A curved single-layer FSS design for gain improvement of a compact size CPW-fed UWB monopole antenna

A Curved Single-Layer FSS Design for Gain Improvement of a Compact Size CPW-Fed UWB Monopole Antenna

SEYF EL ISLEM DAIRA[1], MOHAMED LASHAB[1], HEMZA ABDELFETTAH BERKANI[1], MOUNIR BELATTAR[2], IBRAHIM GHARBIA[3] and RAED A. ABD-ALHAMEED[3]

[1] Department of Electronics, University of Oum El Bouagui, Oum El Bouagui 4000, Algeria
[2] Department of Electrical Engineering, University of Skikda, Skikda 21000, Algeria
[3] Bradford-Renduchintala Centre for Space AI, Faculty of Engineering and Informatics, University of Bradford, BD7 1DP Bradford, U.K

Abstract: A New design of a curved single-layered frequency selective surface with an 11×11 array of a 13×13 mm sized unit cell has been merged with a miniaturized, CPW-fed ultra-wideband monopole of dimensions (20×25 mm^2) for gain enhancement. The suggested prototype, crafted on an FR-4 dielectric substrate and demonstrates a very broad bandwidth starting from 2.66 to 17.98 GHz (148%), which covers the entire UWB frequency band. The combined antenna-curved FSS reflector shows a very important gain improvement from 0.2 ∼ 5.4 dB to 8.8 ∼ 14.9 dB, having a peak gain increase of 10 dB at 10.6 GHz. Basic design features were studied and discussed through simulations, yielding promising results The proposed structure can be used in UWB and GPR applications.

Keys words: Coplanar Waveguide, Frequency Selective Surface, FSS reflector, Gain Enhancement, Ultra-Wideband antenna.

1. Introduction

Back in 2002, the FCC set aside a 7.50 GHz commercial band (3.10 ∼ 10.60 GHz) specifically for the deployment of ultra-wideband telecommunication technology [1]. Since then, UWB communication methods have succeeded in drawing the attention of many industry observers over the past few years, and researchers claim that UWB may be more efficient and successful than other technologies due to the security of wireless networking, low profile, good time domain, constant gain, very wide impedance bandwidth, high data rate, omnidirectional radiation pattern, fast performance, less power usage, less expansive, and ease of fabrication, etc. [2]-[5].

UWB devices are characterized by several features such as; low profile, compact dimension, ultra-wide impedance bandwidth, and low manufacturing cost, they are usually built on planar antennas, primarily monopole and notch, which are fed via a coplanar waveguide (CPW) [6]–[9]. CPW-feed lines are very good candidates for printed antennas because of their decreased radiation loss, reduced sensitivity to substrate thickness, and simpler integration with surface components [10]. This is in contrast to the typical practice of microstrip antennas, in which the patch surface and ground plane are typically distanced by a dielectric substrate. Above the dielectric substrate, the patch radiator and ground plane share the same plane in a coplanar waveguide, as implied by its name. In order to provide a wide impedance bandwidth, several radiating element shapes, including rectangular, circular, triangular, hexagonal, etc., have been evolved by mean research works [11,12]. Diverse geometries of slots have been incorporated in the radiating elements, which considerably improves the impedance bandwidth of these antennas [13].

For particular applications, such as antenna radomes, microwave imaging detection systems, radar cross section (RCS) control, and ground-penetrating radar (GPR), to improve the precision and detection distance, it is imperative to utilize ultra-wideband (UWB) antennas that possess high gain and directivity [14],[15], and these characteristics can be improved using various approaches, including artificial magnetic conductors (AMCs) [16], reactive impedance surfaces (RISs) [17], the employment of antenna arrays [18], and frequency selective surfaces (FSSs) [19].

Remarkably, frequency selective surface (FSS) keeps pace with the evolving requirements for more expanded bandwidth for wireless communication objectives and some other advanced functionality that lean on a specific bandwidth to execute. Thence, a universal race for modern techniques has begun that properly create unique signals across a very wide frequency range [20]. FSSs are meta-surfaces that display an immediate response caused by reproducing a pre-proposed cell component, their configuration encompasses an array of UC resonators mounted on a substrate effectively functioning as a spatial filter, allowing electromagnetic waves to reflect them (stop-band filter) [21] or transmit them (pass-band filter) [22]. Properly developed and built UWB FSS UC reflectors are able to enhance the features of a UWB antenna [23]. Additionally, it makes them easier to use and protects them from neighboring metallic surfaces thereby preserving the optimal performance of UWB antennas, this attribute grants them exceptional adaptability for a wide range of UWB applications [24],[25]. FSS have been extensively employed to amplify the gain and signal strength of UWB antennas in a variety of ways, including multi- and single-layer designs [26],[27].

In this paper, an innovative design of a curved single-layered frequency FSS is combined with a miniaturized CPW-fed UWB monopole antenna for gain improvement is presented. First, a CPW-fed UWB monopole having an overall compact size of 20 x 25 x 1.6 mm^3 is crafted on an FR-4 substrate. Then, the monopole was positioned above the 11 x 11 curved FSS reflector fabricated on FR-4, where the unit cell size is 13 x 13 mm. The combined structure demonstrates a very vast bandwidth from 2.66 GHz to 17.98 GHz (148%), which covers the whole UWB frequency range. The combined antenna and curved FSS reflector provide a very significant gain enhancement from 0.2 ~ 5.4 dB to 8.8 ~ 14.9 dB over the operating band, with directional radiation patterns, having a top gain improvement of 10 dB at 10.6 GHz. Fundamental design characteristics were examined, and the study was conducted to compare the regular FSS method with the proposed one through simulations and measurements, and encouraging outcomes were achieved as a result. The combined antenna-curved FSS reflector was compared with other recently published similar works. The suggested arrangement is adequate for both UWB and GPR applications.

2. UWB Antenna Design

The suggested CPW-fed UWB monopole is crafted on a 1.6 mm thick FR-4 substrate, having an overall compact size of 20 x 25 mm^2, a relative permittivity of ε_r=4.4, and loss tangent tan δ=0.025, The monopole consists of a radiating square formed patch and a conducting ground plane (patch and ground plane are made of annealed copper), both are mounted above of the substrate. The configuration is powered by a 50 Ω microstrip line, where the feed line's width and length measure W_f=2 mm, L_f=6 mm, respectively. Antenna design methodology can be evaluated using equations (1) to (6) to determine antenna dimensions:

$$\frac{\lambda_L}{4} < L_{sub} < \frac{\lambda_L}{3} \tag{1}$$

$$W_{sub} \approx \frac{\lambda_L}{5} \tag{2}$$

$$\frac{\lambda_L}{6} < W_p < \frac{\lambda_L}{5} \tag{3}$$

$$W_g \approx \frac{\lambda_L}{11} \tag{4}$$

$$L_g = 3 \times h \tag{5}$$

$$L_f \approx L_g + h \tag{6}$$

Where λ_L indicates the wavelength associated to the lower band edge of the UWB range, which is 3.1 GHz, and 'h' refers to the substrate thickness. Computer Simulation Technology is used for parametric optimization, the proposed arrangement of the monopole is illustrated in Fig. 1(a), and the parameter values of the suggested design are listed in Table 1(a).

In order to boost the bandwidth to span the whole UWB spectrum, various slots were introduced to the monopole, as depicted in Fig. 1(b). Truncating two small pieces from ground plane and cutting a hexagonal aperture in the middle of the patch, followed by cutting two identical notches at the bottom corners of the patch. These modifications might change the current distribution and influence the capacitance and inductance, resulting in a wide bandwidth for the antenna.

Figure 1(c) depicts the S_11 characteristics of both the basic and proposed antennas. It is evident that the basic design has a narrow bandwidth (−10 dB) from 3.35 to 4.94 GHz (24%), showing a very poor impedance matching. On the other hand, the suggested monopole showcases an impressive impedance bandwidth (-10 dB) from 2.8 to 17.91 GHz (146%), covering the whole UWB spectrum, with exceptional impedance matching, displaying a resonating mode at 3.7 GHz and 13.58 GHz.

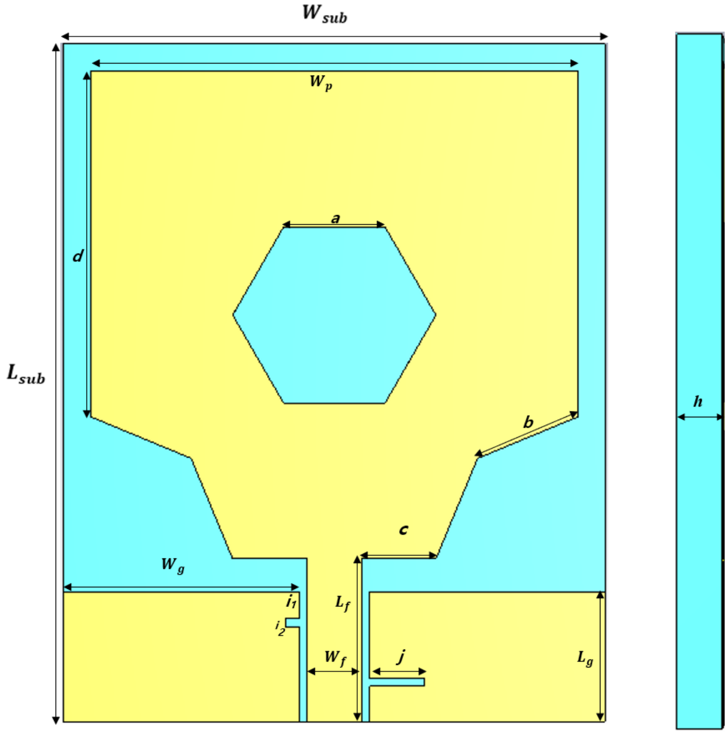
3. FSS Unit Cell Design

Spatial filtering is considered to be a very efficient operation in every signal processing system in the optical and microwave frequency bands [28]. To change the incident electromagnetic wave and give dispersive reflected and/or transmitted features, spatial filters, also known as frequency selective surfaces (FSS), are used [29]. According to their function, FSSs may be classified into low-pass, high-pass, band-stop, and band-pass filters, FSSs design typically involves creating periodic arrays of metal elements (patches and notches) printed on a substrate [30,31]. The most crucial move in the configuration process is determining the proper FSSs array arrangements, dimensions, shapes, and substrate materials [32,33].

The single-layer FSS unit cell geometry used in this paper is portrayed in Fig. 1(d), and its dimensions are restricted in Table 1(b). Its configuration restrains a square patch featuring a 3 × 3 array of hexagon-shaped slots containing small hexagonal forms inside it, the squared patch made of copper is stamped on the substrate boasting an overall dimension of 13 × 13. The unit cell structure of an FSS uses hexagonal slots because they provide many benefits, including high symmetry, which allows for a more uniform distribution of energy and reduces the possibility of unwanted resonances, efficient use of space, which results in higher frequency selectivity to provide a more compact and efficient way of achieving the desired frequency response; and ease of fabrication because hexagonal slots are relatively simple to fabricate.

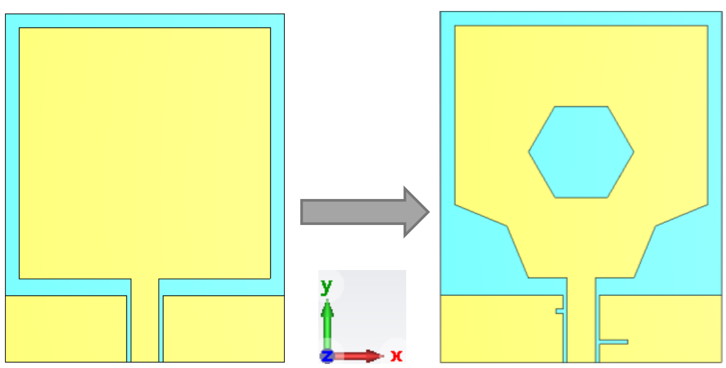
An FSS unit cell structure composed of 3×3 structures might be chosen for a variety of reasons, including improved performance, increased bandwidth, and design flexibility. The greater the number of subcells, the more complex and bigger the FSS’s size, which explains why the proposed UC is composed of a 3×3 subcell array, which offers symmetry to reduce undesired resonances and achieve a reasonable compromise between the number of subcells and the size of the FSS, which presents a good balance between performance, complexity, and size.

The S_11 and S_21(Reflection / transmission coefficients), and the reflection phase of the suggested UC, are depicted in Fig. 1 (e2) and (e3), respectively. It is evident that the S_11 value is near 0 dB, and the S_21 value is less than -10 dB, these values are obtained over a frequency range of 0 to more than 18 GHz. A phase response with a linear decrease in its baseband is fundamental for making the FSS reflective and for ensuring that the reflected wave is added to the transmitted one along propagation's desired direction.



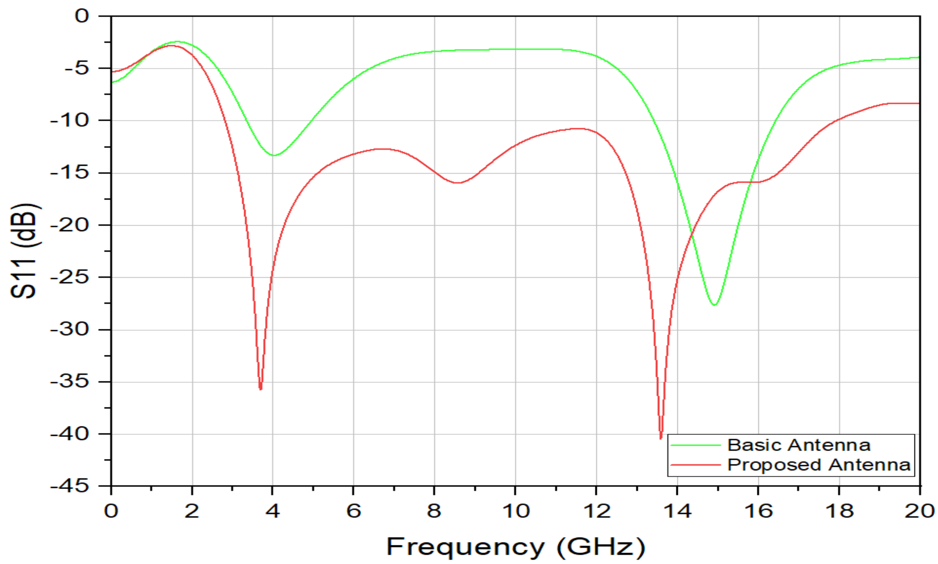
(a1) (a2)

(a)

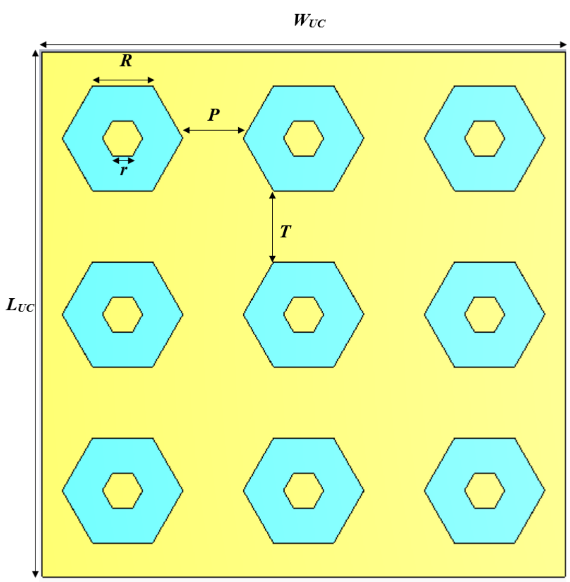


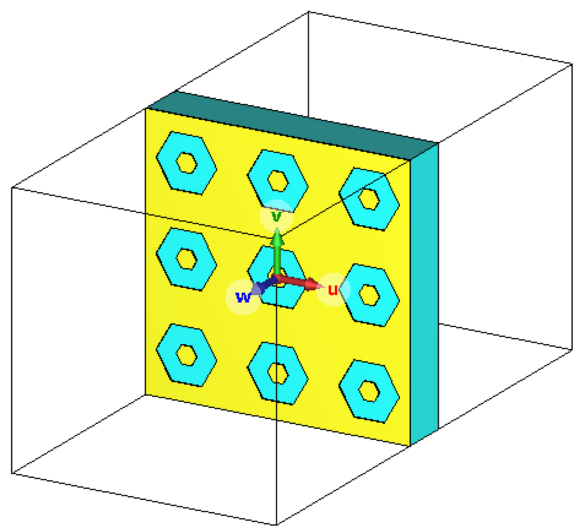
(b1) (b2)

(b)


S11 (dB)
Frequency (GHz)
0
-5
-10
-15
-20
-25
-30
-35
-40
-45
0
2
4
6
8
10
12
14
16
18
20
Basic Antenna
Proposed Antenna

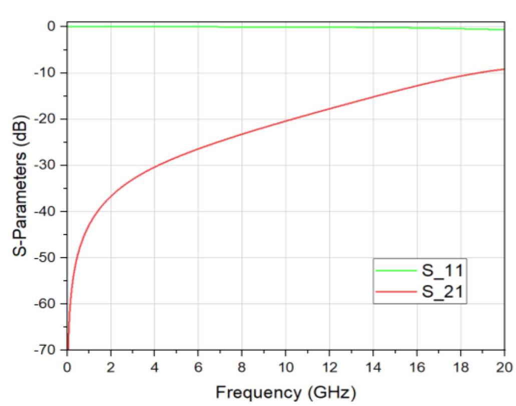
(c)

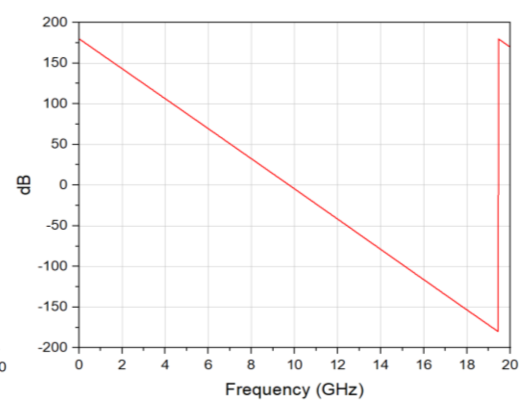

W_{UC}
L_{UC}
R
P
r
T


v
u
w

(d)

(e1)


S-Parameters (dB)
Frequency (GHz)
S_11
S_21


dB
Frequency (GHz)

(e2)

(e3)

(e)

Fig. 1. a - Proposed design configuration. (a1) Top view. (a2) Side view. b- (b1) Basic Antenna. (b2) Proposed Antenna. c- Simulated S-11 Vs frequency. d- FSS unit cell geometry. e- (e1) UC simulation. (e2) Transmission and reflection coefficients. (e3) Reflection phase of the UC.

TABLE I

(a) Values of the design parameters

Parameter	**Value (mm)**	**Parameter**	**Value (mm)**
W_{sub}	20	a	3.75
L_{sub}	20	b	4.02
W_p	18	c	2.75
W_g	8.7	d	12.75
L_g	4.8	i_1	0.5
W_f	2	i_2	0.25
L_f	6	j	2

(b) Values of the FSS UC design parameters

Parameter	**Value (mm)**	**Parameter**	**Value (mm)**
W_{uc}	*13*	R	*0.5*
L_{uc}	*13*	P	*1.5*
R	*1.5*	T	*1.77*

4. Combined Antenna-FSS structure

The major difference between a metallic ground and an FSS unit cell lies in their design and function. An FSS unit cell is a patterned configuration that selectively filters electromagnetic waves relying on their frequency. This structure's principal role is to selectively reflect, absorb, or transmit electromagnetic waves at specific frequencies. Its behavior is determined by the UC size, configuration, shape, and also by dielectric properties of the substrate. While a metallic ground is a continuous sheet of metal that acts as a reference plane for electrical circuits or as a shield against electromagnetic interference which provides a conductive path for the waves. This explains the use of the FSS reflector for gain improvement of the proposed model in this paper.

4.1. Flat Structure

In order to attain high gain and receive directional radiation across the UWB frequency spectrum, the monopole was placed above the FSS array reflector. A thorough parametric analysis was conducted to ascertain the optimal number of UCs and the spacing between the monopole and the FSS reflector.

Initially, reflection coefficient of the monopole for different values of ‘‘d’’ (5 mm, 10 mm, 15 mm, 20 mm, and 25 mm) were investigated to understand the impact of space between monopole and FSS reflector as shown in Fig. 2(a1). As expected, the FSS UCs has an impact on the antenna's impedance bandwidth showing that as "d" increases, so does the antenna bandwidth.

Furthermore, the influence of "d" on the monopole's gain performance is presented in Fig. 2(a1), in which gain is calculated across the Ultra wideband frequency range for various values of "d".

In conclusion, the operating frequency band and maximum gain of the monopole are extremely reliant on distance between monopole and FSS reflector. In this work, it appears that the best "d" value is 25 mm (where: d ≈ $\lambda_L/4$), which offers a satisfying response across the whole bandwidth.

An examination of the impact of the number of FSS_UCs on the performance was obtained, and the outcomes are depicted in Fig. 2(b). FSS UC's reflecting performance is calculated when its size exceeds that of the monopole, and thus the antenna bandwidth becomes the sole FSS dimension; Fig. 2(b1) represents the S11 of the combined design with various numbers of UCs. Fig. 2(b2) represents a parametric analysis of the monopole realized gain, showing that an FSS reflector with 121 elements (11 × 11) has better gain than 81 elements (9 × 9) and 49 elements (7 × 7), which means that the gain is proportional to the number of UCs (gain increases across the UWB range by increasing the number of UCs).

4.2. Curved Structure

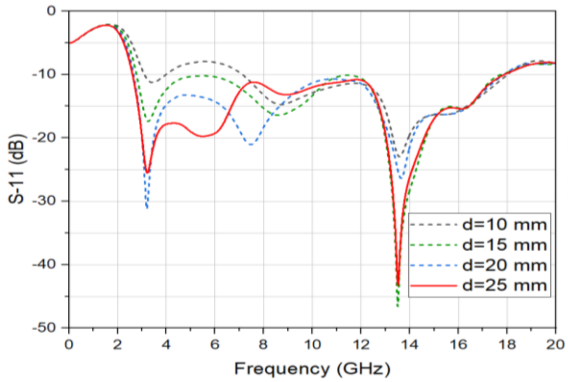
In this section, a new FSS design is suggested. To understand its operating principle, an example is given: a simple lamp that radiates equally in all directions can be said to have an isotropic radiation pattern. Now, let's assume that its light isn't sufficient to allow us to see, and we are not able to boost the power, but we do observe that plenty of the light coming from the lamp is moving in undesirable directions. So, if we choose to place a mirror behind it, the brightness in front of the lamp is virtually doubled, reflecting all the light that would otherwise be wasted in that direction. This can be extended by placing a second mirror to create an angle, which would add more beams.

Furthermore, a curved mirror might be used to achieve an extremely bright yet narrow beam of light. In our case, the simple lamp refers to the antenna, and the mirror refers to the FSS structure. The antenna transforms electrical energy into electromagnetic waves, which can propagate over space. Usually, to double the gain, a flat FSS model is placed at a distance "d" beneath the radiated monopole, as illustrated in Fig. 2(c). Now, to attain more gain, it is possible to bend the flat FSS at a certain degree to create a curved FSS structure, as shown in Fig. 2(d). Where $\beta=10°$ represents the angle between each unit cell and the other at the bending direction, which was obtained after few simulations (Using optimization tool).

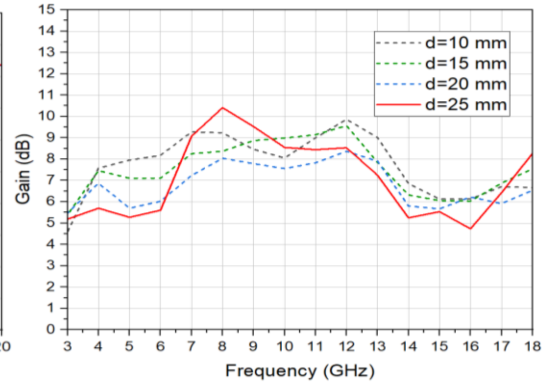
4.3. Curved Vs flat FSS Structure

The reflection coefficients of the flat and curved structures are presented Fig. 2(e1). It can be observed that the S11 parameters of both combined curved and flat structures are almost identical, which means that bending of the FSS does not compromise the impedance bandwidth of the monopole. However, a significant increase in antenna gain was obtained in contrast to the S11 characteristics of the design, as displayed in Fig.10(e2), by bending the FSS, the monopole's gain is boosted from 5.9 ~ 10.6 dBi to 8.8 ~ 14.9 dBi.

The electromagnetic properties of an FSS arrangement may influence the performance of the antenna by adjusting the bending degree. Although the relationship between the antenna gain and the bending degree of an FSS is not direct, they are linked in a way that a precisely built FSS with a suitable bending degree can improve the performance of the antenna, this can be accomplished by minimizing interference, optimizing the antenna's radiation pattern, or boosting the antenna's directivity, which can increase antenna gain.

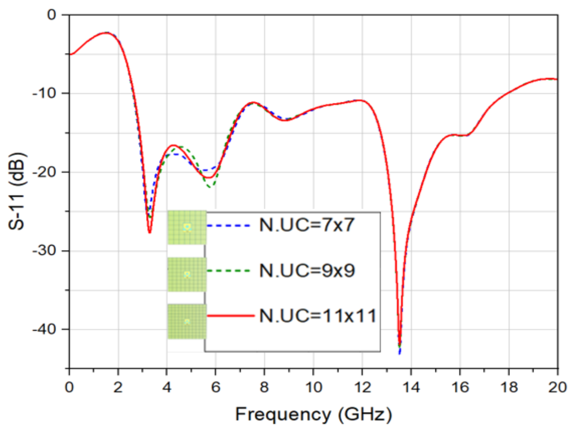


(a1)

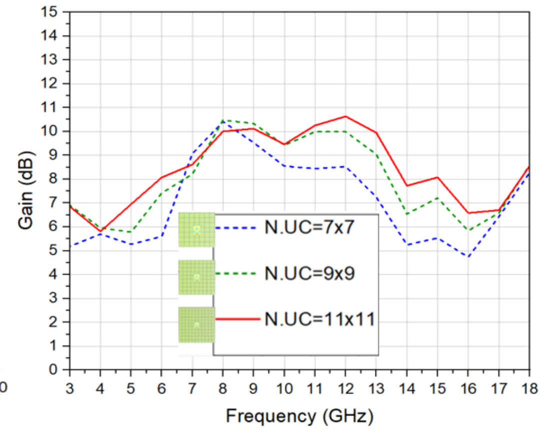


(a2)

(a)

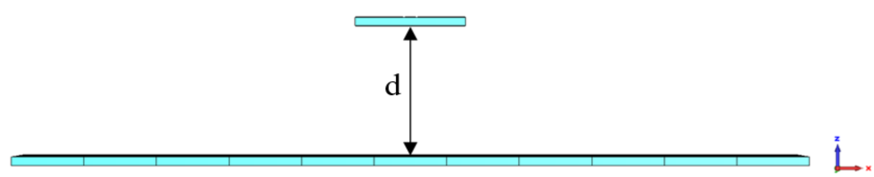


(b1)

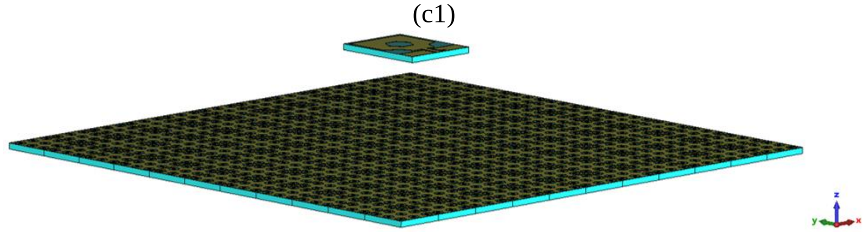


(b2)

(b)

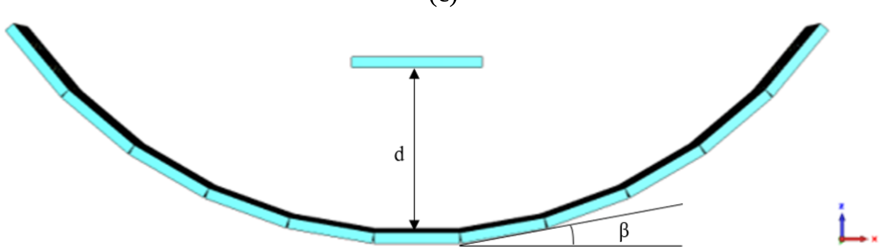


(c1)

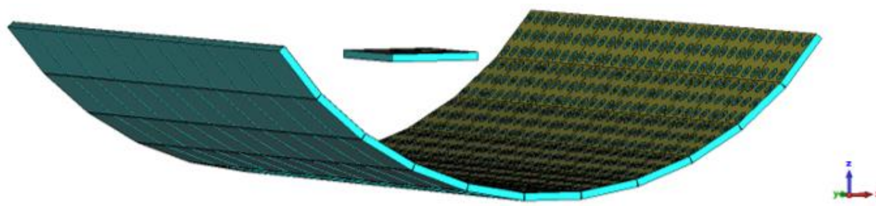


(c2)

(c)

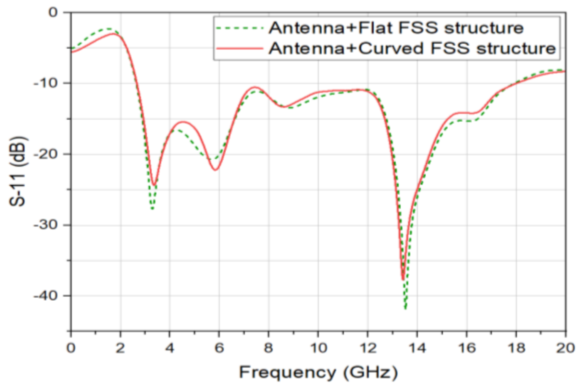


(d1)

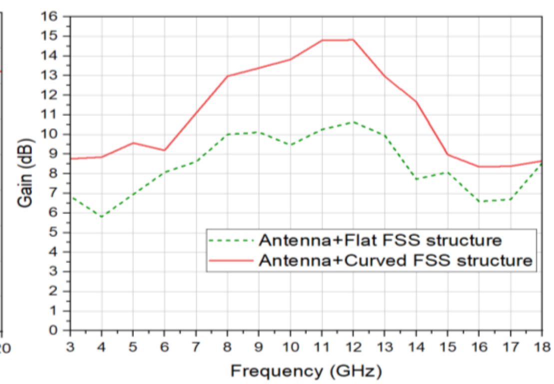


(d2)

(d)



(e1)



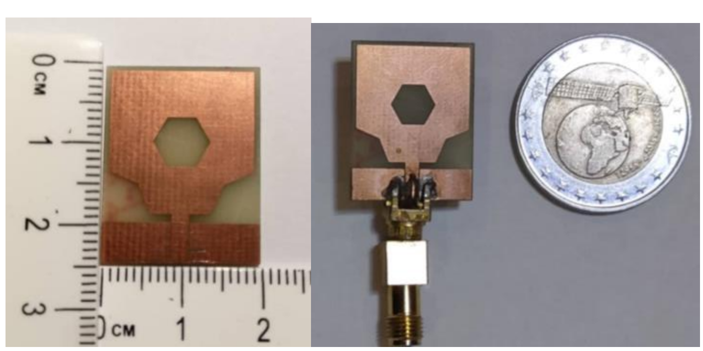
(e2)

(e)

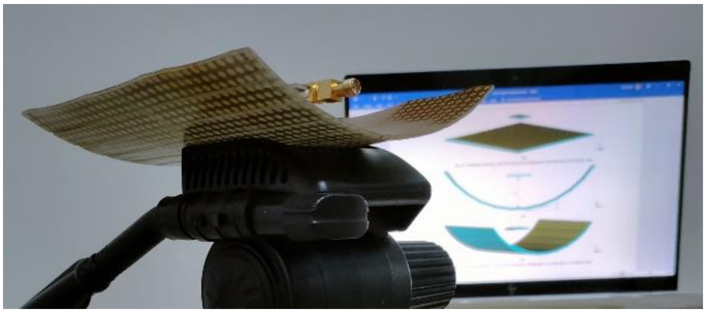
Fig. 2. a- Parametric study of the distance "d" between the antenna and the FSS reflector. (a1) Reflection coefficient for different values of “d”. (a2) Realized gain for different values of “d”. b- Parametric study about the effect of number of UCs on the antenna. (b1) Reflection coefficient for different Number of UCs. (b2) Realized gain for different Number of UCs. c- Combined antenna + flat FSS structure configuration. (c1) Side view. (c2) Angular view. d- Combined antenna + curved FSS structure configuration. (d1) Side view. (d2) Angular view. e- (e1) Reflection coefficient and (e2) Realized gain of the curved and flat FSS.

4.4. Simulation and measurements

This study has evaluated the simulation results for the CPW-fed monopole with and without an FSS reflector in order to define the properties of the crafted prototype, which was printed on an FR-4 substrate, as displayed in Fig. 3.



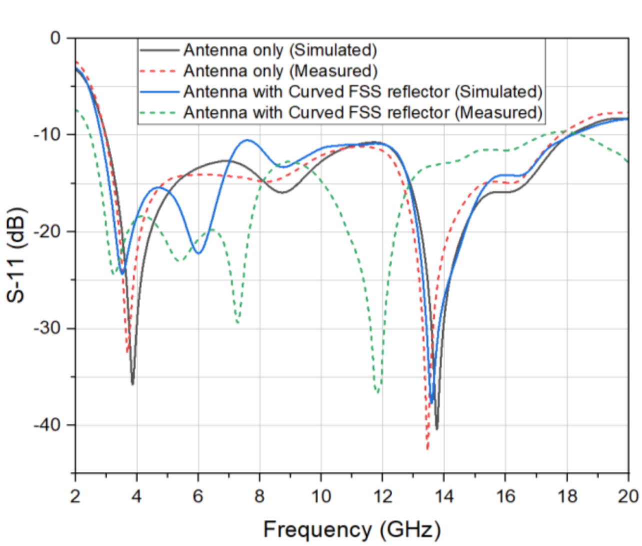
(a)


(b)
Fig. 3. Fabricated designs. (a) UWB CPW-fed Antenna. (b) Combined Antenna - Curved FSS reflector.

Both simulated and measured S_11 of the suggested UWB monopole with and without the curved FSS reflector are given in Fig. 4(a). Solo monopole attains an impedance bandwidth from 2.80 GHz to 17.8 GHz (simulated) (2.79 GHz to 17.6 GHz (measured)), while the combined antenna +Curved FSS reflector achieves a bandwidth from 2.66 GHz to 17.98 GHz (simulated) (2.39 GHz to 17 GHz (measured)), which means that the reflector doesn't have a big impact on antenna's bandwidth.

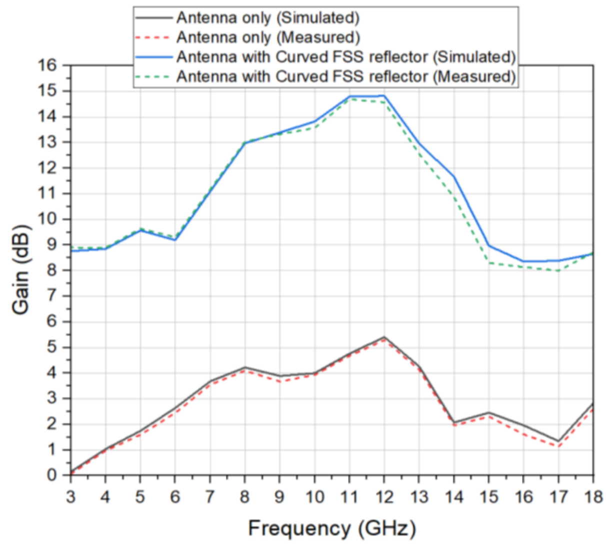
On the other hand, a remarkable increase in maximum gain was obtained, as depicted in Fig. 4(b). As demonstrated, the combined antenna + curved FSS has a gain variation of 8.8∼14.9 dB (simulated) (8.9∼14.8 dB (measured)), indicating a remarkable increase in maximum gain across the solo monopole, which has a gain variation of 0.2∼5.4 dB (simulated) and (0.15∼5.3 dB (measured)). The combined structure shows a max gain of 14.9 dBi over the functional band and the peak gain over the UWB range is 14.5 dB at 10.6 GHz with an amelioration of 10dB compared to the solo monopole.The variations between simulated and measured outcomes of the gain and reflection coefficient are primarily caused by the fabrication flaws.

Fig. 4(c) presents the simulated and measured E-field and H-field of the suggested UWB monopole with and without the curved reflector at 3.6 GHz, 5.8 GHz, and 8.6 GHz. It is evident that the CPW-fed monopole without an FSS reflector shows a figure-eight pattern in the H-plane and an approximately omni-directional pattern in the E-plane. However, radiation pattern became directional after introducing the curved reflector, which enhances the directivity of the proposed design.



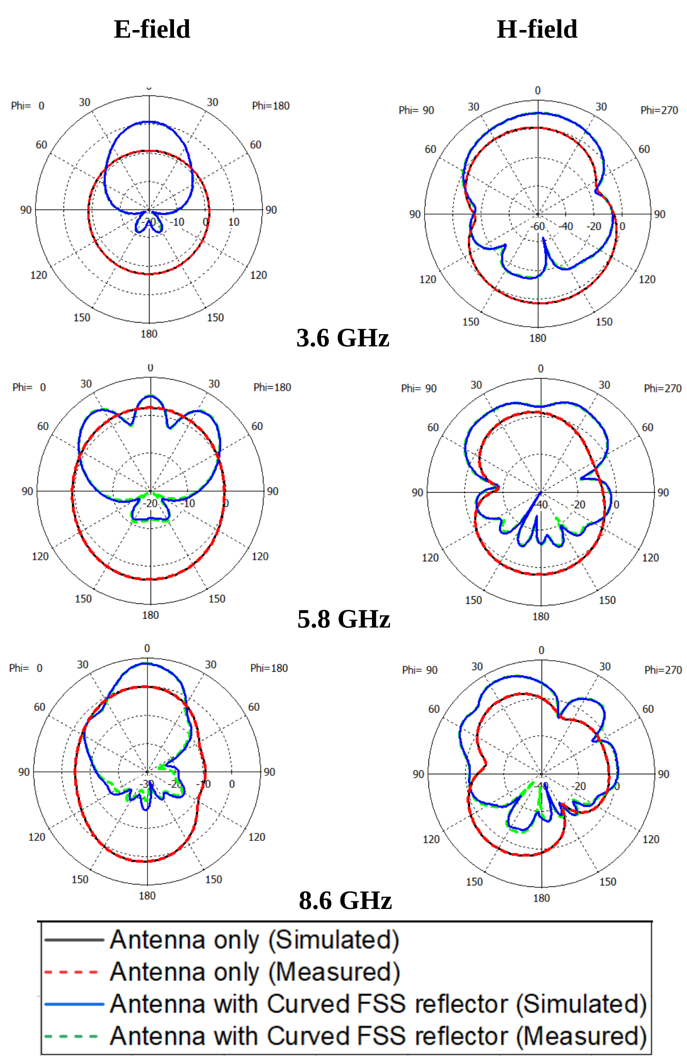
Antenna only (Simulated)
Antenna only (Measured)
Antenna with Curved FSS reflector (Simulated)
Antenna with Curved FSS reflector (Measured)
S-11 (dB)
Frequency (GHz)

(a)



Antenna only (Simulated)
Antenna only (Measured)
Antenna with Curved FSS reflector (Simulated)
Antenna with Curved FSS reflector (Measured)
Gain (dB)
Frequency (GHz)

(b)



E-field
H-field
3.6 GHz
5.8 GHz
8.6 GHz
Antenna only (Simulated)
Antenna only (Measured)
Antenna with Curved FSS reflector (Simulated)
Antenna with Curved FSS reflector (Measured)

(c)

Fig. 4. a- Simulated and measured S-11 of the suggested UWB monopole with and without the curved FSS reflector. b- Simulated and measured gain of the suggested UWB monopole with and without the curved FSS reflector. c- Simulated and measured E-field and H-field of the suggested UWB monopole with and without the curved FSS reflector at 3.6GHz, 5.8 GHz and 8.6 GHz.

A comparison with recent similar works is shown in Table 2.

TABLE 2
Comparison between the suggested design and similar works.

REF	Antenna size (mm)	Number of FSS	Bandwidth (GHz)	Gain (dB)
30	*31.9×30×1.6*	*Single*	*3.8-10.6*	*3.5-8*
31	*27×20×1.6*	*Single*	*4.7-14.9*	*5-8.7*
32	*36×24×0.8*	*Single*	*2.94-15.26*	*5.5-8.5*
33	*26×26×1.6*	*Single*	*3.05-11.9*	*7.87-9.68*
This work	*20×25×1.6*	*Single*	*2.66-17.98*	*8.8-14.9*

5. Conclusions

The aim of this paper is to boost the max gain of a UWB CPW-fed monopole antenna. For this reason, an innovative model of a curved ultra-wide-stop-band single-layered frequency-selective surface is executed. The compact-size coplanar waveguide antenna with an overall dimension of 20 x 25 mm^2 is placed above the curved FSS reflector, which contains an 11×11 array of unit cells measuring 13 x 13 mm. The combined antenna-curved FSS achieves an impressive bandwidth of 15.32 GHz from 2.66 to 17.98 GHz (148%) that covers the entire ultra wideband frequency range, and a high gain of 8.8 to 14.9 dB showing a top gain increase of 10 dB at 10.6 GHz, having directional radiation patterns. Basic design characteristics were studied, and the new FSS design technique is compared with the regularly used method and good results were obtained. The suggested structure has a low and compact profile, shows great features, and can be employed in UWB and GPR applications.

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REFERENCES

[1] Federal Communication Commission, Washington, DC, USA, “First order and report: Revision of part 15 of the Commission’s rules Regarding Ultra-Wideband transmission systems”, ET-Docket98-153, February, 2002.

[2] S. Singhal, P. Singh, “Asymmetrically CPW-Fed Octagonal Sierpinski UWB fractal antenna”, Microwave and Optical Technology Letters, Vol.58, No. 7, pp. 1738-1745, 2016.

[3] M. Elhabchi, M. N. Srifi, and R. Touahni, “A wideband filtering-antenna inspired with symmetric T-shaped slots and rotated L-shaped strips for C and X-band eliminations,” Advanced Electromagnetics, vol. 9, no. 1, pp. 1-6, March 2020.
[4] Chemseddine Zebiri, Djamel Sayad, Issa TE Elfergani, Jamal Sulieman Kosha, Widad Faraj A Mshwat, Chan Hwang See, Mohamed Lashab, Jonathan Rodriguez, Khalil H Sayidmarie, Huthaifa A Obeidat, Raed A Abd-Alhameed, “Antenna for ultra-wideband applications with non-uniform defected ground plane and offset aperture-coupled cylindrical dielectric resonators,” IEEE Access, Vol. 7, Oct. 2019, pp. 166776 - 166787
[5] J. Liang, C. C. Chiau, X. Chen, and C. G. Parini, ‘‘Study of a printed circular disc monopole antenna for UWB systems,’’ IEEE Trans. Antennas Propag., vol. 53, no. 11, pp. 3500–3504, Nov. 2005.
[6] E. S. Angelopoulos, A. Z. Anastopoulos, D. I. Kaklamani, A. A. Alexandridis, F. Lazarakis, and K. Dangakis, ‘‘Circular and elliptical CPW-fed slot and microstrip-fed antennas for ultrawideband applications,’’ IEEE Antennas Wireless Propag. Lett., vol. 5, pp. 294–297, 2006.
[7] S. Chaimool and K. L. Chung, ‘‘CPW-fed mirrored-L monopole antenna with distinct triple bands for WiFi and WiMAX applications,’’ Electron. Lett., vol. 45, no. 18, p. 928, 2009.
[8] Mohamed Lashab, Chemss Eddine, Naeem Ahmed Jan, F Benabdelaziz, RA Abd-Alhameed, Marl Child, “CPW-Fed antenna based on Metamaterial for Broadband application,” Loughborough Antennas and Propagation Conference (LAPC) 2014, pp. 144-147, Loughborough, UK.
[9] Naeem Ahmed Jan, Mohamed Lashab, Chemss-Eddine Zebiri, Djouablia Linda, RA Abd-Alhameed, Fatiha Benabdelaziz Compact, “CPW antenna loaded with CRLH-TL and EBG for multi-band and gain Enhancement,” Loughborough Antennas & Propagation Conference (LAPC) 2016, Loughborough, UK.
[10] T. C. Edward and M. B. Steer, Foundations for microstrip circuit design, 4 st ed., John Wiley & Sons, Chichester (United Kingdom), p. 659, 2016.
[11] R. Cicchetti, E. Miozzi, and or. Testa, “Wideband and UWB antennas for wireless applications: A comprehensive review,” International Journal of Antennas and Propagation, Article ID 2390808, 45 pages, 2017.
[12] A. Esmaeilkhah, Ch. Ghobadi, J. Nourinia, and M. Majidzadeh, “On effect of planar scaling on microstrip patch antenna performance,” Advanced Electromagnetics, vol. 8, no. 1, pp. 1-7, March 2019.
[13] I. Amdaouch, O. Aghzout, A. Naghar, and A. V. Alejos, F. Falcone, “Design of UWB compact slotted monopole antenna for breast cancer detection,” Advanced Electromagnetics, vol. 8, no. 5, pp. 1-6, December 2019.
[14] Jamlos, M. A., M. F. Jamlos, S. Khatun, and A. H. Ismail, “A compact super wide band antenna with high gain for medical applications,” IEEE Symposium on Wireless Technology and Applications (ISWTA), Kota Kinabalu, Malaysia, 2014.
[15] Ali, J., “Ultra-wideband antenna design for GPR applications: A review,” International Journal of Advanced Computer Science and Applications, Vol. 8, 392–400, 2017.
[16] F. Mouhouche, A. Azrar, M. Dehmas, and K. Djafer, “Gain Enhancement of Monopole Antenna using AMC Surface,” Advanced Electromagnetics, 7, 3, 2018, pp. 69-74.
[17] J. Chatterjee, A. Mohan and V. Dixit, «Broadband Circularly Polarized H-Shaped Patch Antenna Using Reactive Impedance Surface, » IEEE Antennas Wireless Propag. Lett., 17, 4, 2018, pp. 625-628.
[18] K. P. Rao, R. M. Vani, and P. V. Hunagund, “Planar Microstrip Patch Antenna Array with Gain Enhancement,” Procedia computer science, 143, 2018, pp. 48-57.
[19] R. Yahya, A. Nakamura, M. Itami and T. A. Denidni, "A Novel UWB FSS-Based Polarization Diversity Antenna, » in IEEE Antennas and Wireless Propagation Letters, 16, 2017, pp. 2525-2528.
[20] Al-Gburi, A.J.A.; Ibrahim, I.M.; Zakaria, Z.; Abdulhameed, M.K.; Saeidi, T. Enhancing Gain for UWB Antennas Using FSS: A Systematic Review. Mathematics 2021, 9, 3301.
[21] S. E. I. Daira, M. Lashab and M. Belattar, "a Compact Size FSS Unit Cell Design for UWB Filtering and Shielding Applications," 2023 International Conference on Advances in Electronics, Control and Communication Systems (ICAECCS), BLIDA, Algeria, 2023, pp. 1-4.
[22] J. D. Ortiz, J. D. Baena, V. Losada, F. Medina, R. Marques, and J. L. A. Quijano, ‘‘Self-complementary metasurface for designing narrow band pass/stop filters,’’ IEEE Microw. Wireless Compon. Lett., vol. 23, no. 6, pp. 291–293, Jun. 2013.
[23] Ranga, Y., L. Matekovits, and K. P. Esselle, “Multioctave frequency selective surface reflector for ultrawideband antennas,” IEEE Antennas and Wireless Prop. Letters, Vol. 2011, 10, 219–222.
[24] Jan, N.A.; Kiani, S.H.; Muhammad, F.; Sehrai, D.A.; Iqbal, A.; Tufail, M.; Kim, S. V-Shaped Monopole Antenna with Chichena Itzia Inspired Defected Ground Structure for UWB Applications. Comput. Mater. Contin. 2020, 65, 19–32.
[25] Narayan, S.; Jha, R.M. A novel metamaterial FSS-based structure for wideband radome applications. Comput. Mater.Contin. 2013, 37, 97–108.
[26] Askari, H.; Hussain, N.; Choi, D.; Abu Sufian, M.; Abbas, A.; Kim, N. An AMC-Based Circularly Polarised Antenna for 5G sub-6 GHz Communications. Comput. Mater.Contin. 2021, 69, 2997 3013.
[27] Liu, C.; Bai, Y.; Jing, L.; Yang, Y.; Chen, H.; Zhou, J.; Zhao, Q.; Qiao, L. Equivalent energy level hybridisation approach for high-performance metamaterials design. Acta Mater. 2017, 135, 144–149.
[28] A. Kapoor, R. Mishra, P. Kumar, Frequency selective surfaces as spatial filters: fundamentals, analysis and applications. Alexandria Eng. J. 61(6), 4263–4293 (2022)
[29] Anwar, R.S.; Mao, L.; Ning, H. Frequency Selective Surfaces: A Review. Appl. Sci. 2018, 8, 1689.
[30] 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, 2019, Art. no. e21757.

[31] P. Das and K. Mandal, "Modelling of ultra-wide stop-band frequency-selective surface to enhance the gain of a UWB antenna," IET Microwaves, Antennas & Propagation, 13, no. 3, 2019, pp. 269-277.
[32] S. Kundu, "Gain Improvement of Ultra-Wideband antenna using compact Frequency Selective Surface," 2020 URSI Regional Conference on Radio Science (URSI-RCRS), Varanasi, India, 2020, pp. 1-4.
[33] 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," in IEEE Access, vol. 8, pp. 92697-92707, 2020.