IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received 22 April 2024, accepted 10 May 2024, date of publication 21 May 2024, date of current version 31 May 2024.

Digital Object Identifier 10.1109/ACCESS.2024.3403719

RESEARCH ARTICLE

A Split Center Resonator FSS-Based Gain Enhancement of CPW Feed UWB Antenna for High Gain UWB Communication

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ABSTRACT In this manuscript, gain improvement is observed for an ultra-wideband (UWB) antenna. The proposed arrangement is optimally designed for high gain wideband communications. This arrangement comprises a low profile and easily circuit integrated antenna covering spectrum ranges from 3.1 GHz to 10.6 GHz for low power UWB communications. Extended impedance improvement is also achieved by employing a co-planar waveguide (CPW) feeding mechanism incorporating a castle shaped profile and wider radiation element. Moreover, a periodic structure based single layered frequency selective surface (FSS) for gain improvement is also suggested. This split center resonator (SCR) FSS is designed and employed owing to a smaller footprint and stable performance. The performance of this antenna-FSS arrangement is analyzed by varying the inter-element spacing of SCR, distance between SCR layer and the proposed CPW fed antenna. The simulations and measurements validate at least 5 dBi of gain improvement while offering wideband impedance matching and stable radiation performance. This improved performance and low-profile design makes the proposed arrangement suitable for modern high gain UWB communication services.

INDEX TERMS Ultra-wideband (UWB), frequency selective surface (FSS), periodic structure, split center resonator (SCR), co-planar waveguide (CPW) feed, gain.

I. INTRODUCTION

UWB is a wireless communication technology that allows for high bandwidth connections with limited energy usage. UWB is a short range communication that provides rapid data transmission with stability. The first UWB designed for military purposes. After the FCC (Federal Communication Commission) approved the commercial use of UWB bandwidth in 2002, it was made available to the public. The organization also approved the usage of the Ultra wide band spectrum bands of 3.06 GHz and 10.9 GHz [1]. Mostly, UWB antenna with very high demand in applications includes GPR (Ground Penetrating Radar), (Microwave Imaging Detection System) and space environments [2]. To improve the detection depth

The associate editor coordinating the review of this manuscript and approving it for publication was Debabrata K. Karmokar.

and accuracy, UWB antennas with high gain and directivity are necessary. CPW-fed antennas may readily achieve wideband impedance matching in comparison to probe-fed and micro strip-fed antennas [3], [4]. It is one of the major techniques in developing UWB antennas for sensing system and radar sensors [5], [6]. These systems are currently profitable for the construction and mineral exploration industries [7].

Since the 1960s, Frequency selective surfaces (FSS) have been the subject of general research. An FSS is used to selectively absorb, redirect, and transmit electromagnetic (EM) waves [8]. These surfaces can be viewed of as spatial filters although they can allow to a specific frequency band across the whole electromagnetic spectrum. Additionally, it serves as EM wave band pass/band stop filters and promotes effective frequency spectrum use [9]. FSS are two-dimensional periodic structures that include frequency and polarization selection characteristics for electromagnetic waves and are made up of metal patches or apertures on metal screens [10]. Meta-materials (MTMs) and meta-surfaces (MSs) based constructions have lately been investigated in this context [11], [12]. The two most identified configurations for FSSs are single-layer and multi-layer. An optimally constructed periodic structure particularly an FSS structure may be able to enhance a UWB antenna's characteristics [13], [14].

A number of such feature enhancement antenna-FSS configurations are reported in recent literature. In [15], A twin FSS layer with a 10.35 GHz band in the 3.05 GHz–13.4 GHz range and a gain boost of 2 dB–4 dB is detailed. The design is bulky, the gain fluctuation in the UWB band is observed, and the complexity of the FSS reflector has increased. In earlier study, three-, four-, and five-layer FSSs designs were demonstrated respectively. Due to their construction, complexity, and high cost, multi-layer FSSs offer UWB response but have partial real-world application in modern communication devices. In [16], A UWB response is obtained covering the band 4.05 – 14.12 GHz, for vertical polarization and 5.05 – 15.00 GHz band, for horizontal polarization. This design also used three-layered FSS configurations to achieve bandwidth enhancement feature. However, stacking architecture notably increases antenna-FSS dimension and computational overhead. Hence multi-layered FSS raises economic concerns to provide wide frequency spectrum and maintaining a consistent gain across the band [17].

Single-layer Frequency Selective Surface can easily be incorporated into communications and electronics devices [18]. Recently, certain single-layer reflectors with UWB-FSS technology are made to provide consistent gain in ultra- wideband frequencies. For UWB applications, a single FSS layer is intended to offer an ultra-wide stopband filter response [19]. In a recent work, Mellita [19] printed on both sides of a single FR-4 dielectric sheet and designed a miniature FSS. The reported FSS, which had an FSS unit size of 12 × 12 × 1.6 mm, was successful in producing a stopband response over the frequency range of 1.01 to 9.84 GHz. The designed FSS is a good option for band stop filtering applications because of its low cost, ease of manufacture and integration. As a result, it can be used to demonstrate effective performance and anti-interference capabilities in future 6G communication [20]. The reported antenna in [18] attained an peak gain of 9.6 dB with a gain increase of 6.2 dB after loading the FSS reflector. The FSS is developed similarly to the square loop construction. A single-layer FSS with a operating frequency of 8.5 GHz for bandwidth ranging from 2.5 to 11 GHz and a gain measurement of 1 dB is presented in [21]. The Rogers RO4350B, relatively a costly material, is used to create the proposed antenna. In [22], the antenna with a novel design of a curved single layer of FSS showed gain enhancement of 8.8–14.9 dB. The reported antenna can be used in 5G and 6G communication applications with a surface-mountable nature, achieving improvement of 12-22% [23]. Consequently, the primary advantage of the reported antenna with reflector is that, it is a cost-effective solution to enhance the gain [24].

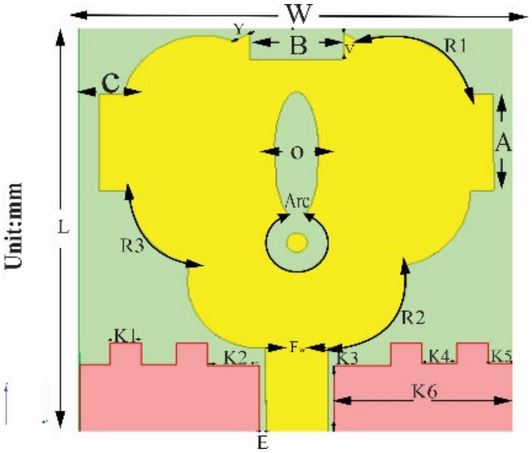


FIGURE 1. CPW fed UWB antenna.

This research emphasis on a new single-layer FSS loaded Coplanar waveguide (CPW) UWB antenna with increased gain. Due to their appealing qualities such compact dimension, ease of manufacturing, light weight, and ease of integration with wireless systems, CPW-fed antennas are frequently utilized and are now growing in popularity in wireless application. A single layered FSS for gain improvement having split center resonator (SCR) FSS is also designed. The proposed antenna-FSS offers least 5 dBi of gain improvement on average while offering wideband impedance matching and stable radiation performance.

The rest of the manuscript is organized as follows. Design arrangement for both antenna and FSS are discussed in section II. Section III details simulations and optimizations of the proposed arrangement, surface current distributions and circuit model analysis of pro-posed FSS. Measured performance of the proposed design is presented in section IV. Section V comprehensively compares the performance of this design with existing literature and finally section 6 concludes this research.

II. DESIGN ARRANGEMENT

A. DESIGNING OF UWB ANTENNA

Fig. 1 illustrates the geometry of the proposed CPW-fed UWB antenna which has an overall physical size of 21mm × 21 mm × 1.6 mm. The employed FR-4 substrate for the modeling has a loss tangent (tan) of 0.035 and a dielectric constant of 4.5. The design patterns, as shown in Fig. 2, demonstrate how the UWB patch developed in relation to the geometry in Fig. 1.

In step no 1, a conventional patch antenna is designed by using basic patch antenna design equations having resonant frequency 6.5 GHz. The radiation element is then beveled with a notch over the top. It is developed to achieve impedance matching over the lower frequencies. The antenna is fed by a coplanar waveguide (CPW) of 50 Ohm by placing two copper plates beside the feed. The S_{11} response is above -10dB for higher frequencies and resonance is observed.

The notch length over the radiation element is decreased and added castle shaped profile on the ground plane. In step no 2, These modifications lead to impedance matching over middle to higher frequency band. However, S_{11} is still above the -10 dB over the majority of the required band.

In step no 3, width of radiator is extended by adding two rectangular strips on both sides of the patch. This bandwidth enhancement mechanism not only improved the impedance bandwidth over the lower band but also improves design profile. To further balance out the spectrum, an increase in the width castle profile is also observed.

An ellipse in combination with and circular resonator is added in the radiation patch in step 4. This resonating structure introduces a sharp resonance over 4 GHz and makes initial band impedance matched. This achieves complete impedance matching over higher band by increasing the size of ground plane (K_6) on both sides.

In step no 5, the careful optimization of the center ellipse size also improves the middle frequency region. Finally, the UWB spectrum responses shows the desired impedance bandwidth having S_{11} well below the -10dB.

B. FSS DESIGN CONFIGURATION

The proposed FSS is printed using FR-4 material as well. The design was chosen to be a loop owing to their ease of integration with communication devices. Fig. 4 illustrates a design process of the proposed FSS, which is summarized over the course of five design steps. The unit cell simulations are performed by deploying periodic boundary conditions as depicted in Fig. 3.

The proposed FSS is set to designed at 7.5 GHz owing to center frequency of the proposed UWB antenna. To further achieve this resonant response, double inverted M shaped Metallic patches are then included in the modelled unit cell, and they are connected to square loop that achieves the stop band at 9.3 GHz with relatively larger dimensions and reduced transmission coefficient (S_{21}) and reflection coefficient (S_{11}) is observed on higher frequencies. The aperture of inverted M is now further enhanced to tune the resonance over lower frequencies 8.9 GHz and reduces the overall size.

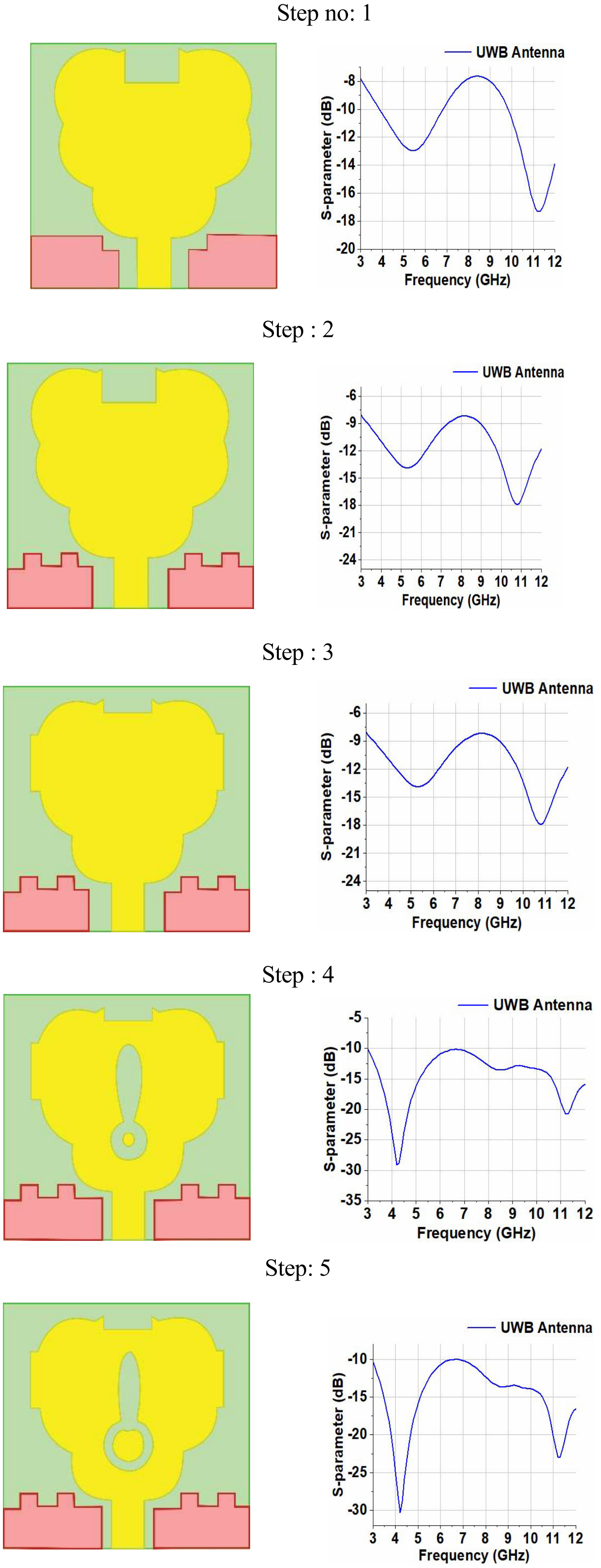
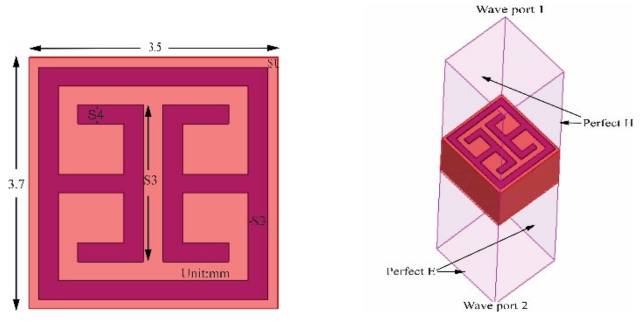


FIGURE 2. Step by step antenna formation from step 1-5.



(a) (b)

FIGURE 3. The SCR design (a) Unit element (b) periodic simulation setup.

Due to the inverse relationship between the aperture of the Inverted M*s* and loop size, the outer edges of the M*s* are made flat and further increased. The resonance dropped to 8.4 GHz with a reduction in overall size of the unit cell i.e. 3.8 mm × 3.8 mm.

Finally, these modified Inverted M*s* are transformed into split center regions to effectively trap the surface currents and produce dual resonant including stopband response at 7.5 GHz and pass band reflection coefficient (S_{11}) at 8.7 GHz. This splits center region also reduces the overall unit element size to 3.5 mm × 3.7 mm.

III. SIMULATIONS AND ARRANGEMENT

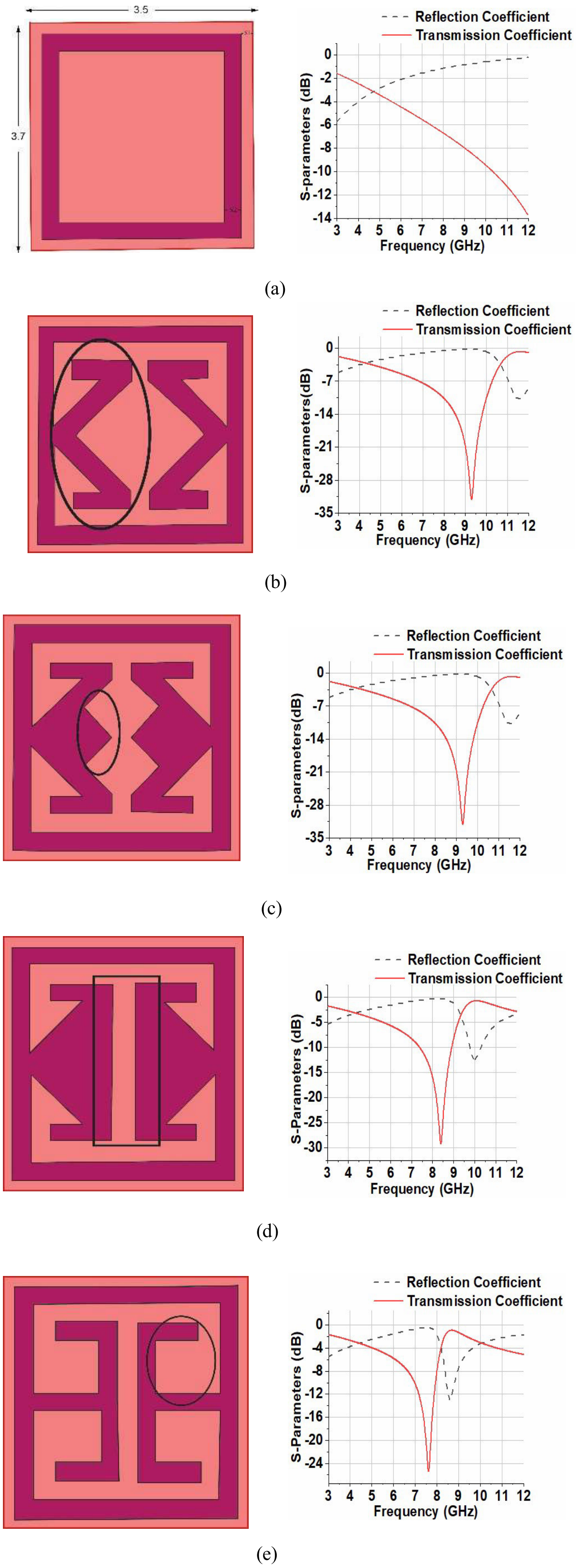
The proposed FSS based reflecting layer consists of an array of SCRs arranged in a rectangular grid with periodicity P and inter-element spacing X as shown in Fig. 5 (a). The overall array size of this layer is 6 × 6 cells. The gain enhancement is achieved from the electromagnetic coupling or cavity effect initiated between the SCR layer and radiating patch. The cavity distance is selected according to the ray theory [25].

$$d = \frac{c}{2f}\left[\frac{\varphi}{2\pi} - 0.5\right] + N$$

The return loss and gain of the proposed arrangement are examined for a range of inter-element spacing X and distance d.

The proposed CPW fed antenna provides improved performance when partial grounding and an SCR-based reflector are used together. Impedance matching is improved with partial grounds, which is essential for reducing reflections and optimizing power transfer from the feed line to the antenna. They may also reduce surface waves, which minimizes losses and raises the radiation efficiency of the antenna. Moreover, by reflecting the emitted energy in a particular direction, the SCR reflector also improves the signal and raises the antenna's gain. Additionally, by serving as a resonant structure that can support several frequencies, it can increase bandwidth as well [26].

Combining these two methods produced a synergistic effect in which the SCR reflector improves gain and bandwidth while the partial grounds offer a stable base with better impedance matching. Applications needing high efficiency in small antenna designs will especially benefit from this combination.



(a)

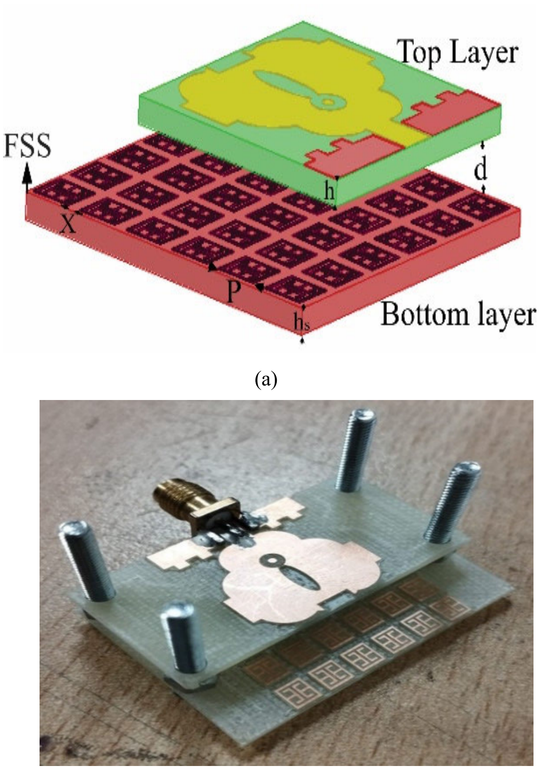
(b)

(c)

(d)

(e)

FIGURE 4. Design process of the SCR-FSS.



(a)

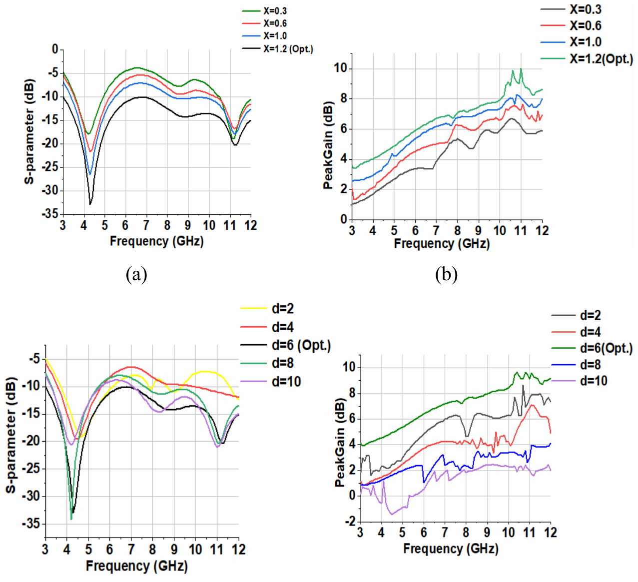
(b)

FIGURE 5. **(a) A simulated 3D picture of the planned antenna- FSS setup; (b) fabricated view.**

As X increases from 0.3 mm to 1.2 mm, impedance matching decline at inter-mediate frequencies. Additionally, enhanced Gain is observed even at higher Xvalues. Based on the optimized outcomes, 1.2 mm is chosen as the ideal value for X of the designed reflecting layer. As the distance d between the antenna and the superstrate decreases, the impedance match in the lower and intermediate frequency bands decreases, as shown in Fig. 6 (c). However, increasing the distance improves both the impedance match and the gain in addition to both. At 10 mm and 5 mm, the gain at lower frequency is slightly better, but overall, a significant gain drop is seen throughout the rest of the spectrum, as shown in Fig. 6 (d). The ideal distance, d is chosen to be 6 mm to maintain better gain while enhancing impedance match.

A. SURFACE CURRENT DISTRIBUTION

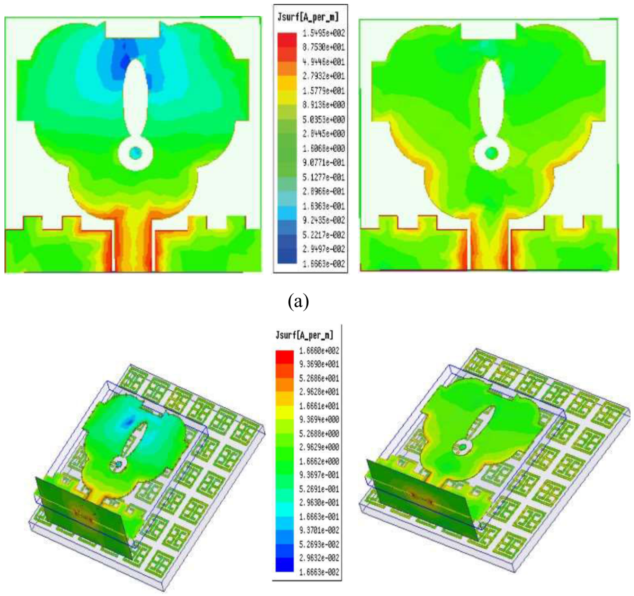
Fig. 7(a) and 7(b) show the surface current distributions at 5 GHz and 9 GHz for the designed UWB antenna for both with and without an FSS Reflector. The distributions show that the feed line and ground plane corners have more saturated current. These designs are targeted to enable fundamental resonating modes and better impedance matching for the middle and higher frequency bands. Moreover, the antenna-FSS combination results in a uniformly distributed surface current.



(a) (b)

(c) (d)

FIGURE 6. **Antenna simulations for various values of (a) X while d = 6 mm and (b) d while $X = 1.2$ mm show the return loss and gain.**



(a)

(b)

FIGURE 7. **Shows the simulated surface current distribution at 5 GHz (left) and 9 GHz (right) in the following configurations: (a) without FSS reflector (b) with FSS reflector.**

B. CIRCUIT MODEL ANALYSIS

The equivalent circuit (EC) was created and simulated using the Advanced Design System (ADS) [27]. The FSS unit cell arrangement served as the foundation for the EC, which provides combinations of inductance (L) and capacitance (C) in the comparable circuit as shown in Fig.8. Fig. 8 illustrates the circuit model of the square loop as a series LC circuit, where L denotes the inductance produced by the vertical metallic conductor and C denotes the capacitors between both

TABLE 1. Antenna specifications.

Variables	Optimized value (mm)	Variables	Optimized value (mm)
L	21	K3	3.4
W	21	K4	1.7
A	5	K5	1.3
B	4.5	K6	8.7
C	1.11	E	0.3
V	1.37	Fw	3
O	2.13	S1	0.15
Arc	2.94	S2	0.3
Y	0.70	S3	2.5
*R*1	2.3	S4	0.3
R2	2.93	Hs	1.6
R3	2.09	H	1.6
K1	1.5	d	6
K2	2.5		

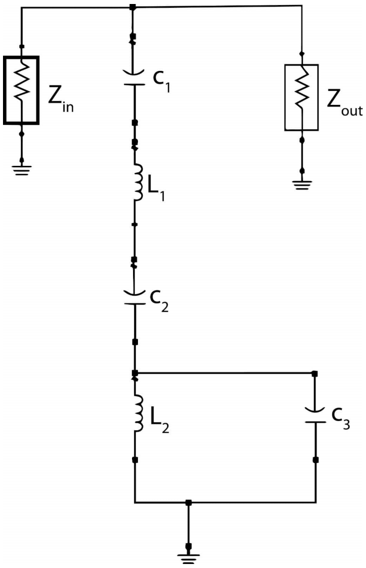


FIGURE 8. Equivalent circuit model.

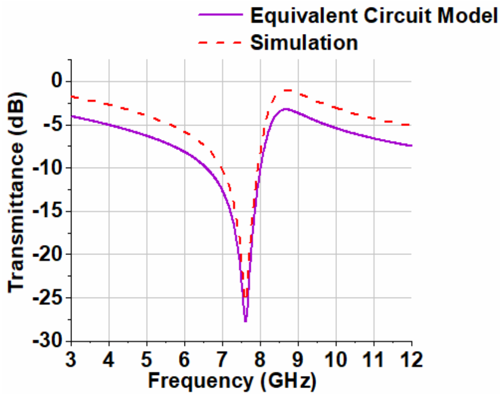


FIGURE 9. Transmission coefficient (S_{21}) of SCR.

TABLE 2. Equivalent circuit parameters.

C_1	C_2	C_3	L_1	L_2
0.199 pF	1.0 pF	0.1179 pF	2.6097 nH	0.01 nH

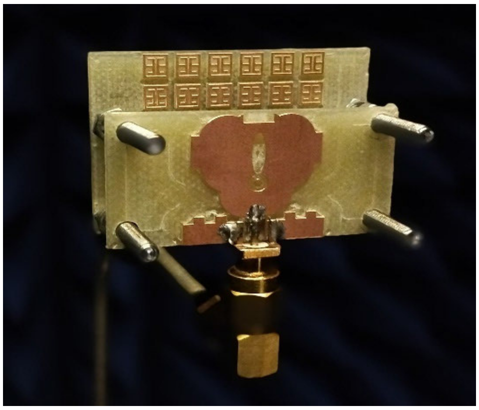


FIGURE 10. Fabricated prototype of the single-layer FSS reflector ultra-wide band antenna.

the horizontal conductors. The inductive effect is formed due to current flow on metal, while the gaps contribute to the capacitance.

The circuit model of the proposed SCR is initially inspired by loop-based band stop FSS then is further developed where the splits in the ring create capacitance and the ring itself produces inductance due to its magnetic properties [28]. LC circuit parameters can be used to approximate the resonance frequency of the SCR. Overall, the equivalent circuit model facilitated rapid prototyping and optimization of SCR employed UWB antennas by understanding its the electrical behavior. The design methodology is expressed as follows;

The SCR is modeled by making a series arrangement of $L_1$and C_1 while parallel combination is employed between $L_2$and C_3. This circuit arrangement achieves band-stop behavior at 7.6 GHz as shown in Fig. 9. Further, the capacitor C_2 is arranged in series with and L_2 to achieve band-stop sharp band stop response and are in good agreement with simulations. Finalized EC for the FSS is illustrated in Fig. 4. The impedance for the SCR is derived in (1) having lumped parameters evaluated in Table 2.

$$Z_{SCR} = (j\omega(L_1 + L_2) + 1) + \left(\frac{j\omega L_2}{1 + j^2\omega^2 L_2 C_3}\right) \quad (1)$$

C. FABRICATIONS AND MEASUREMENTS

To determine the real-world performance of the proposed antenna with a splits Center resonator, this work has validated the simulations by fabricating and measuring of the proposed antenna-FSS arrangement on FR-4 laminate as shown in Fig. 10. The scattering and radiation performance is evaluated by Agilent PNA N5242A network analyzer. Due to manufacturing tolerances and construction errors, there are slight differences between the simulations and measurements.

TABLE 3. Comparison with existing literutre.

Ref.	Antenna Measurements (mm)	Dimension of FSS unit cell (mm)	Bandwidth of the Antenna /FBW(GHz)	Antenna Efficiency %	Gain Enchancement (dB)	FSS Array size	Amount of reflector layers
[26]	50 × 50 × 1.6	5 × 5 × 1.6	136%(2.29– 12.1)	89%	8.4 – 8.8	19× 19	Single
[27]	26 × 26 × 1.6	6 × 6 × 1.6	118%(3.05– 11.9)	92 %	7.87 – 9.68	10 × 10	Single
[28]	22.56 × 14.3 × 0.4	12.7 × 12.7 × 0.8	105%(2.6 – 8.1)	94%	9 – 10	6 × 6	Single
[17]	41 × 34 × 0.8	11 × 11 × 1.6	150%(2.82 -19.9)	90%	2 – 3.5	4 × 4	Single
[18]	31.9 × 30 × 1.6	11 × 11 × 1.6	153%(3.8 – 10.6)	79 %	3 – 3.5	3 × 3	Single
[29]	24.5 × 30 × 0.8	12.8 × 12.8 × 0.8	88.1%(3.5– 5.92)	90%	10.5 – 11.8	5 × 5	Single
[30]	35 × 30 × 1.6	5.35 × 5 × 1.6	130.3%(3.16– 15)	90.1%	4.9 – 10.9	10 ×10	Single
[31]	35 × 30 × 0.8	11 × 11 × 1.6	133%(2.64– 9.36)	80 %	2 – 4	3 × 4	Single
[35]	25 × 20 × 1.6	14 × 14 × 1.6	153.5% (3-24)	85%	2 – 8.9	5 × 5	Single
[36]	16 × 24 × 1.6	13 × 13 × 1.6	138% (3.2-17)	80%	4..4 – 9.5	4 × 4	Single
[23]	20 × 25 × 1.6	13 × 13 × 1.6	148%(2.6-7.9)	85%	8.8 –14.5	11 ×11	Single
[37]	32 × 25 × 1.52	10 ×10 × 1.52	143% (3-18)	90%	6.5 –10.5	5 × 5	Single
[38]	40 × 20 × 1.52	10 ×10 × 1.52	139%(3.4-9.8)	95%	4.5 –9.5	5 × 5	Single
This work	**21 × 21 × 1.6**	**3.5 × 3.7 × 1.6**	**134%(3 - 12)**	**80%**	**3.5 – 9.2**	**6 × 6**	**Single**

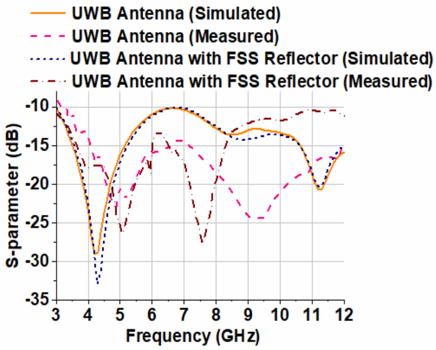


FIGURE 11. Return loss performance.

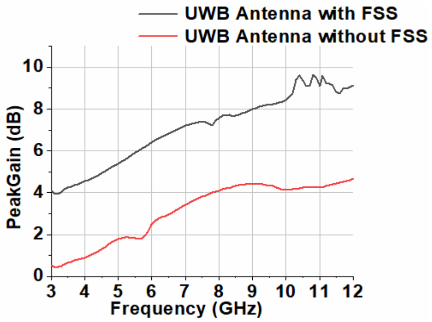


FIGURE 12. Gain performance.

In Fig. 11, the measured performance of the proposed antenna is presented with and without SCR layer. The proposed arrangement offers a wide bandwidth of 3.05 to 11.9 GHz with SCR. The single-layer FSS reflector improves antenna gain at least 5 dBi throughout the whole spectrum of UWB frequencies at an optimum cavity distance of 6mm while maintaining good impedance match as shown in Fig. 12. More importantly, Fig. 13 displays the radiation efficiency of the proposed antennas with and without the single-layer FSS reflector. The graph demonstrates that

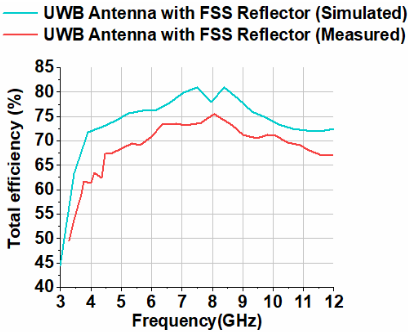


FIGURE 13. Total efficiency of antenna-FSS arrangement.

the UWB antenna alone has a higher efficiency of 80% at 7.4 GHz as compared to the FSS reflector integrating, which had a 75% efficiency at the center frequency. This slight variation of 70-75% in measured radiation efficiency is owing to lossy nature of the FSS layer and fabrication imperfections.

The measured E and H field arrangement at 5 GHz and 9 GHz are shown in Fig. 14. The results reveals that, antennas approximate an Omni-directional pattern in the E-plane and H-plane with and without FSS. However, the use of a frequency-selective surface leads the gain be more directive at higher frequencies.

The 3D gain patterns in Fig. 15 depict radiation performance with and without SCR layer. It is evident from the patterns that, at least 5 dBi average gain improvement is observed with SCR with an omnidirectional response that emits or receives electromagnetic waves equally in all directions over a wide range of angles. The proposed SCR proves its significance by addressing two challenges. Initially it optimizes the antenna radiation at desired frequency band owing to its precise filtering response therefore gain enhancement is observed over wide range of angles. Then it controls the back radiations to suppress the wave propagation losses even at higher frequencies i.e. 9 GHz, thereby maintaining

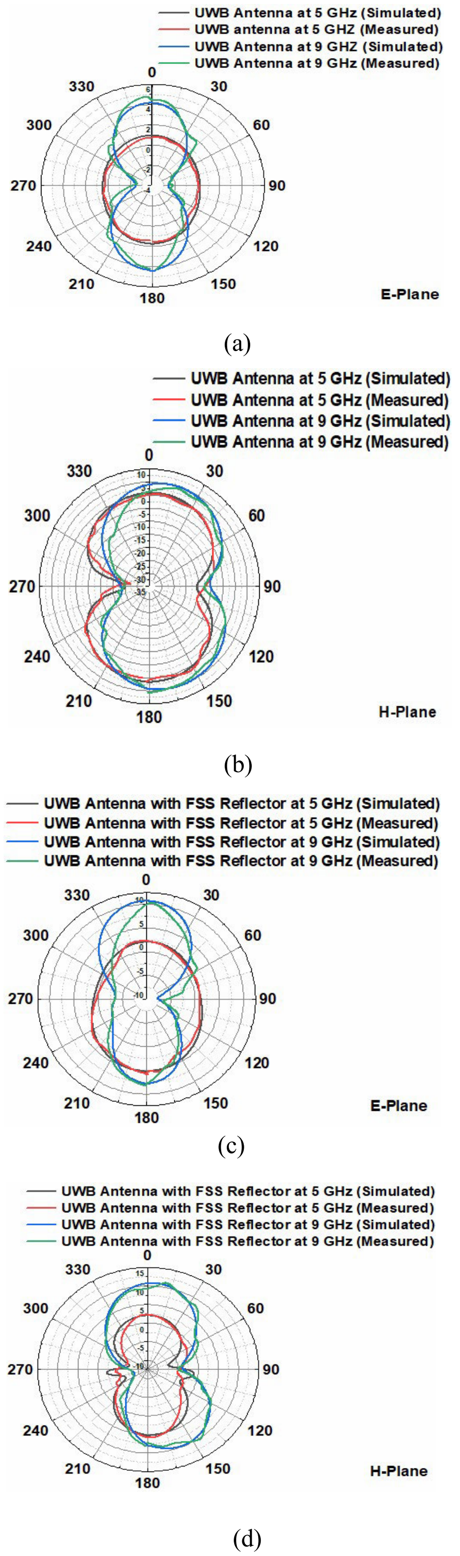


FIGURE 14. Simulations vs. Measured radiation patterns with and without SCR (a) (b) E-plane at 5&9 GHz (c) (d) H-plane at 5&9 GHz.

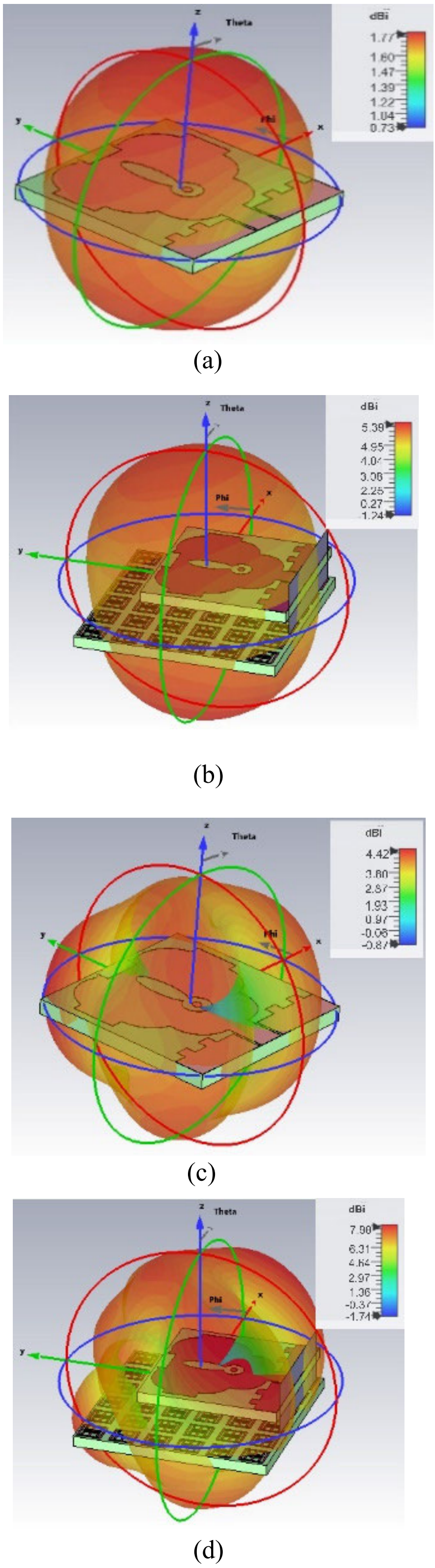


FIGURE 15. 3D radiation pattern; (a) (b) without FSS Reflector at 5 and 9 GHz(c) (d) with SCR at 5 and 9 GHz.

the efficiency of the antenna while integrating it with SCR. The radiation response at higher frequencies is relatively directive, however a wide-angle range is observed. In wireless communication systems, especially for IoT devices, this wide-angle coverage with improved gain is highly desirable.

IV. COMPARISON OF THE RELATED WORK

Table 3 compares the proposed CPW-fed UWB antenna with FSS to existing antenna designs that have been described in the literature. This antenna-FSS arrangement is compared in terms of size, FSS unit element, fractional bandwidth, antenna efficiency, improved gain and number of FSS layers. The proposed antenna is smaller, reduces profile, and has a compact dimension as contrasted to other designs working at this frequency range. The proposed arrangement has a wider fractional bandwidth of 134% and while offering higher gains at the minor cost of efficiency. The proposed design is a great option for future real-time locating and tracking systems (RTLS), medical consumers, and 5th and 6th generation approaches for high-gain and wideband applications.

V. CONCLUSION

This paper presents a CPW fed antenna with a Split Center Resonator FSS (SCR) beveled radiator, modified microstrip feed line, and ground plane that has been optimized to provide a wide impedance match. Additionally, a parametric analysis was conducted to control the periodicity of the FSS unit elements and the distance between the antenna and FSS layer to achieve an optimal return loss and gain. The antenna-FSS arrangement was able to achieve an ultra-wideband fractional bandwidth and a gain enhancement of at least 5 dBi in most of the UWB band with only a single layered SCR screen. Furthermore, the proposed antenna-FSS arrangement is only 7.6mm thick, making it suitable for high gain UWB portable communication services due to its improved performance and low-profile construction.

REFERENCES

[1] P. P. Shome, T. Khan, S. K. Koul, and Y. M. M. Antar, "Two decades of UWB filter technology: Advances and emerging challenges in the design of UWB bandpass filters," *IEEE Microw. Mag.*, vol. 22, no. 8, pp. 32–51, Aug. 2021.

[2] N. O. Parchin, R. A. Abd-Alhameed, and M. Shen, "Gain improvement of a UWB antenna using a single-layer FSS," in *Proc. Photon. Electromagn. Res. Symp. Fall (PIERS-Fall)*, Dec. 2019, pp. 1735–1739.

[3] H. Abdi, J. Nourinia, and C. Ghobadi, "Compact enhanced CPW-fed antenna for UWB applications," *Adv. Electromagn.*, vol. 10, no. 1, pp. 15–20, Feb. 2021.

[4] M. S. Ellis, A.-R. Ahmed, J. J. Kponyo, K. O. Gyasi, K. S. O. Kwakye, and S. Ameyaw, "Improved bandwidth and F/B ratio of a CPW-fed planar monopole antenna," *Heliyon*, vol. 8, no. 8, Aug. 2022, Art. no. e10037.

[5] Y. Du, K. L. Man, and E. G. Lim, "Image radar-based traffic surveillance system: An all-weather sensor as intelligent transportation infrastructure component," in *Proc. Int. SoC Design Conf. (ISOCC)*, Oct. 2020, pp. 161–162.

[6] M. S. A. Azhari, S. N. Azemi, M. D. Ghazali, and H. A. Majid, "A review of various antenna design methods for ground penetrating radar," in *Proc. Int. Workshop Antenna Technol. (iWAT)*, May 2022, pp. 121–124.

[7] F. Lombardi, F. Podd, and M. Solla, "From its core to the niche: Insights from GPR applications," *Remote Sens.*, vol. 14, no. 13, p. 3033, Jun. 2022.

[8] M. Bilal, R. Saleem, Q. H. Abbasi, B. Kasi, and M. F. Shafique, "Miniaturized and flexible FSS-based EM shields for conformal applications," *IEEE Trans. Electromagn. Compat.*, vol. 62, no. 5, pp. 1703–1710, Oct. 2020.

[9] V. K. Kanth and S. Raghavan, "Design and optimization of complementary frequency selective surface using equivalent circuit model for wideband EMI shielding," *J. Electromagn. Waves Appl.*, vol. 34, no. 1, pp. 51–69, Jan. 2020.

[10] T. Hong, M. Wang, K. Peng, Q. Zhao, and S. Gong, "Compact ultra-wide band frequency selective surface with high selectivity," *IEEE Trans. Antennas Propag.*, vol. 68, no. 7, pp. 5724–5729, Jul. 2020.

[11] P. Jiang, W. Jiang, W. Hu, and S. Gong, "An interlaced grid dual-band dual-polarized bandpass FSS with a large band ratio," *IEEE Antennas Wireless Propag. Lett.*, vol. 21, pp. 1027–1031, 2022.

[12] R. Panwar and J. R. Lee, "Progress in frequency selective surface-based smart electromagnetic structures: A critical review," *Aerosp. Sci. Technol.*, vol. 66, pp. 216–234, Jul. 2017.

[13] A. Bhattacharya, B. Dasgupta, and R. Jyoti, "A simple frequency selective surface structure for performance improvement of ultra-wideband antenna in frequency and time domains," *Int. J. RF Microw. Comput.-Aided Eng.*, vol. 31, no. 11, pp. 228–257, Nov. 2021.

[14] G. S. Paul, K. Mandal, and A. Lalbakhsh, "Single-layer ultra-wide stop-band frequency selective surface using interconnected square rings," *AEU Int. J. Electron. Commun.*, vol. 132, Apr. 2021, Art. no. 153630.

[15] S. Kundu, A. Chatterjee, S. K. Jana, and S. K. Parui, "A compact umbrella-shaped UWB antenna with gain augmentation using frequency selective surface," *Radioengineering*, vol. 27, no. 2, pp. 448–454, Jun. 2018.

[16] F. C. G. D. S. Segundo, A. L. P. D. S. Campos, and A. Gomes Neto, "A design proposal for ultrawide band frequency selective surface," *J. Microw., Optoelectronics Electromagn. Appl.*, vol. 12, no. 2, pp. 398–409, Dec. 2013.

[17] A. J. A. Al-Gburi, I. B. M. Ibrahim, Z. Zakaria, B. H. Ahmad, N. A. B. Shairi, and M. Y. Zeain, "High gain of UWB planar antenna utilising FSS reflector for UWB applications," *Comput., Mater. Continua*, vol. 70, no. 1, pp. 1419–1436, 2022.

[18] A. J. A. Al-Gburi, I. B. M. Ibrahim, M. Y. Zeain, and Z. Zakaria, "Compact size and high gain of CPW-fed UWB strawberry artistic shaped printed monopole antennas using FSS single layer reflector," *IEEE Access*, vol. 8, pp. 92697–92707, 2020.

[19] R. A. Mellita, D. S. Chandu, S. S. Karthikeyan, and P. Damodharan, "A miniaturized wideband frequency selective surface with interconnected cell structure," *AEU Int. J. Electron. Commun.*, vol. 120, Jun. 2020, Art. no. 153196.

[20] J. Ruan, Z. Meng, R. Zou, F. Cai, and S. Pan, "Miniaturized frequency selective surface for 6G communication," *Micromachines*, vol. 13, no. 3, p. 427, Mar. 2022.

[21] Y. Yuan, X. Xi, and Y. Zhao, "Compact UWB FSS reflector for antenna gain enhancement," *IET Microw., Antennas Propag.*, vol. 13, no. 10, pp. 1749–1755, Aug. 2019.

[22] S. E. I. Daira, M. Lashab, H. A. Berkani, M. Belattar, I. Gharbia, and R. A. Abd-Alhameed, "A curved single-layer FSS design for gain improvement of a compact size CPW-fed UWB monopole antenna," *Microw. Opt. Technol. Lett.*, vol. 66, no. 1, pp. 339–343, Jan. 2024.

[23] M. D. Lanka and S. Chalasani, "M-shaped conformal antenna with FSS backing for gain enhancement," *Eng. Proc.*, vol. 59, no. 1, p. 143, 2024.

[24] K. M. Patnaik and G. Basavarajappa, "A configuration to double the gain of pyramidal horn antenna using single layer frequency selective surface," *IET Microw., Antennas Propag.*, vol. 18, no. 1, pp. 35–42, Jan. 2024.

[25] G. V. Trentini, "Partially reflecting sheet arrays," *IRE Trans. Antennas Propag.*, vol. 4, no. 4, pp. 666–671, Oct. 1956.

[26] A. A. Ibrahim, H. A. Mohamed, M. A. Abdelghany, and E. Tammam, "Flexible and frequency reconfigurable CPW-fed monopole antenna with frequency selective surface for IoT applications," *Sci. Rep.*, vol. 13, no. 1, p. 8409, May 2023.

[27] T. Tewary, S. Maity, A. Roy, and S. Bhunia, "Wide band microstrip patch antenna with enhanced gain using FSS structure," *J. Microw., Optoelectronics Electromagn. Appl.*, vol. 22, no. 2, pp. 329–345, Jun. 2023.

[28] D. N. Gençoğlan and Ş. Çolak, "Design of SRR-loaded patch antenna for 5G communications and estimation of antenna substrate materials," *Icontech Int. J.*, vol. 7, no. 2, pp. 16–27, 2023.

[29] D. Nguyen and C. Seo, "Frequency-selective surface stopband designed with a genetic algorithm for gain enhancement of a broadband monopole antenna," *J. Electromagn. Eng. Sci.*, vol. 22, no. 3, pp. 236–244, May 2022.

[30] S. Kundu, "A compact uniplanar ultra-wideband frequency selective surface for antenna gain improvement and ground penetrating radar application," *Int. J. RF Microw. Comput.-Aided Eng.*, vol. 30, no. 10, pp. 223–263, Oct. 2020.

[31] R. A. Abdulhasan, R. Alias, K. N. Ramli, F. C. Seman, and R. A. Abd-Alhameed, "High gain CPW-fed UWB planar monopole antenna-based compact uniplanar frequency selective surface for microwave imaging," *Int. J. RF Microw. Comput.-Aided Eng.*, vol. 29, no. 8, pp. 217–257, Aug. 2019.
[32] D. D. Nguyen and C. Seo, "A wideband high gain trapezoidal monopole antenna backed by frequency selective surface," *Microw. Opt. Technol. Lett.*, vol. 63, no. 9, pp. 2392–2399, Sep. 2021.
[33] A. Swetha and K. R. Naidu, "Gain enhancement of an UWB antenna based on a FSS reflector for broadband applications," *Prog. Electromagn. Res. C*, vol. 99, pp. 193–208, 2020.
[34] S. Kundu, "Gain augmentation of a triple notched ultra-wideband antenna using compact uniplanar frequency selective surface for ground penetrating radar," *IETE J. Res.*, vol. 69, no. 2, pp. 813–824, Feb. 2023.
[35] T. Tewary, S. Maity, A. Roy, K. Mandal, S. Kundu, and S. Bhunia, "Design and analysis of frequency selective surface embedded broadband high gain miniaturized antenna," *Int. J. Commun. Syst.*, vol. 37, no. 8, pp. 54–57, May 2024.
[36] T. Tewary, S. Maity, S. Mukherjee, A. Roy, P. P. Sarkar, and S. Bhunia, "FSS embedded high gain 'N'shaped miniaturized broadband antenna," *AEU-Int. J. Electron. Commun.*, vol. 158, pp. 154–465, Jan. 2023.
[37] M. Hussain, M. A. Sufian, M. S. Alzaidi, S. I. Naqvi, N. Hussain, D. H. Elkamchouchi, M. F. A. Sree, and S. Y. A. Fatah, "Bandwidth and gain enhancement of a CPW antenna using frequency selective surface for UWB applications," *Micromachines*, vol. 14, no. 3, p. 591, Feb. 2023.
[38] S. Tariq, Q. Hussain, M. S. Alzaidi, R. M. Ghoniem, M. Alibakhshikenari, A. A. Althuwayb, B. S. Virdee, and M. Aslam, "Frequency selective surfaces-based miniaturized wideband high-gain monopole antenna for UWB systems," *AEU Int. J. Electron. Commun.*, vol. 170, Oct. 2023, Art. no. 154841.

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