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Meta-surface (frequency selective surface) loaded high gain directional antenna systems for ultra-wideband applications

Mohammed Amer Hamed Al-Shamili, Madan Kumar Sharma
Department of Information and Communication Engineering, College of Engineering, University of Buraimi, Al Buraimi, Oman

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ABSTRACT

In this work, a meta-surface (frequency selective surface) loaded high gain directional antenna system is presented. The antenna system is developed using ultra-wideband (UWB) antenna element and meta-surface reflector. The UWB antenna element is designed and simulated without meta-surface reflector. The UWB antenna element has poor impedance bandwidth and directivity. A meta-surface is created using unit cell and equal in the size of the antenna substrate. The meta-surface is placed over the UWB antenna element at optimized height (H=30 mm). The impedance bandwidth, directivity and gain of the proposed antenna are improved by the meta-surface reflector. The proposed antenna is fabricated and experimentally validated by the comparison of the simulated and measured results. The antenna has 3 to 6 GHz wide impedance bandwidth, more than 5 dBi gain and maximum 4.6 dBi directivity at 3.5 GHz frequency. Performance of the proposed antenna is also compared with existing carried out work. Comparatively, the proposed antenna with high directivity is most suitable for IEEE 802.15.4a UWB wireless sensor network (WSN) security application.

Corresponding Author:

Madan Kumar Sharma
Department of Information and Communication Engineering, College of Engineering, University of Buraimi
Al Buraimi Governorate, Oman
Email: madan.k@uob.edu.om

1. INTRODUCTION

In the twenty first century, ultra-wideband-wireless sensor network (UWB-WSN) is an emerging technology for internet of thing (IoT) enabled medical and industrial applications such as: human physical activity monitoring systems, telepathy systems, drug delivery systems, Military surveillance systems, and remote monitoring systems for the industrial plant [1]–[4]. This technology has gained popularity due to its high data throughput at low power and cost. However, these IoT enabled WSN systems are vulnerable to the malicious attacks. Despite this, WSN is immune to threats using message encryption techniques, and authentication of the node [5]–[7]. The antenna technology is an alternative approach to reduce the chance of cyber physical attacks as well as simultaneously improve the link reliability and transmission range [8]. In this regard, a directional antenna system is a beneficial component that can be embedded with the sensor node. Directional antenna can protect the wireless sensor network (WSN) from such malicious attacks, narrow radiation range of the antenna cannot be tracked by attackers easily [9]–[12]. Therefore, the directional antenna is very helpful to mitigate the effect of eavesdropping, jamming and wormhole security risks. The WSN security which is provided by the directional antenna system is shown in Figure 1. Aforementioned favorable characteristics of the directional antenna, the designing of a novel and compact size directional antenna for UWB-WSN is a challenging task for the antenna developer. Because, usually antennas developed in the ultra-wideband (UWB) range are offered omnidirectional pattern and have low antenna gain.

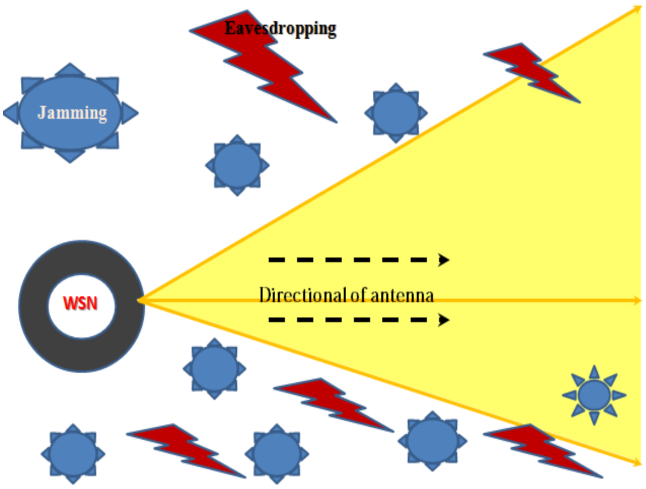


Figure 1. WSN Security through directional antenna systems

Several attempts have been made by the antenna developer to develop small size highly efficient UWB directional antenna for WSN, a few of which are discussed here. Reconfigurable directional antenna system was developed in [13] to improve the node connectivity. The antenna gain, and communication range has been improved by the developed antenna systems. In study [14], antenna directivity has been controlled by beam steering through the reconfigurable mechanism. The beam steering technique used in the reported work is very useful for improving WSN security and network performance. Developed antenna has peak gain of the 4 dBi. A Four bent diamond-shaped directional antenna was implemented in [15], and antenna's directivity was accomplished using a novel feed technique. The claimed antenna size is too large to be embedded in the sensor node. A dual wideband dipole directional antenna has been successfully implemented in [16] for wireless communication system which operated in the two frequencies range i.e. 0.68-1.03 GHz and 1.67-2.8 GHz. A double layer reflector placed above the antenna element to improve gain and directivity of the antenna. High gain directional antenna has been developed in [17] for IEEE802.11a/b and IEEE802.16d/e standards. The antenna has high gain of 9.1 dBi with better directivity and offered the services for Wi-Max and wireless local area network (WLAN). The implemented antenna size is a constraint to deploy it in the small WSN node.

Another, directional antenna has been fabricated and experimentally evaluated for multiband mobile communication in [18], the claimed antenna has provided the services to 2G/3G/LTE mobile systems with great directivity and high gain. Antenna gain and directivity is highly desirable to serve the multiband mobile communication system. But, it cannot be covered the UWB-WSN frequency band 3.1-5 GHz. A coplanar waveguide (CPW) feed ultra-wideband antenna loaded with frequency selective surface (FSS) has been implemented in [19], reported antenna gain and efficiency improved by FSS. The antenna has operating bandwidth 2.2-12.7 GHz and offered peak gain of 11.5 dB at 8.5 GHz frequency. Hexagonal microstrip patch antenna has been developed in [20] which can operate at 3.5 GHz narrowband and can utilize 5G applications. The antenna has been offered 6.938 dB gain at 3.5 GHz frequency. Wide literature review on the antenna gain enhancement using FSS has been done in [21]. The FSS is not only enhance the antenna gain also improve the directivity of the antenna. A wide-band antenna has been claimed in the [22], which can cover 3.5 to 5 GHz frequency band. The antenna was developed on the Rogers RT5880, and it was offered directional radiation patterns at the interested frequency. The antenna size, operating frequency range, gain and directivity are the common concern to design the antenna, specifically for WSN. Therefore, new design techniques are craved by the researcher to attain the antenna design goal for WSN i.e. the antenna loaded with FSS meta-surface. The FSS meta-surface loaded antennas are acquired all the favorable performance criteria and their small size is easily compatible with WSN node [23]–[27].

Proposed work is mainly focused on the development of the FSS meta-surface loaded antenna for UWB-WSN application. The improved directivity of the antenna is considered as a figure of merit in terms of security for the UWB sensor network. The proposed antenna is implemented in four subsequent steps. First, a

FSS unit cell is developed and analyzed. In the next step, the meta-surface is created using unit cell. In the third step, an UWB antenna is designed and simulated. Finally, in the fourth step, meta-surface is placed over the UWB antenna at desired spacing. The reflection parameters of the proposed antenna are analyzed with and without meta-surface, to identify the desired frequency range of the UWB-WSN. Furthermore, the parametric analysis of the proposed antenna is carried out in terms of the spacing between the UWB antennas and meta-surface. Once, the desired performance criteria are attained in the simulated structure of the antenna, the prototype of the same is fabricated and experimentally validated. Whole simulation process is carried out through the high frequency computer simulation technology (CST). Proposed work is comprised in the following section as: the detailed discussion about the antenna development is described in section 2, and section 3 is covered experimental result study, the proposed work is concluded in section 4.

2. PROPOSED ANTENNA DEVELOPMENT METHOD

The proposed antenna structure is shown in Figure 2. The proposed antenna construct with the rectangular patch element, which act as a radiator. A meta-surface of the same substrate size of the patch element is placed at a certain height (H) over the patch element. Detailed design procedure of the development of the proposed antenna is described in the following sections.

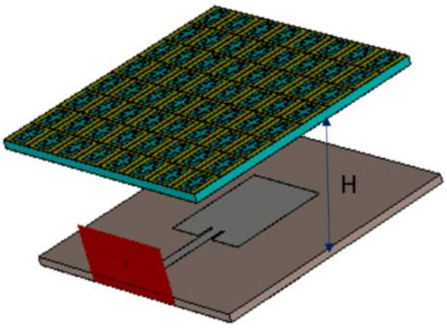


Figure 2. Structure of the proposed antenna with FSS meta-surface reflector

2.1. FSS unit cell development

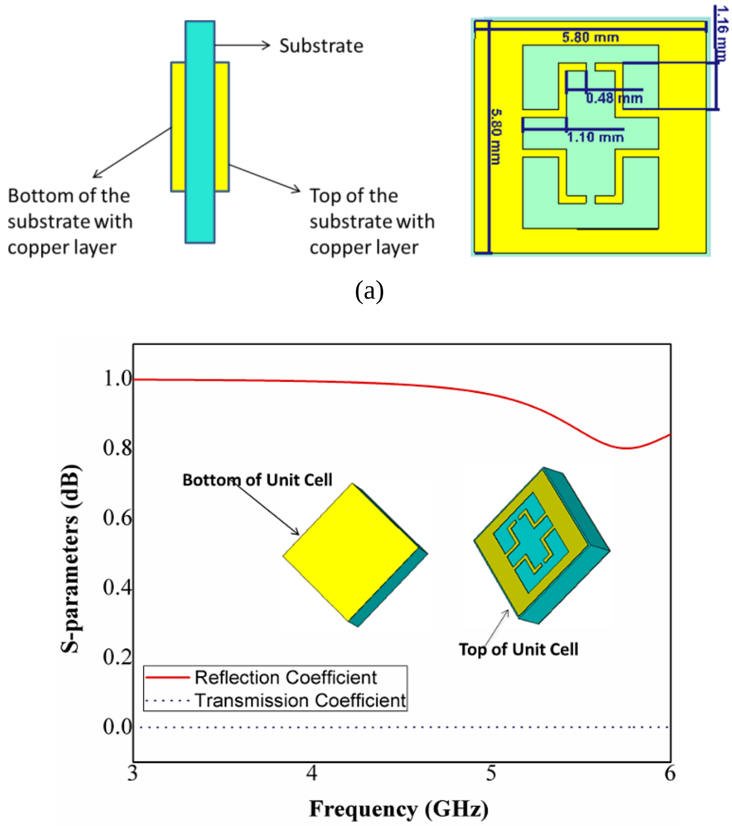
A FSS unit cell is created in CST design environment and simulated using frequency solver to analyze the behavior of transmission and reflection magnitude. Developed unit cell with optimized dimensions is shown in Figure 3(a). A square shaped unit cell is designed on the low cost FR4 substrate with dimension of 5.8 mm, thickness of 1.5 mm and dielectric constant 4.5. The bottom of the unit cell has a complete metallic ground, whereas, the top is etched with a rectangular shaped structure from the center and two inverted L-shaped structure are suspended both side of the etched plane of the top. To analyze the behavior of the unit cell, reflection and transmission coefficients of the unit cell is calculated as defined in [28], [29] and described by the (1) and (2):

$$S_{11} = \frac{R\left(1 - e^{i2nkd}\right)}{\left(1 - R^2 e^{i2nkd}\right)} \quad (1)$$

$$S_{21} = \frac{\left(1 - R^2\right) e^{i2nkd}}{\left(1 - R^2 e^{i2nkd}\right)} \quad (2)$$

where, $R=Z-1/Z+1$, the Z is the impedance of the unit cell, n is the refractive index of the unit cell, k is the wavenumber, and d is the thickness of the substrate used in the unit cell. The boundary conditions of the simulated FSS unit cell is followed as utilized in [30].

The simulated results of the reflection and transmission coefficient for designed unit cell are shown in Figure 3(b). The reflection behavior of the unit cell is observed from the obtained result, the incident power in the unit cell is completely reflected back over the frequency 3-5 GHz. The transmission coefficient is 0 dB, which is indicated that, no power transmitted from the unit cell. The power reflection property of the developed unit cell is useful to develop a meta-surface reflector. The development of the FSS meta-surface reflector is carried out in the following section.



(a)

(b)

Figure 3. Development and analysis of unit cell (a) unit cell structure with optimized dimension and (b) simulated reflection and transmission coefficient results of the unit cell

2.2. Development of FSS meta-surface

The meta-surface is developed from the unit cell and shown in Figure 4. An 8×8 array of the unit cell is perturbed on the top of 50×50 mm^2 substrate. The bottom side of the substrate fully loaded with conducting copper layer. The developed meta-surface is utilized in the final development of the proposed antenna. The meta-surface is act as reflector for the UWB antenna and can enhance the impedance bandwidth, gain and directivity of the proposed antenna.

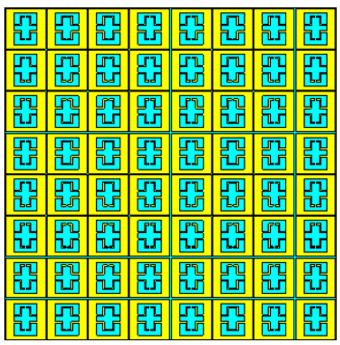


Figure 4. Developed FSS meta-surface from the unit cell

2.3. UWB antenna without FSS meta-surface

Main goal of this section is to develop an UWB antenna element which should be offered desired impedance bandwidth in the frequency range of the UWB-WSN (3.1–5 GHz), i.e. the operating frequency range of the IEEE 802.15.4a. The Structure with dimension of the UWB antenna element is shown in Figure 5. A 19.5×17 mm^2 rectangular-shaped antenna element is perturbed on the top of the substrate. Partial ground plane of the size of 50×16.3 mm^2 is utilized on the bottom side of the substrate. It is reduced the excitation losses of the antenna and improve the impedance bandwidth of the antenna. The Roger 3003 substrate with the size of 50×50 mm^2 and dielectric constant 3.3 is used to develop the UWB antenna element.

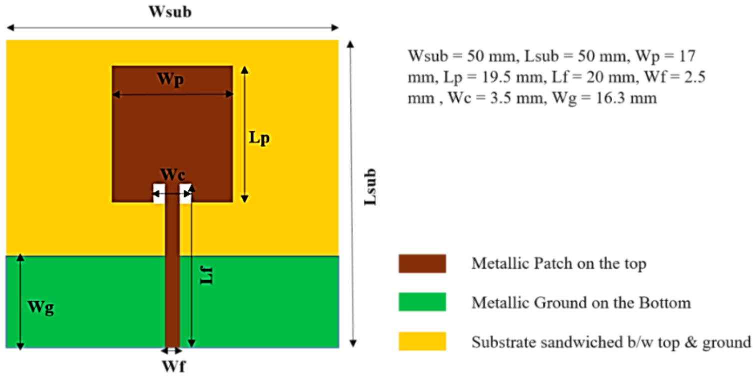


Figure 5. Structure of the UWB antenna element with dimension

2.4. UWB antenna with FSS meta-surface and their simulation results

To further enhance the impedance bandwidth the UWB antenna, the antenna is loaded with meta-surface which is created in the previous section 2.2. The simulated reflection coefficient results of the UWB antenna with and without meta-surface is shown in Figure 6. The UWB antenna element without meta-surface has impedance bandwidth (range of frequency for which $S11 < -10$ dB) is 3-4.2 GHz only. However, the antenna loaded with meta-surface is offered the impedance bandwidth 3-6 GHz. The antenna with meta-surface is offered the good resonance match and reduced the mismatch loss across the antenna port and radiating element.

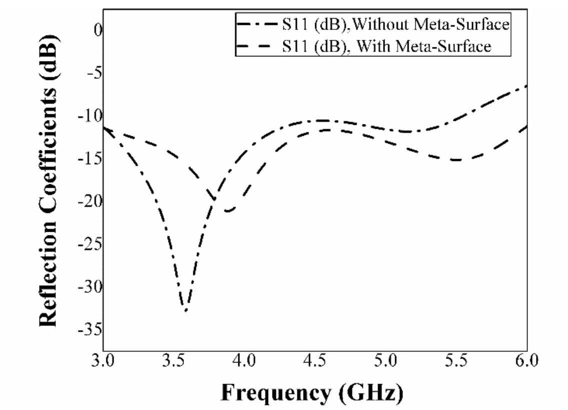
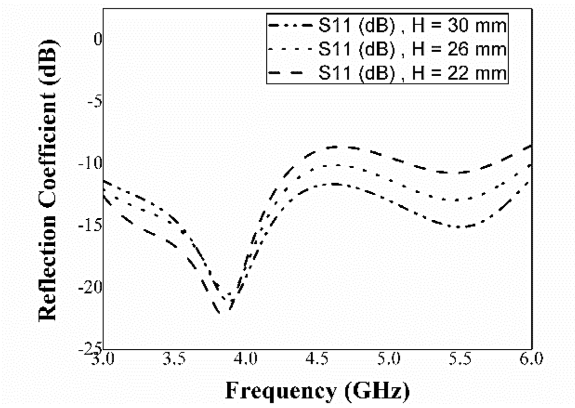
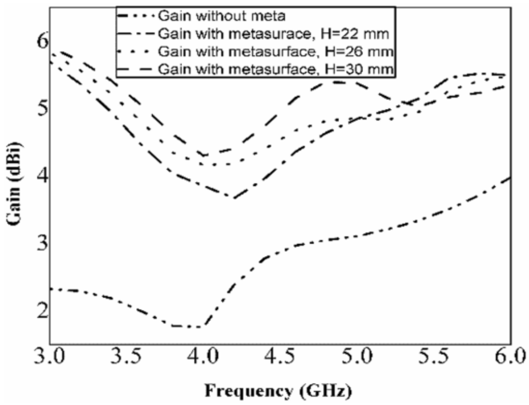


Figure 6. Simulated reflection coefficient results of the antenna with and without FSS meta-surface

Further, parametric optimization of the proposed antenna is also carried out to obtain the desired impedance bandwidth and gain. The spacing between the UWB antenna element and meta-surface (H) is varied. Reflection coefficient results and the antenna gain is analyzed at the spacing $H = 22$ mm, $H = 26$ mm, and $H = 30$ mm. Parametric analysis of the reflection coefficient and antenna gain results are shown in Figures 7(a) and 7(b) Respectively. The optimized reflection coefficient results for $S11 < -10$ dB is achieved at the spacing $H = 30$ mm, and the antenna is offered impedance bandwidth 3 GHz with frequency range of $3 - 6$ GHz which is desirable to covered the UWB-WSN operating range. The results of the Figure 7(b) is clearly shown that, the optimized, improved, and constant gain more than 5 dBi is offered by the antenna with meta-surface at the spacing $H = 30$ mm within the interested frequency range of UWB-WSN. However, antenna without has poor and un- stabilized gain of less than 2 dBi.



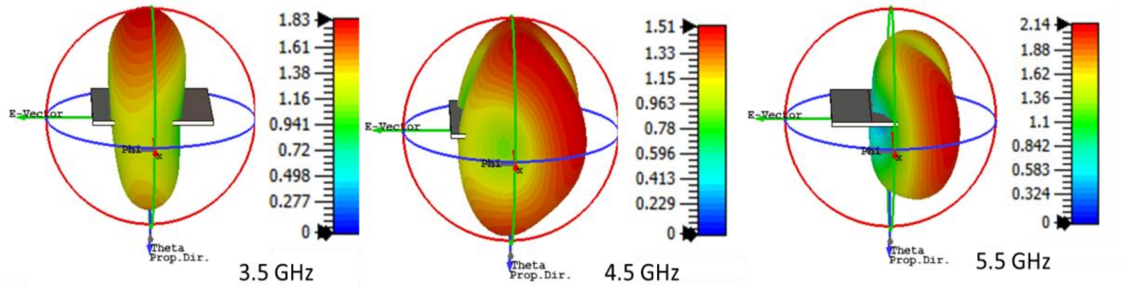
(a)



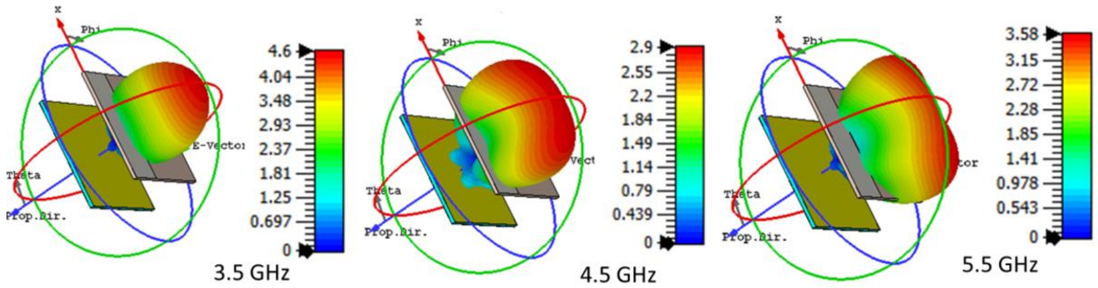
(b)

Figure 7. Parametric analyses of antenna spacing (H) from meta-surface (a) reflection coefficient results and (b) gain results

The reflection coefficient and antenna gain results are not sufficient to finalize the proposed antenna structure. Therefore, antenna directivity and surface current distribution are also included in the analysis of the proposed antenna at the spacing $H = 30$ mm. To notice the effect of the meta-surface on the antenna directivity, the 3D results of the directivity with and without meta-surface is simulated and analyzed. The 3D directivity results with and without meta-surface at the frequency 3.5, 4.5, and 5.5 GHz are shown in Figures 8(a) and 8(b). Results are indicated that antenna with meta-surface is more directional comparatively antenna without meta-surface. For clear understating of the effect of meta-surface on the antenna directivity, the maximum directivity values and improved directivity with meta-surface are collected in Table 1. Here results are indicated that, the directivity of the proposed antenna with meta-surface is improved by the value of 2.8, 1.39, and 1.44 dBi at the frequency of 3.5, 4.5, and 5.5 GHz respectively.



(a)



(b)

Figure 8. Directivity of the antenna (a) UWB antenna without meta-surface and (b) proposed antenna with meta-surface (at the frequency 3.5, 4.5, and 5.5 GHz)

Table 1. Maximum directivity analysis of the antenna with and without meta-surface

Frequency (GHz)	Maximum directivity (dBi) without meta-surface	Maximum directivity (dBi) with meta-surface	Improved value of directivity (dBi) with meta-surface
3.5	1.8	4.6	2.8
4.5	1.51	2.9	1.39
5.5	2.14	3.58	1.44

The surface current density represents the current distribution across the radiator, ground plane and substrate. Efficient antenna systems must be showing the maximum current distribution across the radiator. The current density is evaluated at the frequency 3.5, 4.5, and 5.5 GHz for the antenna with and without meta-surface and results are shown in Figure 9. The antenna without meta-surface has shown more current coupling across the ground plane along with the radiator as shown in Figure 9(a). However, the antenna with meta-surface reflector has shown maximum current distribution across the radiator and less current distribution across the ground as depicted in Figure 9(b). Therefore, the meta-surface reflector not only enhances the directivity of the antenna as well as improves the gain, impedance bandwidth. The performance characteristics of the antenna with meta-surface is sufficient to meet the criteria of the UWB-WSN application. Finally, the antenna with meta-surface with spacing of $H = 30$ mm is known as the proposed antenna. Further, experimental validation of the proposed antenna is carried out in the next section.

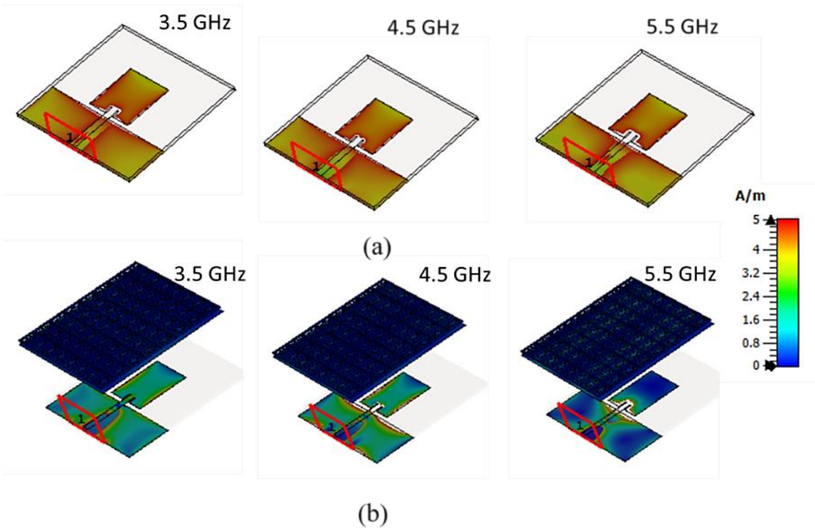
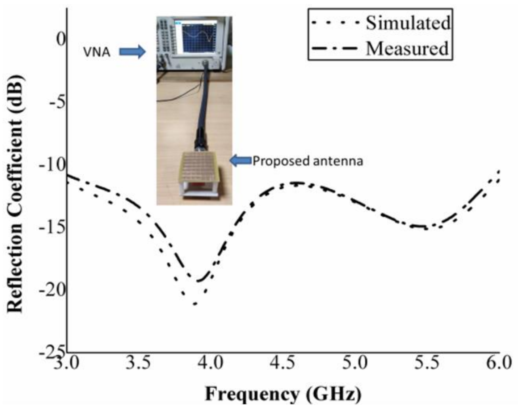


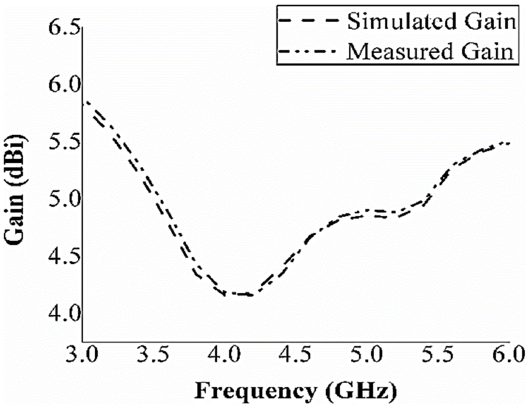
Figure 9. Simulated results of the surface current distribution (a) antenna without meta-surface and (b) proposed antenna with meta-surface (at the frequency 3.5, 4.5, and 5.5 GHz)

3. EXPERIMENTAL RESULTS VALIDATION OF THE PROPOSED ANTENNA

The designed proposed antenna is fabricated and experimentally validated by the comparison of the simulated and measured results. The UWB antenna element is fabricated first and then meta-surface is fabricated. The fabrication process is carried out using printed circuit board (PCB) micro-machine. The reflection coefficient is evaluated using vector network analyzer (VNA). Comparison of the simulated and measured reflection coefficient and gain are shown in Figures 10(a) and 10(b) respectively. The antenna has shown good matching between simulated and measured reflection coefficient results. The offered impedance bandwidth by the antenna is 3 GHz with reflection coefficient $S11 < -10\,dB$ for the frequency range $3 - 6$ GHz. Measured gain of the antenna is shown in Figure 10(b), and these results are also well matched with simulated results. The proposed antenna is offered peak gain of 5 dBi and mostly stable gain within the interested frequency range. However, antenna without meta-surface has poor gain less than the < 2 dBi only as previously discussed in the section 2.4. The more details about gain and efficiency with and without FSS meta-surface is shown in Figure 11. Comparatively, the antenna with FSS meta-surface is offered efficiency more than antenna without FSS meta-surface. The antenna with FSS meta-surface has peak efficiency more than 90% at 4 GHz frequency, however antenna without FSS meta-surface can provide efficiency lower than 20% only. The antenna gain with FSS meta-surface is also enhanced by 3 dBi as compared to antenna without meta-surface.



(a)



(b)

Figure 10. Simulated and measured (a) reflection coefficient results and (b) gain of the proposed antenna

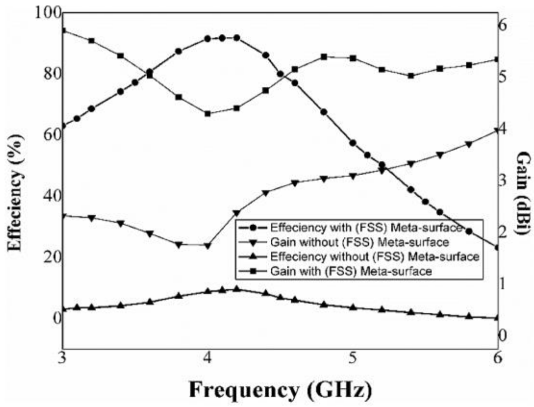


Figure 11. Gain and efficiency of the proposed antenna with and without FSS meta-surface

The measured radiation patterns of the proposed antenna are evaluated in the anechoic chamber. The test antenna is steered using automatic control stepper motor. The test antenna is rotated with step size of 30 degree with respect to reference antenna. The reference antenna is fixed at a certain distance in front of the test antenna. On the basis of received power by the test antenna the radiation pattern is drawn. The radiation patterns are defined the graphical representation of the radiated or received power by the antenna. The patterns are evaluated at the frequency 3.5 and 5.5 GHz and results are shown in Figure 12. Figure 12(a) shows the E-plane results at 3.5 and 5.5 GHz frequency and H-plane results are shown in Figure 12(b) at the same frequencies. The radiation measurement set-up and fabricated prototype of the antenna are shown in Figures 12(c) and 12(d) respectively. The obtained results are directional and stable at the measured frequency of operation of the antenna.

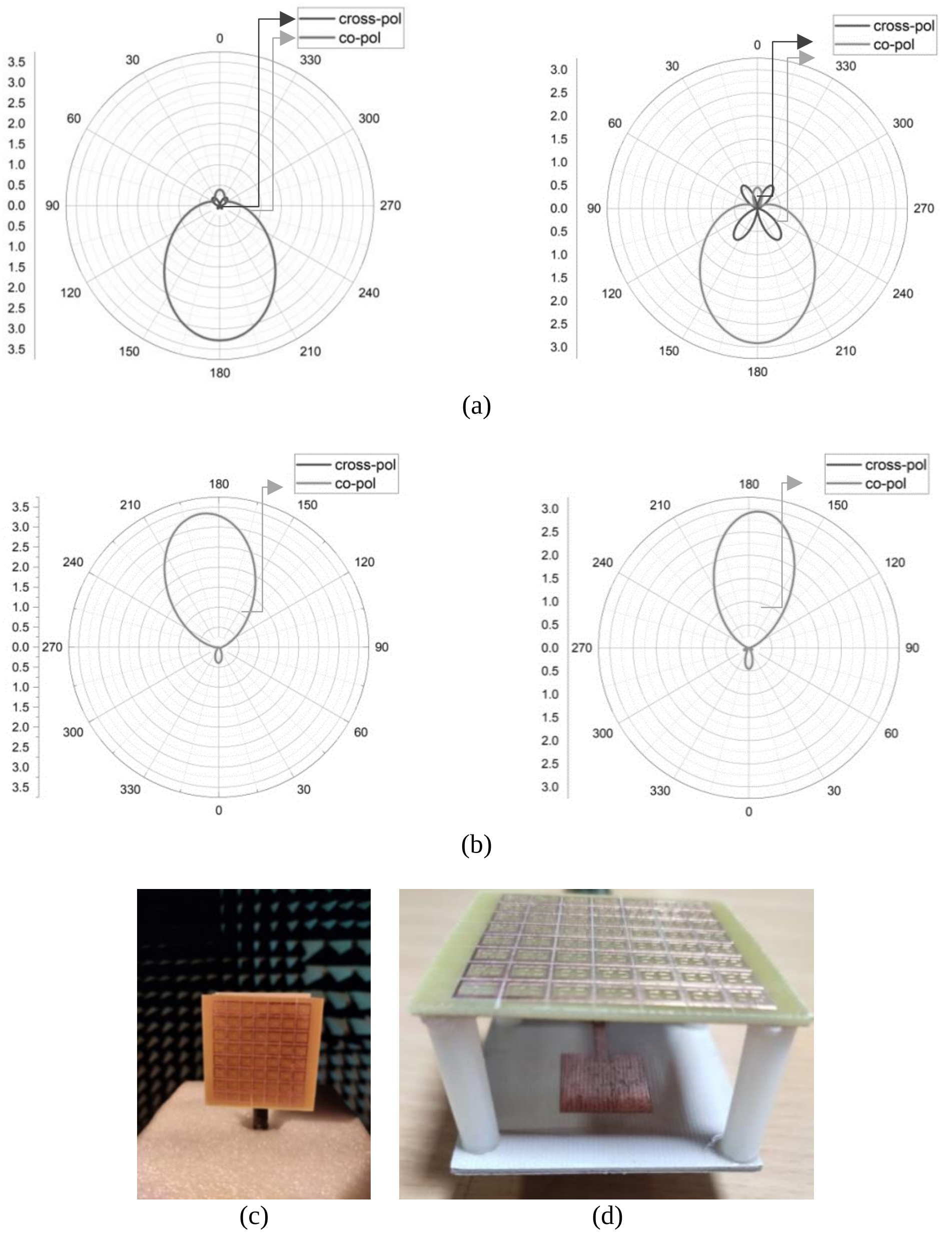


Figure 12. Measured radiation patterns of the proposed antenna (a) E-pane results at 3.5 GHz (left side), at 5.5 GHz (right side), (b) H-plane results at 3.5 GHz (left side), at 5.5 GHz (right side), (c) Measurement setup of radiation pattern in anechoic chamber, and (d) fabricated prototype of the propose

4. COMPARATIVE STUDY WITH EXISTING WORK

The proposed work is compared with existing work. The comparative analysis is done in terms of employed directivity enhancement method, operating frequency range, gain of the antenna, and applications. The compared parameters are collected in Table 2.

Table 2. Comparison study with of the proposed work with existing literature

Ref.	Directivity enhancement method	Operating frequency range (GHz)	Gain (dBi)	Applications
6	Ground stubs used as reflector and director	2.4 – 2.485	4.7	WSN
7	Power splitter, phase shifter	1 - 2	6	HF, UHF, VHF
8	Reflector	0.68 – 1.03	8.35	Wireless Communication
9	Reflecting ground plane	2.5 -2.7 & 3.4 – 3.6	9.1	IEEE 802.11a/b
10	Phase shifter	0.698 -0.96 and 1.7 – 2.6	9.9	Mobile
This work	Meta-surface reflector	3 – 6	5	UWB-WSN

5. CONCLUSION

In this study, a directional UWB antenna system with meta-surface is designed, tested and validated. The antenna directivity, gain and impedance bandwidth performance is enhanced by loaded the antenna with FSS reflector at the height (H=30 mm). The FSS meta-surface is comprised with 6×6 unit cell array. Before the development of the FSS meta-surface, the unit cell performance characteristic is verified by reflection and transmission coefficient results. The FSS meta-surface and antenna element is fabricated separately, then assembled FSS reflector above the antenna. The fabricated prototype is tested using VNA and anechoic radiation chamber. The proposed antenna directivity is observed 4.6, 2.9, and 3.58 dBi at the frequency 3.5, 4.5, and 5.5 GHz frequency respectively. The peak gain offered by the proposed antenna is 5 dBi. The antenna is offered wide impedance bandwidth $3-6$ GHz. The proposed antenna bandwidth, gain, efficiency, and directivity performance is suitable for UWB-WSN application. The directivity achieved in this work is most useful and provide good security to UWB wireless sensor networks.

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BIOGRAPHIES OF AUTHORS

Mohammed Amer Hamed Al-Shamili holds a Bachelor's degree in Electronics and Communications Engineering from the University of Technology and Applied Sciences in the Sultanate of Oman, Muscat in 2017, holds a Master's degree in Cyber Security from Al Buraimi University in the Sultanate of Oman in 2022. Interested in the field of cyber security and issues of communications and digital networks, interested in the development of antennas with high safety specifications. He can be contacted at email: mo123h@gmail.com.

Madan Kumar Sharma received the B.Eng. degree in electronics and communication engineering from UPTU University, Lucknow, India in 2006 and the Master's Degree from MDU, Rohatak in 2009 and Ph.D. degrees in RF microwaves and antenna, from Rajasthan Technical University, Kota, India in 2020.He has more than 15 years of academic experience in Engineering Institutions. Currently, he is an Assistant Professor at the Department of Information and Communication Engineering, College of Engineering, University of Buraimi. His research interests include UWB-MIMO diversity antenna and Microwave Sensor and sensor network security. He has been published more than 30 research articles in referred journal and conference proceeding. He can be contacted at email: madan.k@uob.edu.om.