. The antenna has been designed to be compact and flat in structure while still providing adequate gain and a broad range of frequencies, which makes it suitable for a variety of uses in contemporary wireless communication. To increase the antenna, gain for ultra-wideband applications, an FSS is developed. The FSS has a compact unit cell with physical dimensions of 18 x 18 mm^2. When the FSS is used as a substrate, the antenna reaches a maximum realized gain of 10 dB. Additionally, at UWB frequencies, a gain amendment of up to 4.61 dB is observed.

Keywords - **FSS, Enhanced gain, compact monopole antenna, SWB**

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I. INTRODUCTION

Over the past two decades, the popularity of ultra-wideband (UWB) antennas has increased due to the Federal Communications Commission (FCC) allocating the 3.1–10.6 GHz UWB band for commercial use in 2002 [1]. However, recent research has focused on developing super wideband (SWB) antennas to meet the demand for high-speed data transmission with low latency in modern and future wireless communication applications. SWB antennas can operate over a broader range of frequencies, including RF, microwave, and millimeter-wave spectrums, and they offer higher data rates, better spectral efficiency, and a greater transmission range than UWB antennas. It is anticipated that the development of SWB antennas will play a crucial role in shaping the future of wireless communication by providing reliable, high-speed, and low-latency connectivity for various applications.

A circular SWB (super wide band) antenna with an asymmetrical dipole, which has a size of 135 × 90 mm^2 and can cover the frequency band of 0.8 GHz - 17.46 GHz is reported in [2]. Super wideband antenna with a size of 130 × 120 mm^2 is proposed in [3]. This antenna provides polarization diversity and operates in two frequency bands, namely 0.86 GHz - 30 GHz and 1.04 GHz - 27.2 GHz, at dual ports. A compact SWB antenna with a size of 23 × 12.5 mm^2, which covers a frequency range of 2.89 GHz - 60 GHz is proposed in [4]. A fractal antenna with a size of 80 × 60 mm2 is proposed [5]. This antenna is designed to be suitable for wireless body area networks and operates in the frequency range of 1.4–20 GHz. In [6] a trapezoid shape monopole antenna with a size of 57 × 34 mm^2, which covers the frequency spectrum of 1.42 GHz - 90 GHz is reported. A compact UWB (short for "ultra-wide band") rounded antenna with a total dimension of 35 × 30 mm^2 is proposed in [7]. This antenna covers the frequency spectrum of 3.1 GHz - 20 GHz. A compact SWB antenna having single band suppression that covers the frequency spectrum of 2.89 - 60 GHz is suggested in [8]. A compact patch antenna with slots to create three band-notches, improving the overall bandwidth for SWB applications in the range of 2.6 – 23 GHz, is presented in [9]. The article [10] provides a description of a miniature

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SWB antenna that is powered by a CPW. The dimensions of the antenna are 140 × 100 mm². In [11], a tree-shaped elliptical monopole antenna is discussed. The antenna has three iterations and the ground plane has been changed to be semi-elliptical. It is quite small, measuring 170 × 150 mm^2, however, its impedance bandwidth ranges from 0.65 - 35.61, which is very good. The antenna's average gain is 3.24 dB, while its peak realised gain is 6.51 dB. Between the ground plane and the radiator, a gap is made in [12] so that SWB characteristics can be generated at frequencies spanning from 2.5 - 110 GHz.

A circular ring that is microstrip-fed, has four elliptical spokes, and a central disc, as well as a notch-loaded rectangular partial ground is reported in [13]. The designed antenna has a high bandwidth of 2.3 - 34.8 GHz with good radiation properties, and the antenna has a miniature overall size of 35 × 35 × 1.6 mm^3 with a high dimension ratio. A CPW- fed super wideband antenna is discussed in [14]. The antenna is made up of two different-shaped ground planes and a vertical patch that looks like a modified bow tie. It measures 24.5 × 20 mm^2 and operates across a wide frequency band of 3.035 – 17.39 GHz (140.56%). Its radiation patterns are nearly omnidirectional, and an average gain of 4.56 dBi, along with an average efficiency of 76.62%.

A small SWB monopole antenna is proposed in [15] that covers a wide frequency range of 0.7 – 18.5 GHz, which includes both the low and high-frequency bands. An ultra-wideband antenna is proposed in [16] that performs in the frequency spectrum of 2.68 – 8.72 GHz. Since the antennas described in [2, 3, 5, 10, and 12] were cumbersome, most portable wireless applications were not appropriate for such designs. There were also other miniature antenna designs that were suggested [4, 7, 9, 13, 16], although these antennas had a very small bandwidth. To boost radiation in the desired direction, one potential option is to employ reflecting surfaces that can reflect back the waves that are being radiated in the direction of propagation on the broadside. Due to a design constraint that prevents the separation between the antenna and reflector in the super wideband range from being fixed at one fourth of the wavelength, metallic reflectors are avoided.

With a high gain antenna, EM signals can be effectively transmitted and received, which makes the gain of the antenna a vital necessity in wireless communication. To address this, numerous gain enhancement technologies have been presented in the literature, with AMC [17–20], Metamaterial [21–22], and FSS [23–30] being the three main ones. Metamaterial approaches are depending on the permittivity and permeability of the material to improve gain, while the use of AMC and FSS techniques helps manage the grating lobes produced by the antenna, redirects the radiation in specific directions, and enhances the overall antenna gain. The application of Artificial Magnetic Conductor technology is featured in a multi-band antenna in [17], with the reflection phase angle being the key factor in determining the enhancement of gain. A rectangular loop fractal Artificial Magnetic Conductor is placed parallel to the ground plane in a wideband antenna to achieve gain improvement, as described in [18]. In [19], a modified circular loop AMC is installed as a reflector in a CPW antenna to enhance its gain. In [20], an ultra-wideband (UWB) monopole antenna with increased radiation in the 2.4 GHz to11.2 GHz band was proposed through its integration to a circular cross slot artificial magnetic conductor. According to [21], a metamaterial unit cell positioned diagonally in the ground plane improves the dual-band antenna's gain. The gain of the antenna is amended in [22] through the use of two hexagonal metamaterial cells positioned behind it that possess metamaterial properties that are double-negative. For the antenna functioning in the sub-6 GHz frequency, a single layer FSS with a modified loop structure is developed in [23]. [24] employs a frequency-selective surface (FSS) consisting of four non-uniform rectangular conducting components having a circular slit in one unit cell to create a ultra-wideband antenna. In [25], which describes how a dual-layer FSS was made, the goal is to improve gain in the ISM band. With an FSS arrangement, the gain of umbrella-shaped antennas can be increased by up to 4 dB, as shown in [26], which describes the development of a two-layer FSS with an air space between the arrays. According to [27], stopband characteristics are shown across the whole working band when frequency selective surface is achieved with four connected square loop metallic paths. In [28], a thin FSS is constructed with two layers, the top of which is cross-shaped and the bottom of which is circular. An UWB with an FSS designed to for frequency rage of 3.16 to 15 GHz spectrum, as reported in [29]. The antenna has been designed to achieve a high gain of 4.9 -10.9 dB across the frequency range. The use of the frequency selective surface has augmented the gain of the antenna. An UWB strawberry-shaped artistic-shaped antenna having dimensions of 61mm x 61mm x 1.6mm and a FSS to improve its gain was reported in [30]. The suggested antenna has a wide impedance bandwidth of 8.85 GHz, and the FSS reflector improves the gain by 6.22 dB. [31] employs a dielectric superstrate to boost gain, with the effective permittivity being adjusted by altering the radius of the superstrate's slots. In addition, many antennas with notch characteristics are described in [32-36] for use in ultra-wideband and super wideband applications.

The article describes an frequency selective surface that has an ultra-wide stop band and is comprised of a single layer. The unit cell of the frequency selective surface has a simple and compact geometry, with a physical size of 18 mm x 18 mm^2. The suggested FSS is adequate for UWB applications due to its excellent stop band characteristics, despite being single-layered and compact in size. Furthermore, when utilized as a reflector, the designed FSS provides a considerable gain improvement of up to 4.61 dB.

II. DESIGN OF SWB ANTENNA

A novel antenna has been proposed for use with the F4B substrate, which has a dielectric constant of 2.65 and a tan δ value of 0.002. The substrate is 1mm thick, and the copper metallization layer is 0.035mm thick. The antenna's dimensions are 14mm x 25mm x 1mm. The evolution of the antenna from its original reference design can be observed in Figures 1 (a–c), with the final structure depicted in Figure 1 (c) along with the dimensions. The simulated impedance bandwidth of the suggested antenna is revealed in Figure 2.

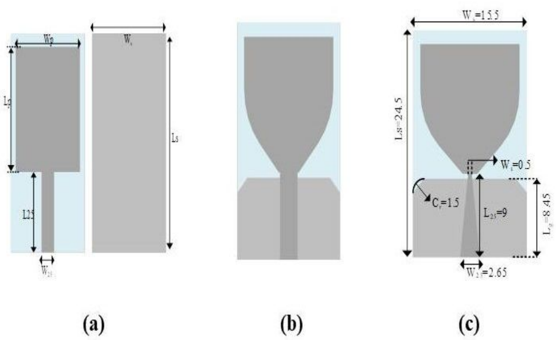


Fig. 1. Suggested Antenna Design Steps (a-c)

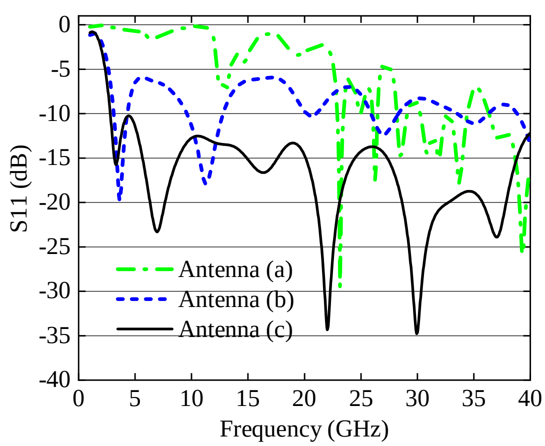


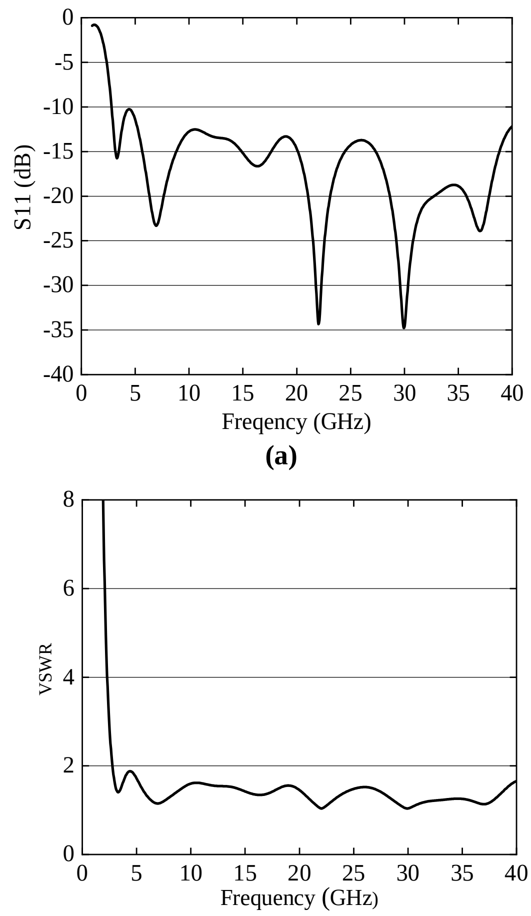
Fig. 2. Suggested Antenna S-parameters

To design the antenna, initially a rectangular element (W_p, L_p), full ground plane (W_s, L_s) and rectangular shape feed line with length (L_{25}) and width (W_{25}) is taken as illustrate in Figure 1 (a). The operation of a suggested antenna with a rectangular shape radiator and full ground was degraded, as represented in Figure 2, therefore the rectangular shape radiator is modified to U shape and also the full ground plane is modified to chamfered cornered partial ground plane (L_g). By modifying the radiating part and ground plane the bandwidth performance has improved as depicted in Figure 1 (b), but the antenna's operations remain unsatisfactory. Finally, to attain the SWB characteristics and the required impedance bandwidth the width (W_{25}) of the feed line have been transformed to tapered feed having width (W_t) and is optimized to achieve 50-Ω impedance as illustrated in Figure 1 (c). The antenna was developed and its performance was simulated utilizing the CST Microwave Studio software.

III. Analysis of Antenna Characteristics

The functionality of the SWB antenna was evaluated through simulations using the 2019 version of the CST Microwave Studio software suite.

The simulated reflection coefficients along with the VSWR features of the suggested antenna are revealed in Figure 3 (a) and Figure 3 (b). It reveals 173.8% fractional band and high BDR of 5432.18.



(b)

Fig. 3. Suggested Antenna (a) S11, (b) VSWR

The U-shaped antenna's performance is outlined in Figure 4, showcasing its behavior across several resonance frequencies: 5, 10, 15, and 25 GHz. The Figures 4 (a-d) exhibits the distributed current of the antenna, which represents how the electrical current flows along the antenna's radiating elements. The U-shaped antenna has a uniform distribution of current along the U-shaped radiating element and the feed line, which means that the current flows evenly throughout the antenna. However, the current distribution peaks at the outer ends of the radiator and is lower towards the center, which suggests that the radiation is evenly spread out across the entire operating range. This suggests that the antenna is efficient at radiating electromagnetic energy, as the current is concentrated at the antenna's edges, where it is most

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effective in radiating. The construction of an extremely wideband antennas requires careful consideration of the overlapping of adjacent modes. Figure 4 (a-d) demonstrates that an increase in the operating frequency leads to an increase in the total number of resonances, which means that the antenna has multiple resonant frequencies where it can efficiently radiate energy. This information is essential for designing antennas that can operate effectively over a wide range of frequencies.

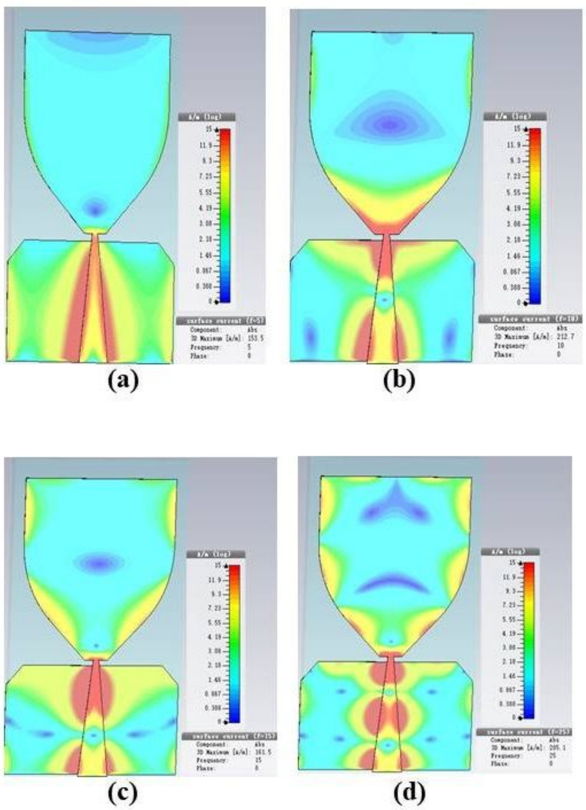

Fig. 4. Suggested Antenna Current distribution

Figure 5 shows the simulated radiation efficiency and total efficiency which is larger than 94% across the whole operation frequency band

Figure 6 depicts the correlation between the real and imaginary components of the input impedance. The real part is represented by thick lines, whereas the imaginary part is shown as dotted lines.

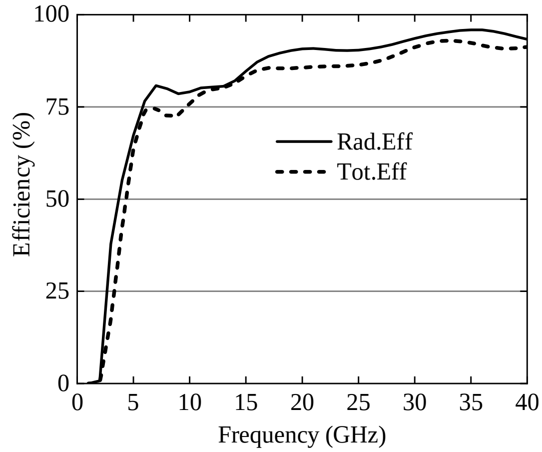

Fig. 5. Suggested Antenna Rad. And Tot. Efficiency

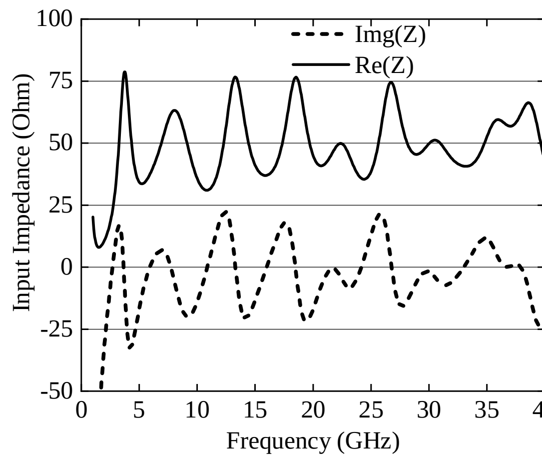

Fig. 6. Suggested Antenna Input Impedance

The real part oscillates around 50 ohms across all resonant frequencies, whereas the imaginary part stays around 0 ohms. This indicates that the antenna has a typical input impedance of 50 ohms and functions well in the super wideband region, as calculated in this way. Essentially, this means that the antenna matches well with the transmission line, which leads to efficient power transfer from the transmitter to the antenna, and that the antenna performs well in the frequency range of interest.

Figure 7 displays the results of a study on co-polarization and cross-polarization in both E-plane and H plane at 10 GHz, 20 GHz, 30 GHz, and 40 GHz. The antenna has omnidirectional radiation in both planes, but cross polarization is sometimes higher due to the hybrid mode.

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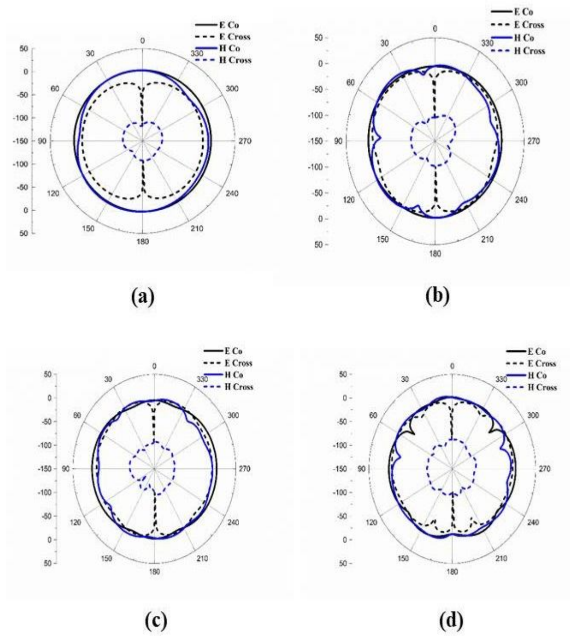

Fig. 7. Suggested Antenna Co and cross polarization at 10, 20, 30 and 40 GHz

IV. DEVELOPING AND ANALYZING AN FSS

The FSS that is being suggested is intended to be used for UWB frequency applications, in which the FSS superstrate will be placed below the antenna. Once the reflection of electromagnetic waves from the frequency selective surface substrate and the emission of the antenna are in the same direction, then the gain enhancement in the antenna can be raised to its greatest potential. The FSS unit cell has the shape of a circular ring with stubs and is optimized for frequencies between 5.5 and 12.5 GHz. The development of the FSS and its analysis are going to be covered below.

V. FSS DESIGN

The behavior of a frequency-selective surface (FSS) is totally determined by the layout of the unit cell that makes up the surface of the cell. An FSS consisting of a circular ring with stubs is developed to achieve stopband characteristics at the UBW frequency. The layout of the FSS unit cell that has been proposed is depicted Figure 8 (a, b) along with dimensions. The FSS is made on a low-cost dielectric substrate known as F4B. This substrate has a height of 1.5 millimeter, a relative permittivity of 2.65, and a loss tangent of 0.002.

The suggested FSS unit cell is made from a circular ring with stubs on both sides of the F4B substrate. The unit cell has a total physical dimension of 18 mm by 18 mm. Repeating the unit cell through the x and the y-axis results in the construction of an array with 49 elements (7 x 7), as depicted in Figure 9. In order for the FSS to be able to reflect back radiation produced by the antenna, it is positioned beneath it. If the waves that bounce off the frequency-selective surface have the same phase as the waves emitted

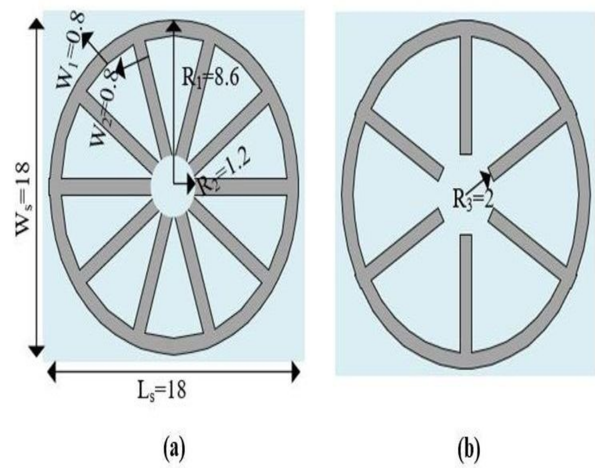

Fig. 8. (a) FSS Top Layer (b) FSS Bottom Layer

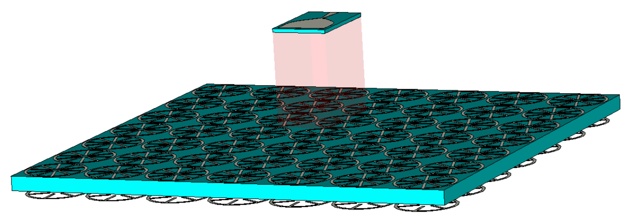

Fig. 9. Proposed antenna with FSS

by the antenna at the antenna plane, it will lead to an improvement in the front-to-back ratio and directivity of the antenna. As the frequency of the signal increases, the phase of the waves projected by the antenna toward the frequency selective surface becomes more advanced. In order to ensure that there is constructive interference at the antenna plane, the phase of the reflected waves needs to become more phase-retarded as the frequency increases.

Figure 10 displays the reflection coefficient, the transmission coefficient and reflection phase of the frequency selective surface. The proposed FSS is capable of transmitting electromagnetic energy below -10 dB within the 5.5–12.5 GHz frequency range. Moreover, the reflection coefficient, or S11 level, remains almost 0 dB across the entire frequency band, as illustrated in Figure 10. Therefore, the single-layer FSS functions as an efficient reflector across a wide bandwidth. The computed reflection phase of the FSS decreases linearly with frequency. The linearity of the reflection phase of the suggested FSS is satisfied across the entire band from 5.5 to 12.5 GHz. This special feature extends the recommend application of our suggested FSS to include a variety of systems where a linearity decreasing phase is required

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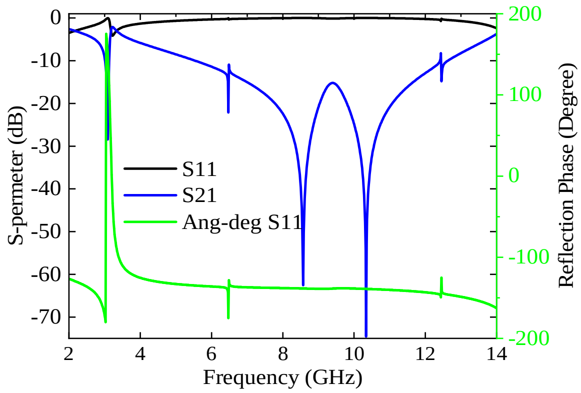


Fig. 10. FSS Transmission and reflection coefficients

VI. FSS DESIGN

The space between the FSS substrate and the antenna is the most important factor in getting more gain. Equation (1), which is shown below, can be used to figure out this distance.

$$\varphi FSS - 2KF_d = 2N\pi \quad (1)$$

In the equation, the variables F_d, which represents the distance between the antenna and the FSS, and K, which is a constant equal to 2π divided by the wavelength (λ). The value of N can be selected as any integer.

The impact of the separation distance between the antenna and the frequency selective surface on the highest gain of the antenna is investigated and exhibited in Figure 11. In the analysis, the location of the FSS is modified between λ and λ/4, with respect to the center frequency i.e., 8.9 GHz of the proposed operating UWB frequency range. Figure 11 illustrates the highest gain of the antenna with an FSS substrate at varying locations, with the most significant gain enhancement at a separation distance of λ/2. Additionally, it is noticed from Figure 11 that the antenna with FSS substrate attains better impedance matching at a separation distance of λ/2, with S-parameter below -10 dB over the entire frequency band. Thus, an optimum distance of λ/2 is concluded between the frequency selective surface substrate and the antenna. Figure 12 depicts the peak gain of the proposed antenna with and without FSS at different frequencies. The average gain of the antenna in the UWB spectrum was 2.55 dB. When an FSS substrate is positioned under the antenna, the average gain of the suggested antenna in the UWB spectrum is increased to 7.16 dB. In other words, there is a gain amendment of 4.61 dB due to the application of the FSS. The maximum gain of 10 dB for the composite antenna is accomplished at 10 GHz. The utilization of FSS significantly enhances the gain of the antenna. Table 1 relates the gain improvement using the single-layer frequency selective surface substrate to the currently available technology.

TABLE I. SUGGESTED ANTENNA GAIN ENHANCEMENT TECHNOLOGY COMPARISON WITH EXISISTING WORKS

Reference No.	Dimensions (mm^2)	Frequency: range (GHz)	Technique used	Gain Enhancement (dB)
18	64 × 64	3.36 – 9.09	AMC	3.58
19	70 × 70	1.9 – 6.95	AMC	3.06
20	16 × 22	2.4 – 11.2	AMC	3.5
22	38 × 38	2.4 – 5.82	Metamaterial	3.69
23	35 × 25	5.6 – 10.3	Metamaterial	3.2
24	30 × 30	3.6 – 6.1	FSS	4.0
25	20 × 27	4.7 – 14.9	FSS	4.5
26	63.65 × 51.16	3.1 – 10.6	FSS	4.3
27	35 × 30	3.0 – 13.4	FSS	4
28	40 × 30	8.1 – 13.2	FSS	3.3
Our work	15.5 × 24.5	5.4 – 12.5	FSS	4.61

Figure 13 displays the results of a study on 3-D radiation pattern at the center frequency of the suggested FSS within UWB spectrum. From the Figure 13 it can be seen that with the use of FSS the backward radiation become reduces and the gain of the is increased in the propagation direction.

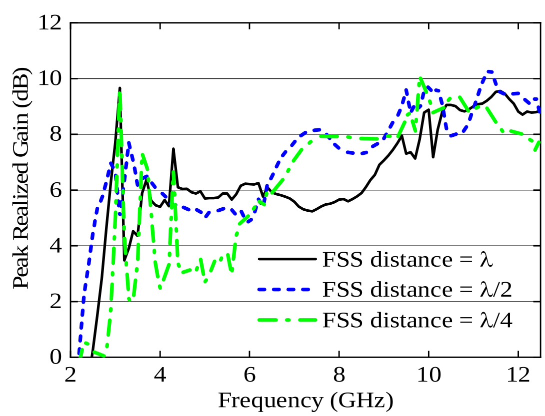


Fig. 11. Realized gain of the suggested antenna at different distance from the FSS

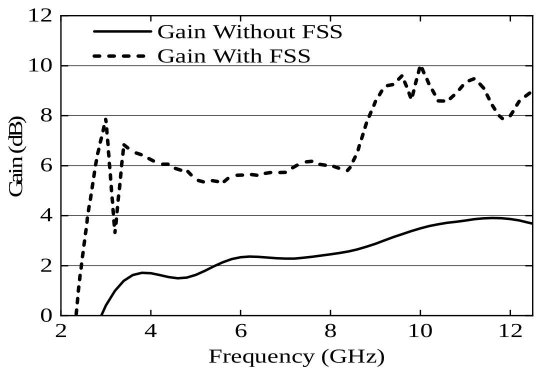
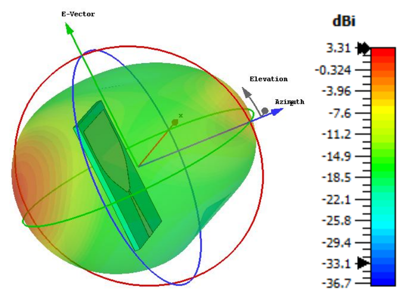
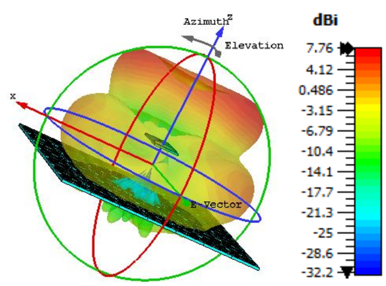


Fig. 12 Suggested antenna Gain with and Without FSS.



(a)



(b)

Fig. 13 3-D Radiation (a) without loaded FSS and (b) with loaded FSS of the proposed antenna at center frequency

VII. CONCLUSION

The article describes a miniature U-shaped super wideband monopole antenna that integrates with reflective frequency layer surface layer at an optimum λ/2 air gap, resulting in a consistent higher gain profile. The U-shaped radiator enhances the operating bandwidth, and the chamfered cornered defected ground improves the antenna's impedance matching. The high BDR of the proposed SWB antenna confirms its compactness. The antenna has a single-layer FSS substrate beneath it, which is reflecting the grating lobes and boosts the antenna's gain up to 4.61 dB. By adding this FSS, the antenna's average gain in the UWB range goes from 2.55 dB to 7.16 dB. The maximum gain achieved by the suggested design is 10 dB.

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