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A Compact 2-Element Symmetrically Fed MIMO Antenna with a Ground Isolation Stub for Ultra-Wideband Communication Systems

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Abstract
In this paper, a compact multiple-input multiple-output (MIMO) antenna, with a ground isolation stub for ultra wideband (UWB) communication systems, is presented. The proposed design is based on two symmetrical semi-circular patches, fed by stepped-impedance microstrip lines, on the top side of the substrate, and a partial ground plane with two symmetrical large rectangular-shaped defected ground structure (DGS) units with a stub in between, and two symmetrical thin rectangular-shaped DGS units, on the bottom side. The two radiating elements are fed using a symmetrical feeding technique for future MIMO antenna systems. The 2-element UWB MIMO antenna with a simple structure and small size of 24×35 mm^2 is printed on FR4 substrate material. This study has resulted in an impedance bandwidth from 3.3 to 20 GHz which insures that the UWB spectrum is properly covered. In addition to that the elements are well isolated due to the fact that the isolation coefficient is smaller than −20 dB for the whole range of frequencies. The proposed structure exhibits stable omni-directional patterns and nearly bidirectional patterns in both E- and H-planes with an increasing gain across the operation bandwidth. An acceptable agreement between measured and simulated S-parameters is obtained.

Keywords UWB · MIMO · DGS · Isolating stub

1 Introduction

Ultra wide band (UWB) technology has became a hot topic for researchers in the last few years due to the attractive features and options that has added to wireless communication systems such as reduced energy consumption, increased data rate, and low price. This technology has been limited to military use before 2002 [1]. After that the Federal Communication Commission (FCC) has legally authorized the commercial use of UWB

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technology in frequency spectrum of 3.1–10.6 GHz [2], this technology has strongly attracted researchers in different research fields such as wireless communication systems, radars and medical imaging due to its important features such us the capability of using two different modulation modes [3], the impulse radio (IR) modulation and the multi band OFDM (MB-OFDM) used for small distance high data rate communications. Another feature of UWB is its capability of penetrating through obstacles because it uses RF pulses with high gain especially in medical fields [4].

Multiple-input multiple-output (MIMO) technology is used for wireless communications in which several antennas are employed at both the transmitter (source) and receiver (destination). The antennas at each end of the communications circuit are combined to minimize errors, optimize data speed and improve the capacity of radio transmissions by enabling data to travel over many signal paths at the same time [5].

Creating multiple versions of the same signal provides more opportunities for the data to reach the receiving antenna without being affected by fading, which increases the signal-to-noise ratio and error rate. By boosting the capacity of radio frequency (RF) systems, MIMO creates a more stable connection and less congestion. MIMO technology is used for cellular fourth-generation (4G) Long-Term Evolution (LTE), Wi-Fi networks and fifth-generation (5G) technology in a wide range of markets, including law enforcement, broadcast TV production and government [6].

Antennas are very important components in any wireless communication system, as they are installed at both emission and reception stations [7]. When designing an antenna, several parameters should be studied and optimized in order to enhance the performance of the designed antenna, in terms of reflection coefficient, radiation pattern and gain. Furthermore the cost, size and power consumption of the antenna should be reduced. In other hand, the antenna should be suitable for the intended application. Printed microstrip antennas are highly preferred for UWB systems [8], because due to their stable radiation pattern, good gain and the coverage of the entire UWB spectrum. In order to apply MIMO technology in UWB antennas, the mutual coupling between MIMO elements should be as small as possible to maintain good performance [9]. The challenge is to design a UWB and MIMO applications-oriented structure which means achieving good isolation and ultra wideband operation frequency bandwidth, the distance between elements should be minimized yet to keep them highly isolated. Hence, the size of the antenna should be as compact and miniaturized as possible.

Recently, various designs of UWB antennas with MIMO technology have been proposed [9–15]. Parasitic elements are used in [10] to improve isolation over a wide bandwidth. However, decoupling techniques employed over a large range of frequencies often enlarge the size and complexity of the structure. In [16, 17], the shapes of MIMO elements are different that gave high isolation, although both ports have different impedance matching and different radiation characteristics. Two octagonal shaped fractal antennas are separated by L shaped structure that is extended from the ground in to minimize the mutual coupling between the radiating elements. In [9, 18, 19], orthogonal radiation patterns with low correlation are obtained by placing elements orthogonally hence resulting in high port isolation. On this basis, several methods are proposed to further minimize the overall size of the MIMO antennas. Co-radiator technology is a very effective way to miniaturize the conventional antennas in [20, 21]. Another miniaturization technique is employing the asymmetric coplanar strip (ACS) structures presented in [22]. Furthermore, in [23] and [24] a modified defected ground structure (DGS) along with an isolating stub are used for enhancing isolation.

In this work, a novel two-element UWB MIMO antenna is proposed. The antenna is printed on FR-4 dielectric substrate with thickness of 1.6 mm, relative dielectric constant of 4.4, and loss tangent of 0.017. The simulated and measured return losses and isolations are presented and discussed. Moreover, the simulated radiation patterns, gain, radiation efficiency and envelope correlation coefficient (ECC) are as well presented and discussed. The tested antenna provides acceptable results in terms of reflection coefficient and isolation indicating that it is well-suited for UWB MIMO wireless applications.

The future scope of this field is undoubtedly high because it may include designing more antennas, like 2×2 and 4×4 elements, for possible UWB MIMO applications. The use of appropriate methods such as of metamaterials and fractal geometries, the combination of many techniques for size reduction of the designed antennas can be explored.

2 Antenna Structure and Design Procedure

2.1 Antenna Configuration

The geometry of the proposed two-element MIMO antenna for UWB application is presented in Fig. 1 whereas the geometrical dimensions are listed in Table 1. It consists of two symmetrical semi-circular patches, fed by a stepped microstrip lines, on the top side of the substrate, and a partial ground plane with two symmetrical large rectangular-shaped DGS units with a stub in between, and two symmetrical thin rectangular-shaped DGS units, on the bottom side. The full-wave solver CST studio software is used to study the antenna performance, and to perform all simulations for the parametric study.

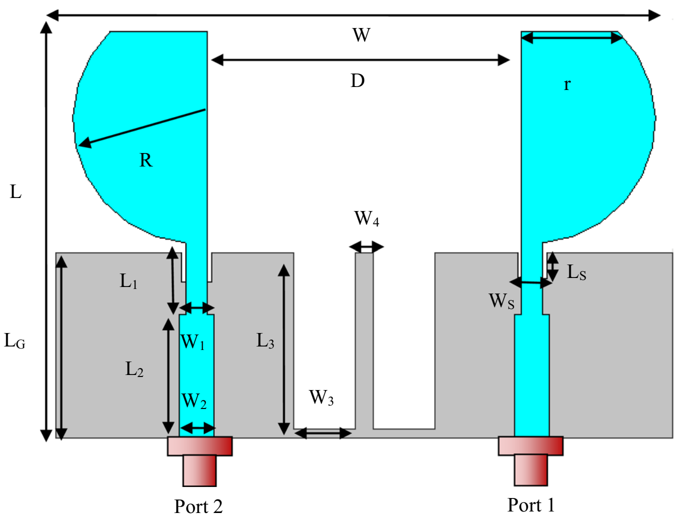


Fig. 1 Geometry of the proposed UWB MIMO antenna

Table 1 Geometrical dimensions of the proposed antenna

Parameter	Value (mm)	Parameter	Value (mm)
W	35	L_G	10.5
W_S	1.2	L_S	3
W_1	1.2	L_1	4
W_2	2	L_2	7
W_3	3.5	L_3	10
W_4	1	R	7
L	24	r	5.4
D	17.8		

2.2 Design Evolution of the Proposed UWB MIMO Antenna

The step-by-step design evolution of the proposed UWB MIMO antenna is depicted in Fig. 2. The first stage of the design focuses on covering the UWB frequency spectrum where two symmetrical semi-circular patches, fed by stepped -impedance microstrip lines, and a partial ground plane along with two symmetrical thin rectangular-slots is designed as shown in Fig. 2a, denoted as Antenna 1. This in fact insures that the ground plane size effects directly the antenna's reflection and isolation coefficients. In order to increase the isolation between the two radiators, with good impedance matching, the next step consists of etching a wide rectangular-slot in the middle of the ground plane as illustrated in Fig. 2b. This antenna, operates from 3.0 to 16.1 GHz, is referred as Antenna 2. Finally, a last step is added in the design process to achieve the final antenna. The reduction of mutual coupling effect between the two radiators is obtained when embedding a narrow stub in the middle of ground plane as shown in Fig. 2c, denoted as Antenna 3. The magnitudes of the reflection coefficients $|S_{11}|$ for the three different antenna structures are presented in Fig. 3a. From this figure, one can observe clearly that $|S_{11}|$ of the Antenna 1 is greater than −10 dB for the frequency band extending from 9.7 to 11.1 GHz which means that the UWB spectrum is not totally covered in the first stage while Antenna 2 and Antenna 3 cover frequency range from 3.1 to 14 GHz which includes frequency band of interest (3.1–10.6 GHz). Figure 3b depicts the isolation coefficients for the three different antenna structures. It can be seen that, $|S_{21}|$ of the Antenna 1 is below −20 dB from 6.5 to 11 GHz. For Antenna 2, $|S_{21}|$ is below −20 dB from 4 to 12 GHz which means that when making a rectangular slot in the centre of the ground plane, the isolation is remarkably improved. In the last stage, embedding a thin stub at the centre of the ground plane results in an isolation coefficient below −20 dB from 2.9 to 16 GHz, hence a good isolation of MIMO elements is achieved with total coverage of UWB impedance bandwidth.

2.3 Parametric study

In order to obtain optimized geometrical parameters for the final UWB MIMO antenna structure and to improve its performances for the desired application, there are some critical parameters that should be taken into consideration. For that reason, a parametric study is carried out; each parameter is varied while the others are kept constant. The first parameter that is varied is Ls which is the length of the narrow rectangular

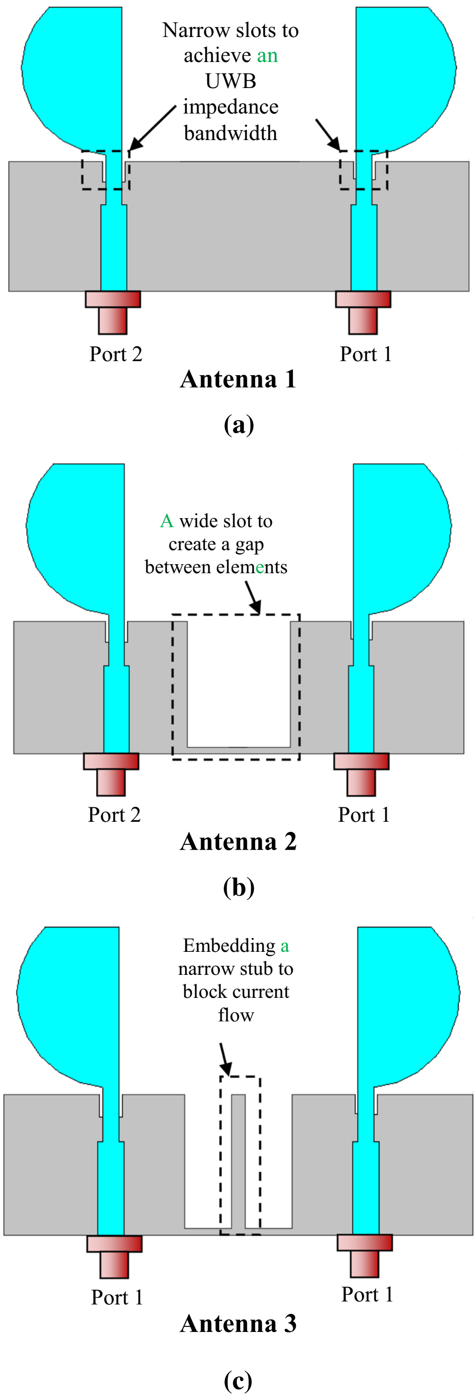
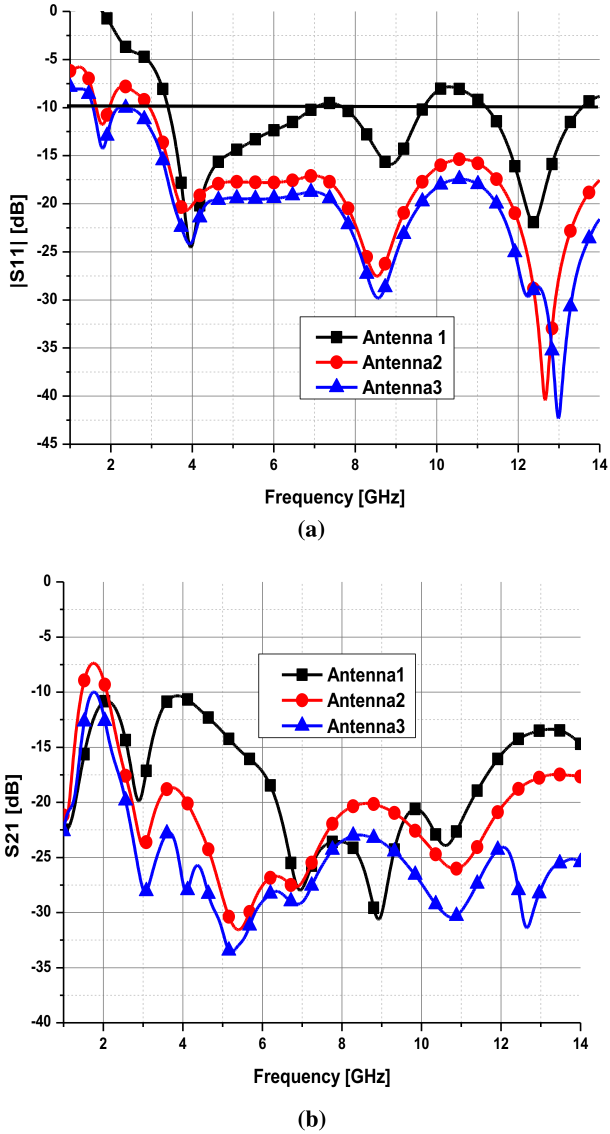


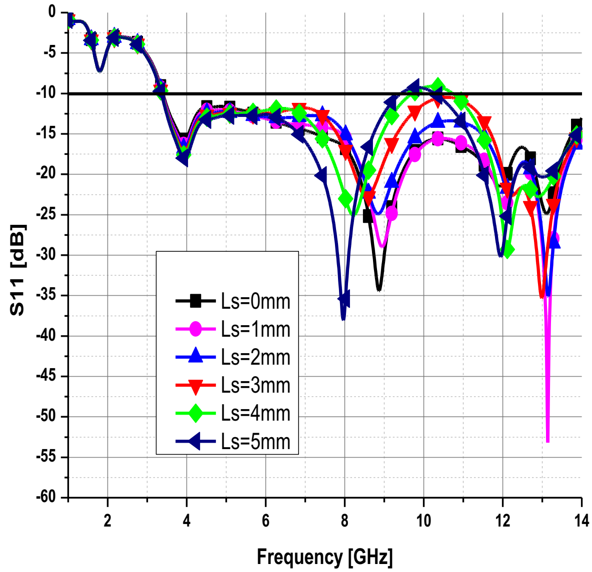
Fig. 2 Evolution procedure of the proposed UWB MIMO antenna geometry. **a** Antenna 1, **b** Antenna 2, **c** Antenna 3

Fig. 3 Reflection and isolation coefficients $|S_{11}|$ and $|S_{21}|$ of different antennas

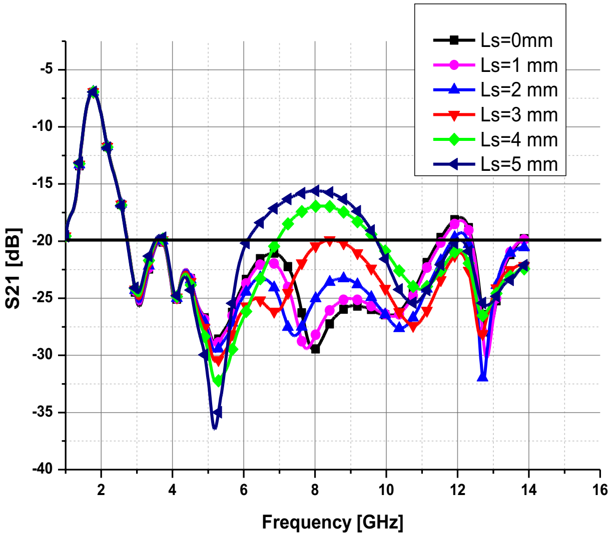


ground notches that are etched under each feeding line of both elements. The magnitudes of the reflection coefficients of different values of Ls are depicted in Fig. 4a. It is clearly seen that when the value of Ls is increased from 0 to 3 mm, $|S_{11}|$ is greater than −10 dB for the frequency spectrum 3.1–14 GHz. But when Ls is more than 3 mm, the frequency band of interest is not covered. The isolation coefficient for different values of Ls is presented in Fig. 4b. This figure shows that the $|S_{21}|$ is greater than −20 dB for the band ranging from 6 to 9.9 GHz when Ls = 4 mm or 5 mm. However, when Ls is less than 3 mm, the isolation coefficient is smaller than -20 dB for the frequency spectrum 2.6–11.5 GHz. For the value of Ls = 3 mm, the antenna elements are well isolated since

Fig. 4 Reflection and isolation coefficients $|S_{11}|$ and $|S_{21}|$ for different values of L_S



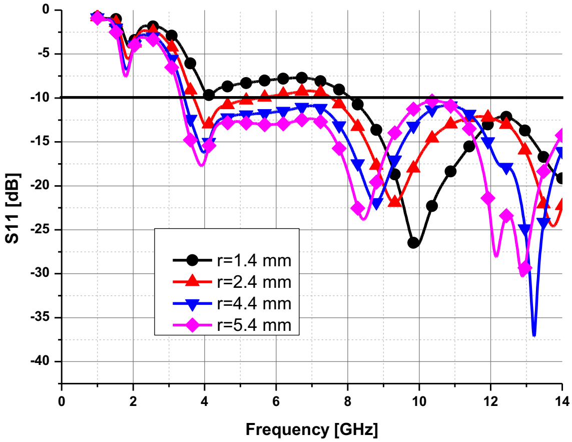
(a)



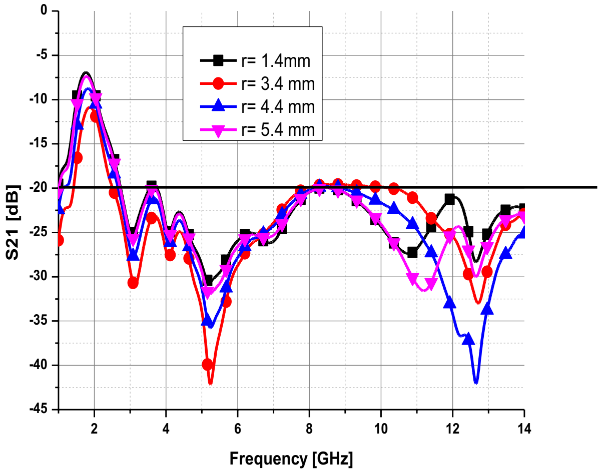
(b)

$|S_{21}|$ is less than −20 dB from 2.5 to 14 GHz. The second parameter to focus on is r, it is the length of the small part that is removed from both semi-circular patches. Figure 5a presents the magnitudes of the reflection coefficients for multiple values of r, when the value of r is increased, from 1.4 to 5.4 mm, the amplitude of S_{11} is below −10 dB from 3.3 to 16 GHz. In other words, if the surface of the semi-circular patches is reduced, the impedance bandwidth becomes wider. The isolation coefficient is below −20 dB when

Fig. 5 Reflection and isolation coefficients $|S_{11}|$ and $|S_{21}|$ for different values of r



(a)



(b)

r is increased from 1.4 to 5.4 mm as shown in Fig. 5b, hence the isolation is enhanced by increasing this parameter. The length of the thin ground stub L_3 is a key parameter that controls the isolation between the two elements of MIMO antenna. The effect of the stub length is presented in Fig. 6. If L_3 is increased from 1 to 10 mm, the amplitude of the reflection coefficient becomes smaller than −10 dB which means that the UWB bandwidth is achieved. Moreover, the isolation is enhanced and $|S_{21}|$ becomes smaller than −20 dB, when $L_3 = 10$ mm. In other words, when the stub is elongated enough means that the path of the current that flows in the direction of the stub is elongated too. Clearly, the current that flows in the direction of the other element is now concentrated only on the stub. This leads to the fact that this stub is blocking away any current that comes from the other element and stopping any mutual coupling between MIMO elements.

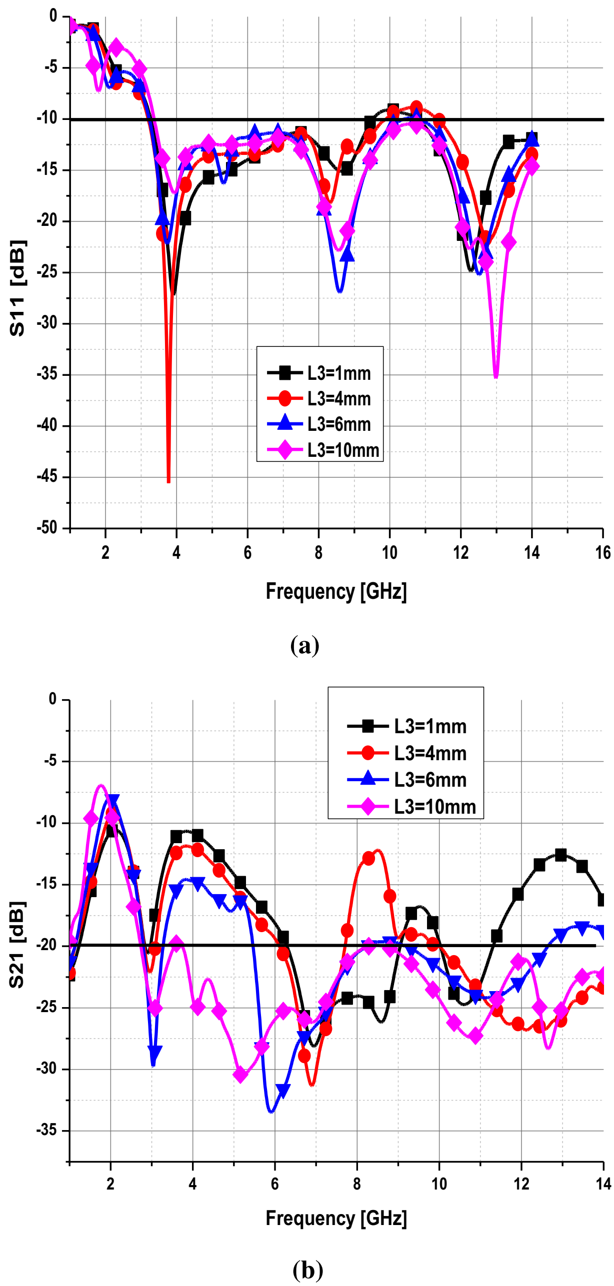


Fig. 6 Reflection and isolation coefficients $|S_{11}|$ and $|S_{21}|$ for different values of L_3

2.4 Surface current distributions

To more examine the operating mechanism of the presented UWB MIMO antenna, namely Antenna 3, the surface current distributions is simulated at two different frequencies, 7.5 GHz and 14 GHz, when port 1 is exited, while port 2 is matched with a 50 Ω load, and vice versa as shown in Fig. 7. It can be seen that, the surface current density is mostly concentrated along the exited radiator (red and yellow color), and the surface current on the matched is very weak (blue color). Due to the symmetry of the structure and the excitation, the same results can be observed while Port 2 is excited. For higher frequencies at 14 GHz, the current is also concentrated along the isolating stub (red color).

3 Fabrication and measurements

A prototype of the proposed UWB MIMO antenna was fabricated and tested to validate the proposed design. A photograph of the fabricated structure is shown in Fig. 8. The S-parameters were measured using a Rohde & Schwarz R&S®ZNB vector network analyzer. The obtained measured results are compared to the simulation ones as depicted in Fig. 9. The simulated and measured results present an acceptable agreement with slight discrepancies due to errors in the fabrication and measurement apparatus. The measured operation bandwidth is from 3.3 to 16 GHz for $|S_{11}|<-10$ dB thus the FCC spectrum for UWB is completely covered. The isolation coefficient $|S_{21}|$ is below −25 dB throughout the operating band which proves that the mutual coupling between antenna elements is minimized.

The 2-D far-field radiation patterns are depicted in Fig. 10. It is found from the plots that the proposed antenna exhibits stable omni-directional patterns in the H-plane and nearly bidirectional patterns in the E-plane. Due to the symmetry property of the MIMO antenna, the other port exhibits similar radiation patterns.

In addition, the maximum gain and radiation efficiency of the two-element MIMO antenna are shown in Fig. 11. The gain is stable with less than 2 dB variation, and the radiation efficiency is above 60% across the UWB spectrum.

The ECC is an important tool used for examining the diversity performance of MIMO antenna. For good diversity conditions, the level of ECC should be below 0.5. Considering that the antenna operates in a uniform multipath environment, the ECC value can be derived

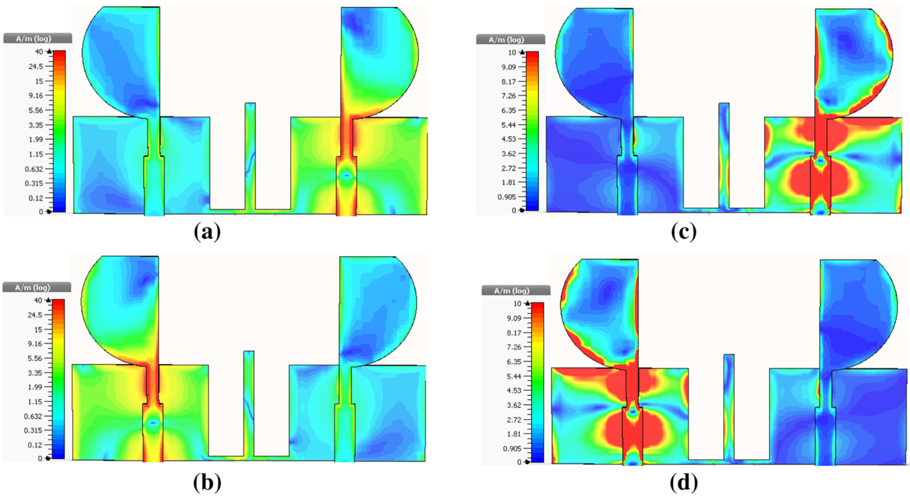
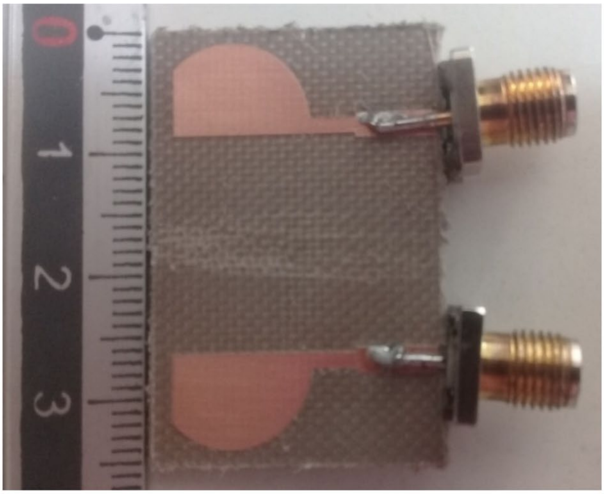
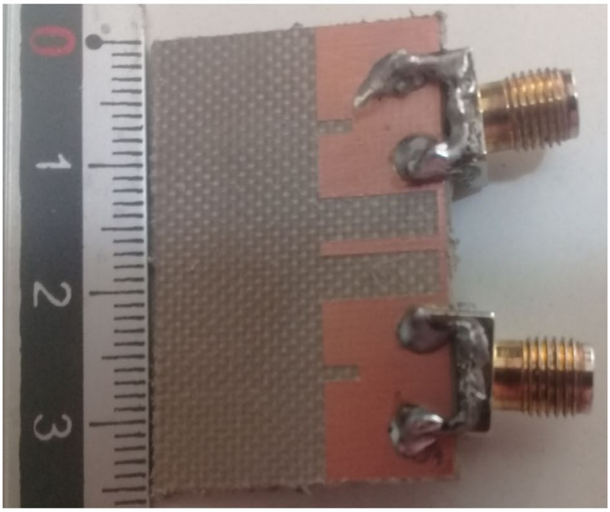


Fig. 7 Current distributions at different frequencies. **a** at $f=7.5$ GHz with port 1 excited and port 2 matched, **b** at $f=7.5$ GHz with port 2 excited and port 1 matched, **c** at $f=14$ GHz with port 1 excited and port 2 matched, **d** at $f=14$ GHz with port 2 excited and port1 matched

Fig. 8 Photograph of the proposed antenna



Top view

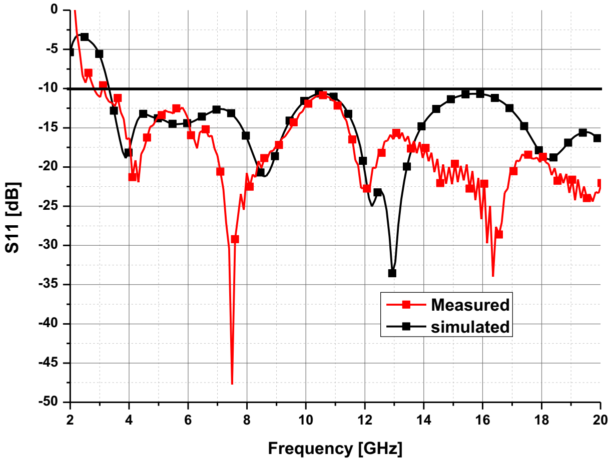


Bottom view

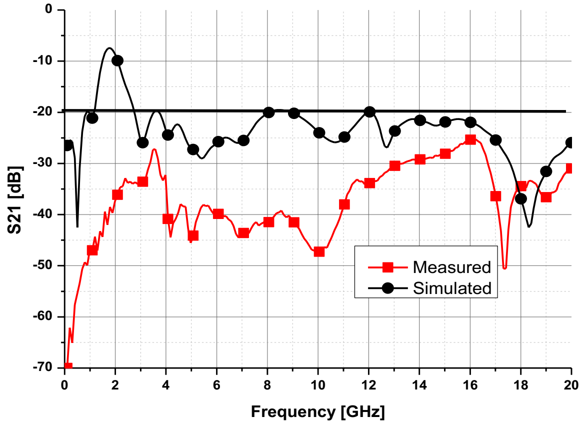
from the measured *S*-parameters [2]. As observed in Fig. 12, the ECC between Port 1 and Port 2 is found below 0.02 across the whole working band, which is much less than 0.5 to ensure good MIMO performance.

The proposed structure is compared with other references. By analyzing the data presented in Table 2, it is clear that the UWB MIMO antenna not only has wider bandwidth and better isolation but it has smaller size hence it presents better performances.

Fig. 9 Measured and simulated S-parameters of the antenna, **a** reflection coefficients $|S_{11}|$, **b** isolation coefficients $|S_{21}|$, **c** measurement setup



(a)



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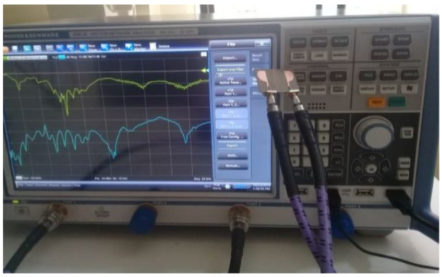

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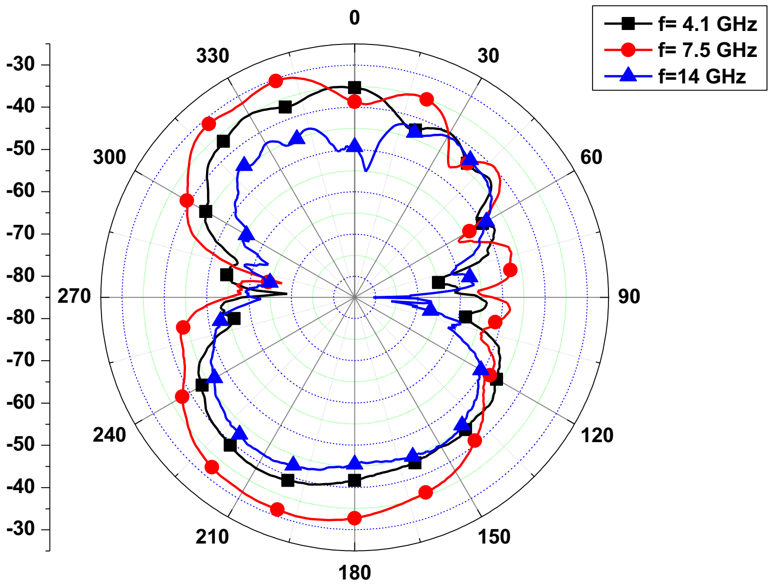
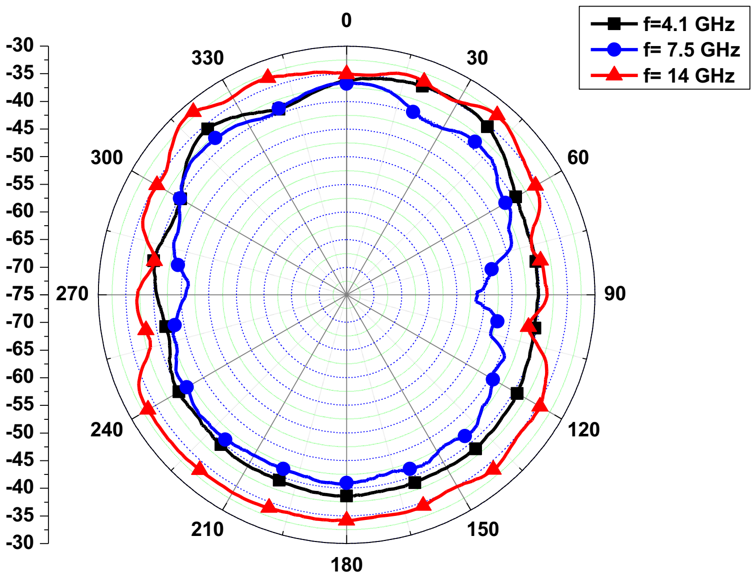


E-plane



H-plane

Fig. 10 Radiation patterns of the proposed antenna at 4.1 GHz, 7.5 GHz and, 14 GHz

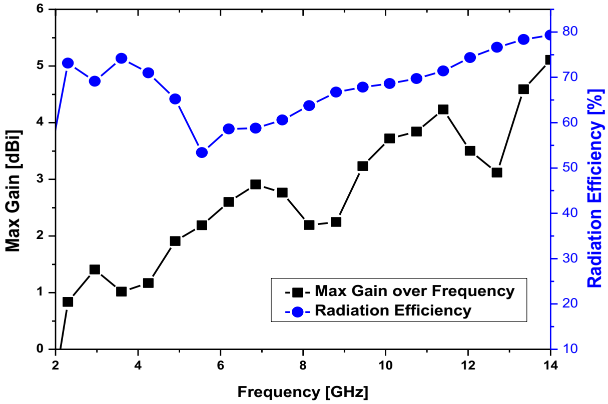


Fig. 11 Maximum gain and efficiency of the proposed antenna

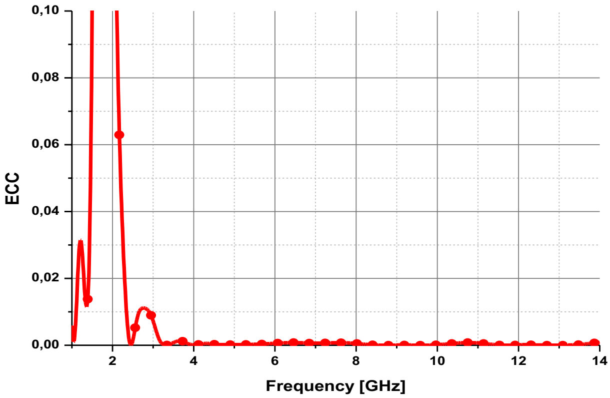


Fig. 12 Correlation coefficient of the structure

Table 2 Comparison between the proposed work and other designs

References	Size mm^2	BW (GHz)	S_{21} (dB)	ECC
Proposed work	24×35	3.3–16	<−25	<0.02
[10]	40.2×54	3.1–10.6	<−17	<0.07
[12]	42×24	3.2–16	<−22	<0.02
[18]	50×28	2.8–11.5	<−18	<0.04

4 Conclusion

In this paper, a new compact two-element UWB MIMO antenna has been designed, fabricated and tested. The achieved results in simulation and measurement show behaviour of an UWB MIMO antenna with high performance. The presented antenna, with compact size of 24×35 mm^2, covers a measured operational frequency bandwidth from 3.3 to 16 GHz along with a good isolation of −25 dB and a small ECC that ensures excellent MIMO performances. The proposed UWB MIMO antenna can be implemented in UWB applications such as wireless personnel area networks (WPAN), and wireless body networks (WBAN).

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Availability of Data and Materials All data generated or analyzed during this study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest All authors declare that they have no conflict of interest.

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