International Journal of Microwave and Wireless Technologies

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Four ports MIMO printed antenna with high isolation for UWB and X-band systems

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Research Paper

Cite this article: Ibrahim AA, Eltokhy A, Daw AF (2023). Four ports MIMO printed antenna with high isolation for UWB and X-band systems. *International Journal of Microwave and Wireless Technologies* **15**, 1601–1609. https://doi.org/10.1017/S1759078723000296

Received: 12 June 2022
Revised: 9 March 2023
Accepted: 9 March 2023

Keywords:
Connected ground; high isolation; MIMO antenna; slot antenna; UWB technology

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Abstract

In this work, a compact size 4 ports multiple input multiple output (MIMO) slot antenna with the connected ground for Ultra-Wide Band (UWB) and X band applications is introduced and discussed. The single antenna is a cross-shaped slot antenna in the ground plane and a 50 Ω microstrip line with a small L-stub is used to feed the antenna on the other side. The suggested MIMO antenna has four identical elements arranged to be orthogonal to each other to enhance the MIMO system performance. The antenna elements are connected with a small strip to compose the proposed connected ground antennas. The suggested MIMO antenna has an overall size of 47 mm × 47 mm. The antenna has tested and simulated bandwidth with $S_{11} < -10$ dB extended from 4– 14 GHz and has isolation greater than 20 dB between ports without utilizing the decoupling elements and with good consistency between results. The MIMO antenna has peak gain and efficiency, envelope correlation coefficient, diversity gain, and channel capacity loss of 5.6 dBi and 80%, <5 × 10−3, 10 dB, and <0.4 bit/s/Hz, respectively which prove that our antenna can be suggested for the UWB MIMO applications.

Introduction

Ultra-Wide Band (UWB) is a widely used technology in communication systems as it provides a high data rate and reliable communication. UWB technology has been attracting much attention and rapidly advancing and leading to innovations [1]. However, it is utilized only in a specific application that requires a short distance for communicating due to its low power and its multipath problem [2]. The antenna is the critical component in the UWB technology design because it needs several demands such as small size, low cost, simplicity, wide operating band, and special radiation patterns features [3–7]. Many antenna types had been utilized such as planar radiators [8, 9], slotted annular ring monopole antenna [10], and slot antenna [11, 12] as a single element to be integrated into the multiple input multiple output (MIMO) systems. The single-element design should take into consideration the challenges raised by the integration process. One of the most popular antennas to be used in the MIMO system is the slot antenna. It is the most attractive antenna due to its favorable impedance characteristics, simple implementation, and ease of integration with active devices [11].

MIMO technology is merged with UWB technology to reduce the multipath problem and increase the system's data rates. A lot of work is done in the UWB-MIMO field and is faced with many challenges in their designs for instance suppressing the coupling between the MIMO elements and increasing the number of elements of the design [2].

In MIMO systems, mutual coupling between two antennas has a negative effect on the efficiency of designs [13,14]. As multiple antennas are placed close to each other to design a compact device, so, mutual coupling between them should be minimized to attain high isolation between them. It also affects the individual antenna performance efficiency [15]. Many suppressing mutual coupling techniques are presented as decoupling structures [16] such as tree-like structures [17], parasitic meander lines [18], and inserting stubs [19–21]. Also, a variety of stub and slot structures were inserted between the antenna elements to reduce the mutual coupling for better MIMO performance. These structures have been added to increase the current path, and suppress the mutual coupling. Also, as reported in references [7–9, 15, 22,23] the elements were perpendicularly fed and high isolation was achieved using polarization diversity.

Another mutual coupling technique presented in [24] utilizes a metal reflector at the back of the antenna elements. Moreover, the neutralization line is also an efficient suppressing technique between the close elements. These decoupling structures are useful; however, few of them can achieve high isolation of more than 20 dB over the UWB band, especially when the elements share a connected ground [25].

This paper presents a compact UWB-MIMO antenna using a connected ground slot antenna with an L-stub feedline, in addition to 4-port compact MIMO system measurement

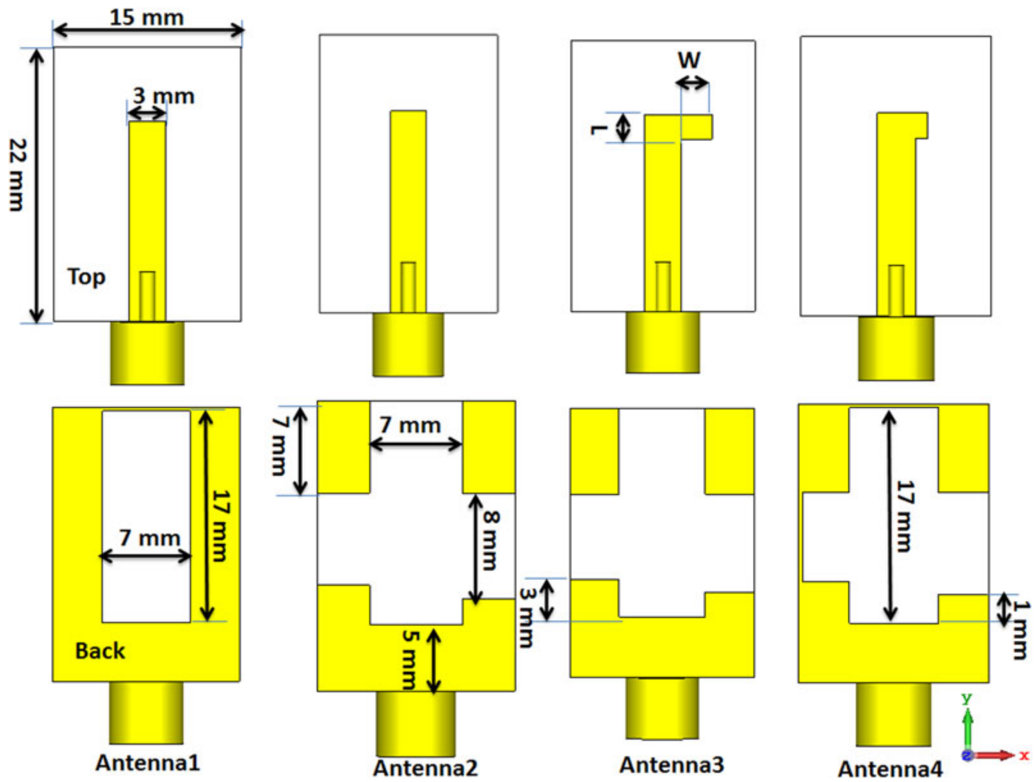

Figure 1. The suggested UWB single-slot antenna evolution.

methodologies and challenges. The single element of slot antenna design investigated the effect of stub feed and connected ground effect on the antenna performance. A design of 4-port MIMO antenna is presented, analyzed, and measured. The CST microwave studio software is utilized to extract the simulation outcomes. The organization of the paper is as follows: 'UWB single-element slot antenna design evolution' is the design evolution of the single UWB slot antenna. The four-port MIMO antenna is investigated in 'MIMO slot antenna with connected ground design'. 'MIMO Analysis' discussed the MIMO analysis and performance. Finally, 'Conclusion' is the conclusion.

UWB single-element slot antenna design evolution

This section introduces the antenna single element 4 versions and their design details. The suggested antenna evolution is presented in Fig. 1. The first antenna design (see "Antenna 1" in Fig. 1) is given by a slot antenna with a rectangular slot in the ground plane and a 50 Ω microstrip line printed on the other side of the FR4 substrate with 4.4, 0.003, and 1.6 mm dielectric constant, tan δ, and thickness, respectively. The antenna is worked with $S_{11} \le -10$ dB from 8–13 GHz as illustrated in Fig. 2 (dashed blue line). To improve the antenna bandwidth, the second antenna design is created as shown in Fig. 1. The slot shape is

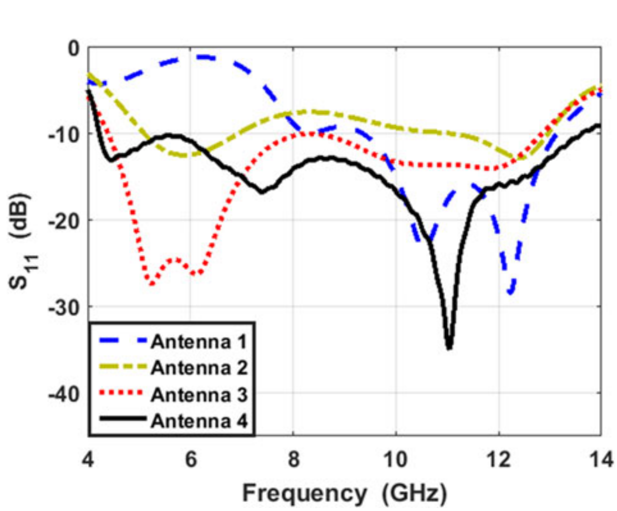

Figure 2. The S_{11} simulated results of the four versions of the slot antenna.

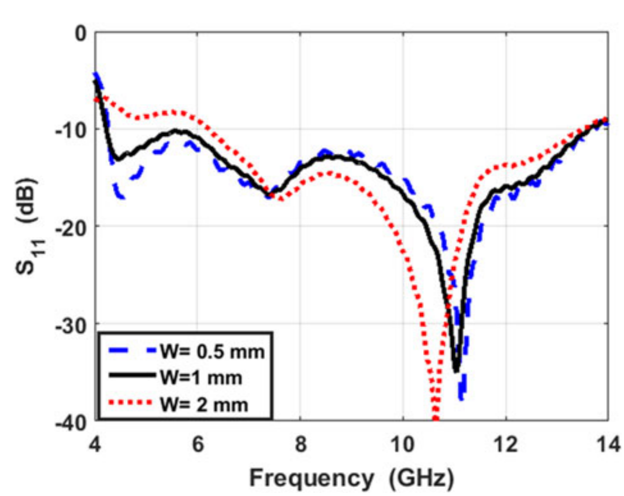

Figure 3. The S_{11} simulated results of the suggested slot antenna with varying stub length (W).

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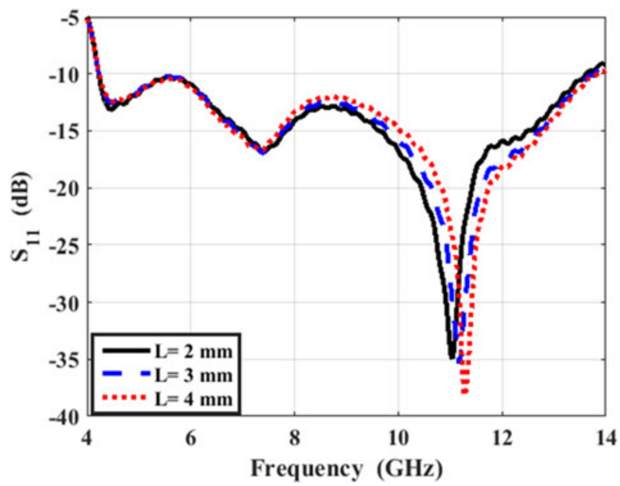

Figure 4. The S_{11} simulated results of the suggested slot antenna with varying stub width (*L*).

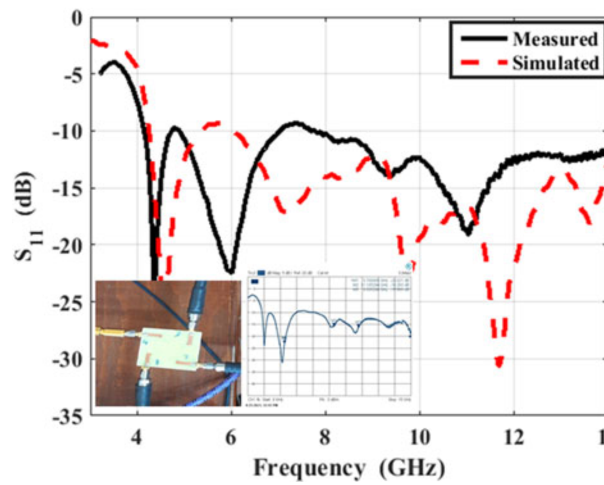

Figure 6. Simulated and measured reflection coefficient of the proposed antenna at port 1.

changed from rectangular to cross-shaped. The antenna matching is improved especially at the lower frequency band from 5.5–6.5 GHz as displayed in Fig. 2 (dotted dashed green line). The feeding line length of the proposed antenna can affect the antenna matching so any change in it the antenna matching can be changed and improved. So, the third antenna configuration is developed as shown in Fig. 1. The slot length and width are the same with antenna 2 while an open stub resonator (*L*-shaped) is added at the end of the microstrip line to improve the antenna matching as shown in Fig. 2. The antenna 3 has bandwidth with $S_{11} \leq -10$ dB from 4.3–12.5 GHz as illustrated in Fig. 2 (dotted red line).

Finally, to connect the antennas with the same ground as we will discuss in the next section to compose the proposed MIMO, a small stripline is connected as shown in Fig. 1, and the stub length and width are optimized to achieve the desired frequency band as shown in Fig. 2 because the antenna response is changed by adding the small strip. The suggested structure (antenna 4) has bandwidth with $S_{11} \leq -10$ dB from 4–14 GHz as illustrated in Fig. 2 (black solid line) which can be utilized in

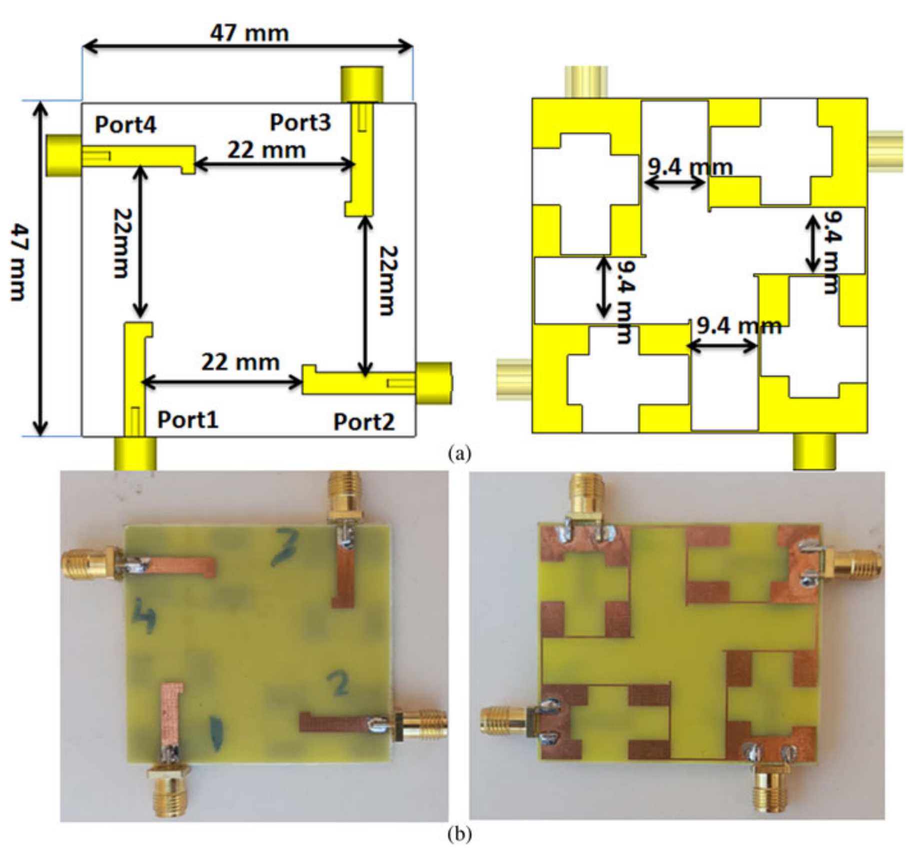

Figure 5. 4 ports UWB slot antenna configuration (a) front and back 2 D layout with dimensions (b) The front and back photo of the fabricated prototype.

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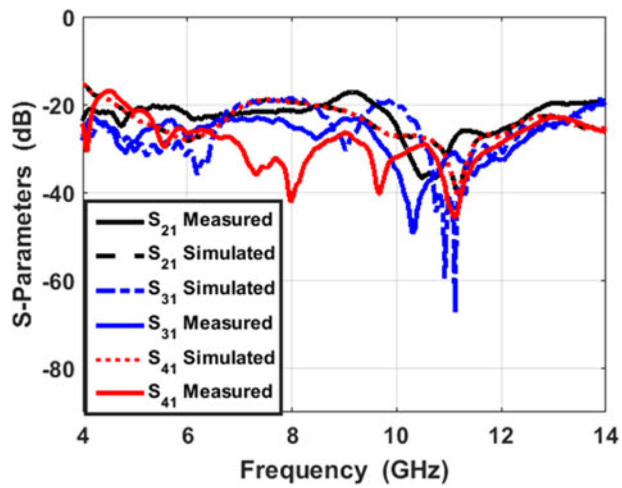

Figure 7. Simulated and measured mutual coupling coefficient results of the proposed antenna at port 1.

the UWB system. The effect of the open stub *L*-shaped resonator length (*W*) and width (*L*) on the suggested antenna matching (antenna 4) is displayed in Figs 3 and 4 respectively. It is seen that the antenna matching can be affected by increasing the stub length (*W*) from 0.5 to 2 mm especially at the lower frequency band as shown in Fig. 3. While the stub width (*L*) doesn't have a critical effect on the antenna response as shown in Fig. 4.

MIMO slot antenna with connected ground design

Figure 5(a) displays the front and back layout of the suggested 4 ports slot antenna. The single unit discussed in the previous section is arranged perpendicularly to each other as shown in Fig. 8. The antenna at port 1 has a 90° orientation with antennas at port 2 and port 4 while has a 180° orientation with the antenna at port 3. A small strip is used to connect all antennas to achieve the connected ground configuration. The separation between the feed lines is 22 mm (0.29 λ_0 at 4 GHz). While the separation between the slots in the ground plane is 9.4 mm (0.12 λ_0 at 4 GHz). The suggested MIMO antenna has an overall size of 47 mm × 47 mm. Due to the symmetry property of the suggested antenna, the results that appeared at port 1 are only extracted and discussed. Figure 5(b) shows the fabricated front and back photos of the suggested MIMO antenna prototype with an SMA connector. The suggested antenna is fabricated using a chemical etching process (photolithographic technique).

The VNA (R&S ZVB 20) with 4 ports is utilized to measure the antenna S-parameters as shown in Figures 6 and 7. The tested and simulated S_{11} of the suggested MIMO slot antenna at port 1 is illustrated in Fig. 6. Also, Fig. 6 displays the suggested antenna connected with VNA cables and the S_{11} screenshot from the VNA screen. The antenna shows tested and simulated results with $S_{11} \leq -10$ extended from 4–14 GHz with good consistency between results. The S_{21}, S_{31}, and S_{41} simulated and tested results (at port 1) of the suggested antenna are shown in Fig. 7. The tested results have isolation of more than 23 between the antenna in orthogonal orientation (antennas at port1, 2, and the port at 1, 4). The isolation is reduced to 20 dB between antennas at port1,

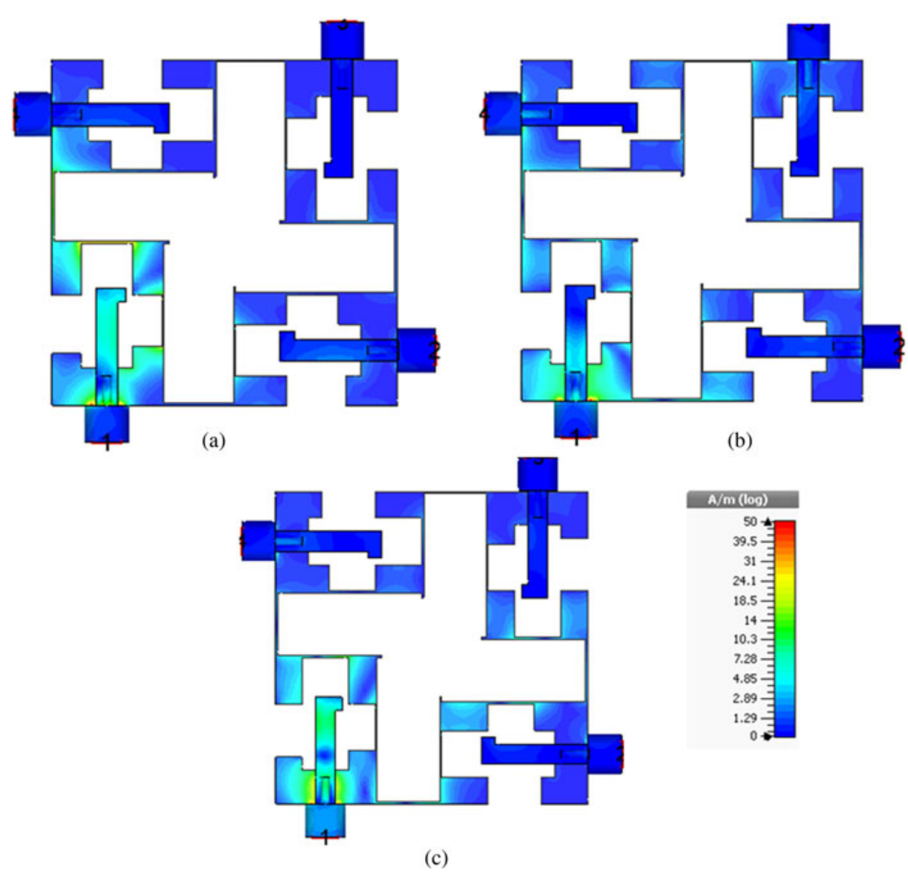

Figure 8. The suggested 4 ports UWB slot antenna current distribution at port 1 (a) at 4.5 GHz (b) at 6.5 GHz (c) at 8.5 GHz.

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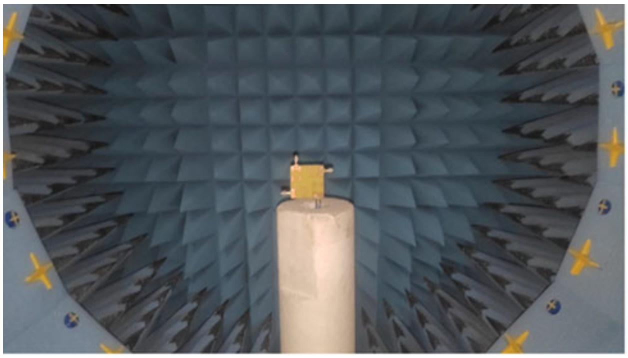

Figure 9. The setup inside the anechoic chamber of the suggested antenna for radiation patterns measurements.

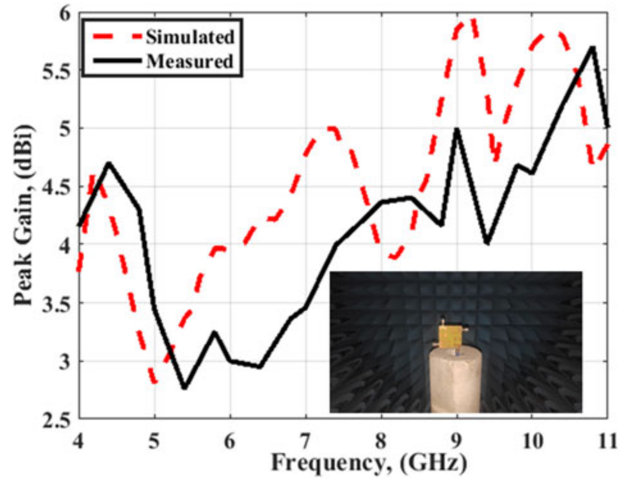

Figure 11. The suggested 4 ports UWB slot antenna peak gain at port 1.

and 3. As well, a good trend is achieved between the two results with a small shift because of the fabrication, soldering process, and human errors which can't be avoided.

From the previous results, we can say that, achieving high isolation of more than 20 dB over the UWB band, especially when the elements share a connected ground and compact size are big challenges that confirm the novelty of our work in MIMO antenna design.

Figure 8 illustrates the current distribution results of the suggested 4 ports slot antenna at port 1 at 4.5, 6.5 and 8.5 GHz. The concentration of the current is around the slotted ground of antenna 1 and a small amount of current is passed in the nearby antennas at the displayed three frequency bands which validate the low coupling between elements. The radiation patterns measuring the setup of the suggested antenna at port 1 are illustrated in Fig. 9

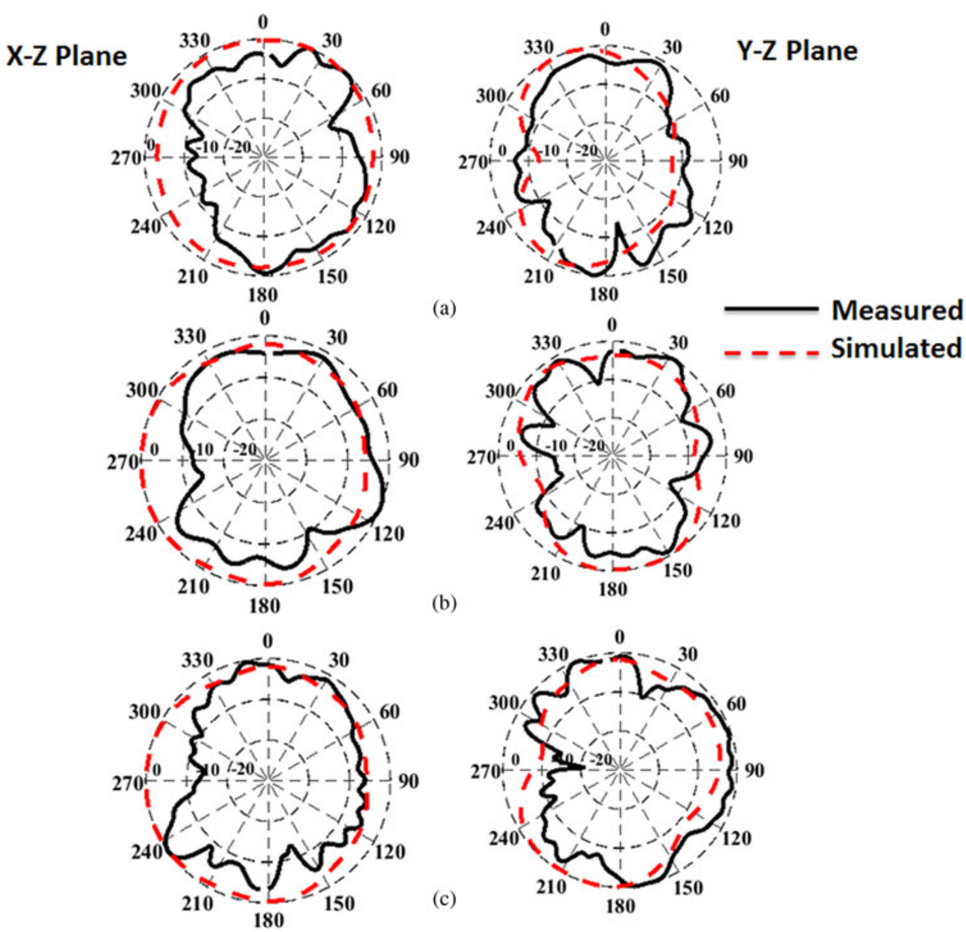

Figure 10. The suggested 4 ports UWB slot antenna normalized radiation patterns at port 1 (a) at 4.5 GHz (b) at 6.5 GHz (c) at 9.5 GHz.

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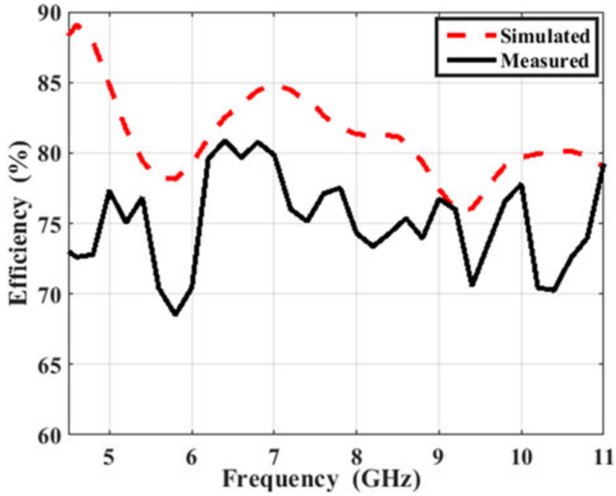

Figure 12. The suggested 4 ports UWB slot antenna efficiency at port 1.

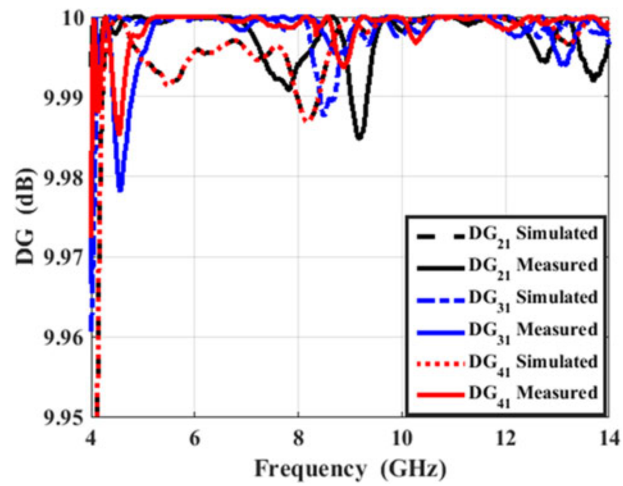

Figure 14. DG results of the suggested 4 ports UWB slot antenna at port1.

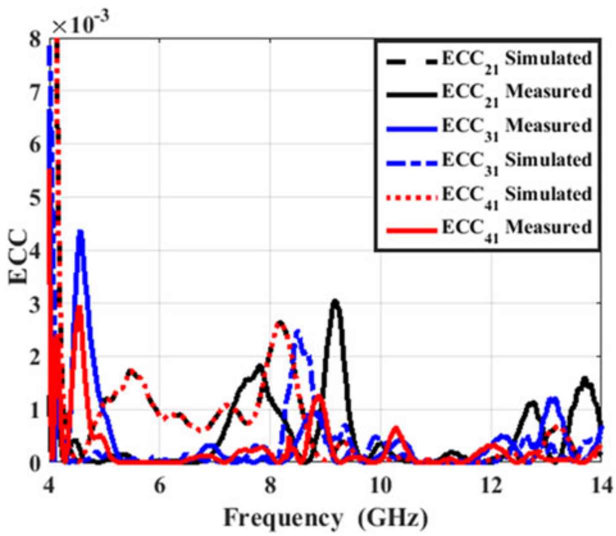

Figure 13. ECC results of the suggested 4 ports UWB slot antenna at port 1.

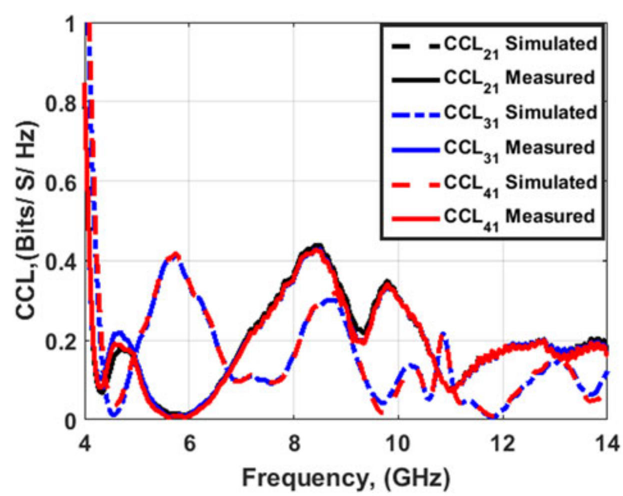

Figure 15. CCL results of the suggested 4 ports UWB slot antenna at port 1.

The normalized radiation patterns in the x–z and y–z planes of the suggested 4 ports slot antenna at port #1 and the other ports attached with matched loads at 4.5, at 6.5 and at 9.5 GHz are shown in Fig. 10. The semi-omnidirectional patterns are achieved in the x–z plane and the semi-directional patterns are achieved in the y–z plane. But, it can be seen that at higher frequency bands the semi-omnidirectional patterns can be observed at the two planes. Also, the same trends between the two results (simulated and tested) can be observed. The peak gain of the suggested antenna at port 1 is displayed in Fig. 11. The antenna has tested a peak gain of 5.6 dBi at 10.5 GHz and the gain is ranging between 3 dBi to 5.6 dBi within the designed frequency bands. Also, good matching between the two results is accomplished. The efficiency of the suggested antenna at port 1 is measured and displayed in Fig. 12. The value of efficiency is more than 75% this is due to the high losses introduced by the FR4 substrate.

MIMO analysis

The envelope correlation coefficient (ECC), diversity gain (DG), and channel capacity loss (CCL) are the three main important parameters used to check the quality and diversity of the MIMO systems. The three parameters can be extracted and calculated from the simulated and tested S-parameters and also from the far-field outcomes. When these MIMO parameters have acceptable limits that are mean, the suggested antenna can be used in the desired application. The linking between ports can be determined by the ECC MIMO parameter. The lower value of ECC produces higher MIMO performance. The acceptable limits of the ECC are lower than 0.5 and it can be extracted and calculated from equation (1) [26,27].

$$ECC = \rho_e = \left|\rho_{ij}\right| = \frac{\left|S_{ii}^{*}S_{ij} + S_{ji}^{*}S_{jj}\right|^2}{\left(1-\left(|S_{ii}|^2+\left|S_{ji}\right|^2\right)\right)\left(1-\left(\left|S_{jj}\right|^2+\left|S_{ij}\right|^2\right)\right)} \quad (1)$$

The measured and simulated ECC results of the MIMO antenna at ports 1 between ports 1, 2, ports 1,3, and ports 1,4

Table 1. Comparison between the suggested MIMO antenna and the other selected designs.

Ref	Size (mm^2)	No of antennas	Ground connection	B.W. (GHz)	ϵr/thickness (mm)	Gain (dBi)	Isolation (dB)	ECC/ DG
[9]	42 × 42	4	No	3.2–12	4.4/1.6	4	≥17	0.01/9.96
[10]	38 × 38	4	No	3–15	3.2/0.762	3.5	≥20	<0.5/–
[11]	40 × 40	4	Yes	2.9–14	4.4/1.57	4	17	0.03
[13]	25 × 25	2	Yes	3.7–9	4.4/1.6	3.8	15	<0.01/9.8
[14]	π × 225	2	No	7.96–8.76	7.2/2	6.3	>21	<0.18/10
[15]	39.8 × 23	2	No	2.5–12	4.5/1.5	2.8	>21	<0.55/–
[19]	50 × 30	2	Yes	2.5–14.5	4.4/1.6	4	>20	<0.04/8
[20]	45.5 × 33	2	No	3–12	3.55/1.5	4	≥20	0.09/–
[21]	66 × 36	2	No	2.6–12.5	3.38/0.813	4	≥20	0.001/ 9.97
[24]	36 × 36	4	Yes	3.1–10.6	4.4/1	3.5	15	0.02/–
[25]	30 × 50	2	Yes	3–10.9	4.4/1.6	3.5	≥20	0.09/9.5
Proposed	47 × 47	4	Yes	4–14	4.4/1.6	5.5	≥20	0.003/ 9.98

are displayed in Fig. 13. The ECC values for the simulated and tested results are lower than 0.005 within the working frequency bands with a good tendency between the two results. The extracted value of the ECC is lower than the acceptable limits which confirm the higher isolation between ports which leads to higher MIMO performance.The *DG* is linked to the *ECC* and its value can be taken from equation (2) [28]

$$DG(dB) = 10 \times \sqrt{1 - |ECC|} \tag{2}$$

Figure 14 illustrates the measured and simulated *DG* results of the MIMO antenna at port 1 between ports 1, 2, ports 1,3, and ports 1,4. The *DG* values for the simulated and tested results are around 9.98 dB within the working frequency bands with a good tendency between the two results.The *CCL* (bit/s/Hz) is the third parameter that evaluates the transmitted data rates over the channel and its value can be calculated from equations (3), (4), and (5) [29,30].

$$C(Loss) = -\log_2 \det(\psi^R) \tag{3}$$

$$\psi^R = \begin{bmatrix} \rho_{11} & \rho_{12} \\ \rho_{21} & \rho_{22} \end{bmatrix}, \rho_{ii} = 1 - \left(|S_{ii}|^2 + |S_{ij}|^2\right) \tag{4}$$

$$\rho_{ij} = -(S_{ii}^* S_{ij} + S_{ji}^* S_{ij}), fori, j = 1or2 \tag{5}$$

The measured and simulated *CCL* results of the MIMO antenna at port 1 between ports 1, 2, ports 1,3, and ports 1,4 are illustrated in Fig. 15. The *CCL* values for the simulated and tested results are ≤0.4 bit/s/Hz (the acceptable limits) within the working frequency bands with a good tendency between the two results. Finally, the suggested antenna is compared with the other designs from the literature to confirm the proposed design's novelty and application as tabulated in Table 1. The suggested antenna permits an increased number of ports with the connected ground and miniaturized size. Also, the antenna has high isolation with suitable gain which suggests our antenna to be utilized in the UWB systems.

Conclusion

A compact size 4 ports MIMO slot antenna with low mutual coupling, wide bandwidth, suitable radiation pattern features, low *ECC*, high *DG*, and low *CCL* has been discussed and validated successfully. The high isolation has been accomplished without placing any extra structures. This is because of the antenna orientation in orthogonal configuration. The antenna was operated from 4–14 GHz with isolation greater than 20 dB between ports. As well as, the antenna has achieved high diversity realization which guarantees high MIMO realization. The good results of the suggested antenna qualify it to be appropriate for UWB and X-band MIMO systems.

Author contributions. All authors contributed equally to analyzing data and reaching conclusions, and in writing the paper.

Financial support. There is no funds, grants, or other support was received to conduit this study.

Conflict of interest. The authors report no conflict of interest.

Data availability statement. There are no supplementary materials, and the data is available upon reasonable request.

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https://doi.org/10.1017/S1759078723000296 Published online by Cambridge University Press

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