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Experimental Investigation and Design of UWB MIMO Antenna with Enhanced Isolation

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Abstract—In this paper, a compact two ports Multiple Input Multiple Output (MIMO) antenna for Ultra Wide Band (UWB) application has been proposed. The presented antenna consists of two symmetrical radiators, developed on an FR4 substrate with an overall size of $34 \times 18 \times 1.6\,\text{mm}^3$. The proposed antenna is fed with a $50\,\Omega$ microstrip line. The antenna has good impedance matching in the range of UWB band. The isolation is lower than $< -15\,\text{dB}$ from 3.1 to 5 GHz and $< -18\,\text{dB}$ from 5 GHz to 11 GHz. Envelope Correlation Coefficient (ECC) < 0.01 and Diversity Gain (DG) $> 9.96\,\text{dB}$. The performance of the proposed antenna is analyzed and examined in terms of return loss, gain, radiation efficiency, ECC, DG, and isolation between two ports.

1. INTRODUCTION

The Federal Communication Commission (FCC) officially assigned the unlicensed bandwidth of UWB (3.1 GHz to 10.6 GHz) in 2002 [1]. In the last decade, UWB technology have received great attention and extraordinary development due to greater data rate and channel capacity, but there is also some limitation of multipath fading in such communication [2]. MIMO antennas are used widely to overcome multipath fading degradation in wireless communication system and enhanced system capabilities [3]. To achieve these goals, different approaches have been proposed for MIMO antenna in literature [4–6]. When MIMO antennas are placed in a tiny space, it will result in weak isolation between these antennas elements. Designing a MIMO antenna with small size and enhanced isolation is the goal of current work. Antennas with various shapes are proposed for UWB applications [7–11]. A tapered shape antenna in [7], a hexagonal shape antenna in [8], an octagonal shaped antenna in [9], a quasi-antenna in [10], half-square and half-circular antenna in [11] are proposed for UWB communications.

MIMO antennas are the combination of multiple antennas which require high isolation and small size. To achieve high isolation and compact size, various techniques have been used such as Defected Ground Structure (DGS), Complementary Split Ring Resonator (SRR), Electromagnetic Band Gap (EBG), Neutralization Line, and Decoupling Stubs, integrated with different antenna structures [12–30]. Different reduction techniques for mutual coupling are summarized in [12]. In [13], a two-layer EBG structure is proposed to minimize mutual coupling of two monopole antennas closely placed. The dimensions of the antenna are $60 \times 50\,\text{mm}^2$; the resonant frequency is 3–6 GHz; and improved isolation is above $-20\,\text{dB}$. A neutralization line is proposed between two circular patches to reduce mutual coupling in [14]. Dimensions of antenna are $35 \times 16\,\text{mm}^2$, and the operating frequency is 3.1–5 GHz. The secured isolation between radiating components is above $-22\,\text{dB}$. In [15], an F-shaped stub is added between two radiating elements to minimize mutual coupling. Dimensions of the antenna are $50 \times 30\,\text{mm}^2$; improved isolation is lower than $-20\,\text{dB}$; and the resonant frequency is 2.5–14.5 GHz. In [16], the isolation is enhanced by using fa requency selective surface decoupling structure, and the dimensions of antenna are $38.2 \times 26.6\,\text{mm}^2$. The operating bandwidth is 3.1–10.6 GHz, and obtained mutual coupling of the

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presented antenna is lower than −16 dB in UWB. In [17], a T-shaped strip is proposed to secure high isolation. The radiating components are placed perpendicular to one another for better impedance. The overall dimensions of the antenna are $38.5 \times 38.5\,\text{mm}^2$. The frequency bandwidth is from 3.08 to 11.08 GHz, and mutual coupling between ports is lower than −15 dB. In [18], a vertical slotted T-shaped stub is proposed to secure improved isolation between two rectangular radiating elements. The comprehensive antenna size is $22 \times 36\,\text{mm}^2$. The antenna operates from 3.1 to 11 GHz, and the enhanced isolation between two ports is lower than −15 dB. A UWB diversity antenna with CSRR and an inverted stub is proposed in [19]. The proposed diversity antenna size is $23 \times 29\,\text{mm}^2$; antenna impedance bandwidth is from 3 to 12 GHz; and achieved mutual coupling is lower than −15 dB.

A semi-ring UWB two-component MIMO antenna is presented in [20]. The fork-shaped decoupling structure has been proposed to enhanced isolation between two radiating components. The comprehensive dimensions of the nominated antenna are $50 \times 90\,\text{mm}^2$. The resonant frequency is from 1.85 to 10.6 GHz, and secured isolation is lower than −10 dB. A crescent-shaped antenna is proposed in [21]. The isolation between two ports is enhanced by a sickle-shaped strip, and port isolation is above −15 dB. The antenna dimensions are $27 \times 28\,\text{mm}^2$, and the resonant frequency is 3–10.6 GHz. In [22], slots etched in the ground are proposed for the enhancement of isolation. The antenna consists of meandering monopoles. The antenna impedance bandwidth is from 3.1 to 10.6 GHz, and enhanced isolation between radiating elements is lower than −16 dB. The comprehensive dimensions of antenna are $30 \times 40\,\text{mm}^2$. In [23], a miniature MIMO antenna is presented for UWB response with an overall size of $31 \times 20\,\text{mm}^2$. An EBG structure is presented to obtain better isolation. Operating bandwidth is from 3.8 to 7.8 GHz, and enhanced isolation is lower than −15 dB. A CPW-fed circular antenna is presented in [24]. A protruded stub is presented to secure high isolation. The overall dimensions of the antenna are $40 \times 40\,\text{mm}^2$; the resonant frequency is 3.4–12 GHz; and enhanced isolation is above −15 dB. A diversity UWB MIMO antenna with a Y-shaped DGS is used to reduced mutual coupling [25]. The comprehensive dimensions of the proposed antenna are $30 \times 30\,\text{mm}^2$. The operating frequency is 3.5 to 10.6 GHz, and mutual coupling is lower than −15 dB.

In [26], two half planer radiating elements are proposed for UWB communication. A compact T-shaped stub having a vertical slot is introduced to further enhance isolation. The complete antenna dimensions are $22 \times 31\,\text{mm}^2$. The operating bandwidth of the presented antenna is 2.9–12 GHz, and mutual coupling is lower than −15 dB in the complete UWB range. In [27], a multi-branch stub with square monopoles is designed to reduce mutual coupling. The comprehensive dimensions of the antenna are $40 \times 20\,\text{mm}^2$. The operating bandwidth is from 3 to 11 GHz, and isolation is lower than −15 dB. In [28], a shorted elliptical MIMO antenna is presented. The dimensions of antenna are $58.6 \times 46\,\text{mm}^2$; the resonant frequency is from 3.1 to 10.6 GHz; and port isolation is above −13 dB in UWB range. In [29], a common radiator UWB antenna is proposed. The comprehensive dimensions of the antenna are $45 \times 45\,\text{mm}^2$. A slot is etched in the radiator to increase isolation. Port isolation is above −17 dB, and operating frequency is 3–12 GHz. A hexagonal ring components MIMO antenna is proposed in [30]. The dimensions of antenna are $45 \times 25\,\text{mm}^2$, and isolation is enhanced by using an arc-shaped stub. The secured isolation is above −15 dB, and the resonant frequency is 3.1–12 GHz. The detailed comparison between the presented design and literature is mentioned in Table 1.

In this proposed research work, a compact elliptical slot circular-shaped antenna is proposed. The UWB is achieved by using two identical circular radiators with an elliptical slot. The presented antenna consists of a T-shaped stub attached to a partial ground plane. The proposed MIMO antenna has good impedance bandwidth ranging from 3.1 to 11 GHz and enhanced isolation between ports < -15 dB from 3.1–5 GHz and < -18 dB from 5 GHz to 11 GHz. The proposed MIMO antenna is stable and has nearly omnidirectional radiation pattern. The ECC of the proposed design is lower than 0.01, and DG is greater than 9.96 dB, respectively. The presented MIMO antenna is smaller in size and has reduced mutual coupling as compared with the articles above discussed. Good agreement is observed between simulated and measured results, showing that the proposed antenna is a suitable candidate for modern portable wireless front-ends due to its lower ECC, higher DG, and enhanced isolation. The presented antenna is simulated and analyzed in Computer Simulation Technology (CST) microwave studio.

Table 1. Comparison of the proposed antenna with antennas in literature.

Ref. #	Size (mm)	Bandwidth (GHz)	Isolation (dB)	Gain	Efficiency	Diversity Gain (dB)	ECC
[4]	26 × 26	3.1–10.6	−15	3.5 dBi	NA	NA	NA
[11]	24 × 42	3.1–10.9	−15	Peak 3.5 dB	75%	9.80	0.2
[17]	38.5 × 38.5	3.1–10.6	−15	1.4–3.6 dBi	75%	NA	0.02
[18]	22 × 36	3.1–11	−15	0–4 dB	65–80%	NA	0.1
[19]	23 × 29	3–12	−15	1.2–5.9 dB	82%	NA	0.15
[20]	50 × 90	1.85–10.6	−10	3.5 dB	51.8%	9.50	0.16
[21]	27 × 28	3–10.6	−15	3 dB	80%	NA	0.02
[22]	30 × 40	3.1–10.6	−16	NA	70–77.5%	NA	0.15
[23]	31 × 20	3.8–7.8	−15	NA	NA	NA	NA
[24]	40 × 40	3.4–12	−15	4.5 dB	NA	NA	0.025
[25]	30 × 30	3.5–10.6	−15	NA	NA	NA	0.03
[26]	22 × 31	3.43–10.1	−15	2.31 dBi	60%	NA	0.3
[27]	40 × 20	3–11	−15	2–5 dB	80%	NA	0.3
[28]	58.6 × 46	3.1–10.6	−13	NA	NA	NA	0.02
[29]	45 × 45	3–12	−17	−4 to 2 dB	90%	NA	0.01
[30]	45 × 25	3.1–12	−15	4.5 dB	70%	> 9.8	0.2
Proposed work	34 × 18	3.1–11	< −15 dB from 3.1–5 GHz and < −18 dB from 5 GHz to 11 GHz	0.9–4 dB	60–83%	> 9.96	< 0.01

2. DESIGN AND ANALYSIS OF UWB MIMO ANTENNA

The structure of the presented UWB MIMO antenna, the effect of slot and stub structures are discussed in this section. Figure 1 shows the structure of the presented antenna etched on a dielectric FR4 substrate. The dielectric FR4 has low cost and is easily available commercially, thus minimizes the overall cost of the system, which is appropriate for consumers. The final compact size of the proposed antenna is $34 \times 18 \times 1.6\,\text{mm}^3$.

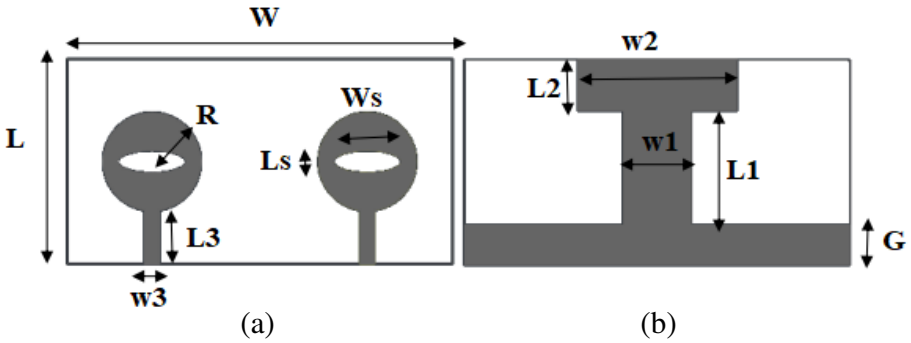


Figure 1. Geometry of the presented antenna. (a) Front view, (b) back view.

For obtaining resonance at a minimum frequency, the size of radiating components will be large enough to demand a huge current path. The proposed MIMO antenna consists of two circular radiating components with an elliptical slot at center. The elliptical slot in the radiating element is for increasing the current path and enhancing bandwidth [31]. The radiating components are placed contiguous to one another to achieve better wideband matching and component spacing [15]. Common ground is used for

the radiating elements to minimize the size of the MIMO antenna. The presented antenna is composed of two circular radiators with radius 4.3 mm and elliptical slot $Ws \times Ls$. A 50 Ω strip line is connected to the radiating patch of size $w3 \times L3$. The two circular radiators share identical ground plane of size $W \times G$ below the substrate of the antenna. Weak isolation exists between the two radiating components of antenna due to the small size and ground surface current. To overcome such a problem, a T-shaped stub is used between the radiators for better isolation. The size of the vertical block of stub is $w1 \times L1$, and the size of the horizontal block is $w2 \times L2$. After introducing of a T-Shaped stub, there is no need for further decoupling network or any other decoupling element as clear from Figure 1. Table 2 shows the dimensions of the presented antenna. All the parameters measurements are in millimeter.

Table 2. Optimized values for dimensions of UWB MIMO antenna.

Parameters	Dimensions (mm)	Parameters	Dimensions (mm)
W	34	R	4.3
L	18	Ws	3
G	3.5	Ls	1
$L1$	10	$w1$	6
$L2$	4.5	$w2$	14
$L3$	4.74	$w3$	1.3

To validate the presented antenna, all the simulations were carry out in (CST) microwave studio. The overall effect of ground on MIMO antenna bandwidth is studied in Figure 2; all the other parameters of the proposed antenna in Table 2 are the same. It is observed from Figure 2 that antenna bandwidth improves at 3.5 mm ground length which is the proposed antenna ground length.

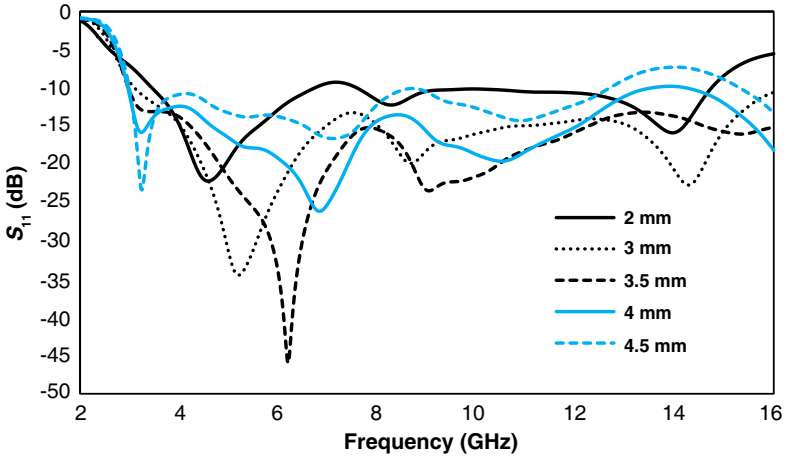


Figure 2. S-parameters plot against frequency for several values of ground G.

The simple decoupling stub structure has been presented between the radiating components to minimize mutual coupling between them. A simple T-shaped decoupling structure attached to the ground plane is presented to enhance isolation. The evaluation process of the stub structure for the presented antenna is verified from Figure 3. In the first step, a simple conventional ground plane is designed and investigated for the results. In the second stage, an I-shaped stub is added to the ground plane for modification. The I-shaped stub is further reshaped to a T-shaped stub. The T-shaped stub will result in desirable enhanced isolation.

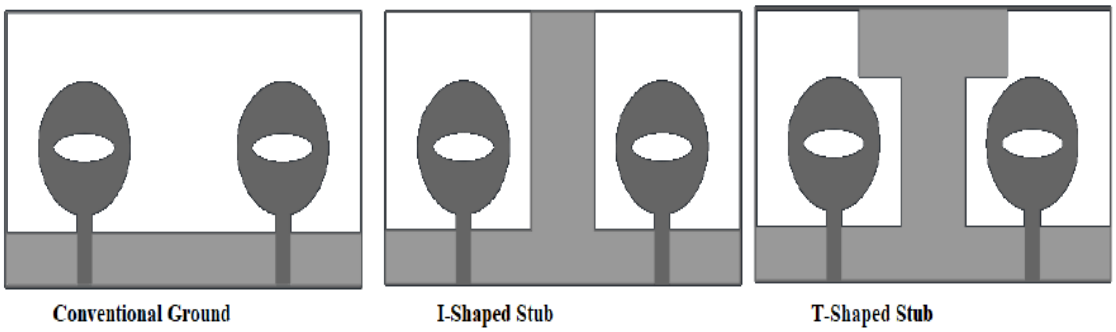


Figure 3. Evaluation of decoupling structure for the proposed MMO antenna.

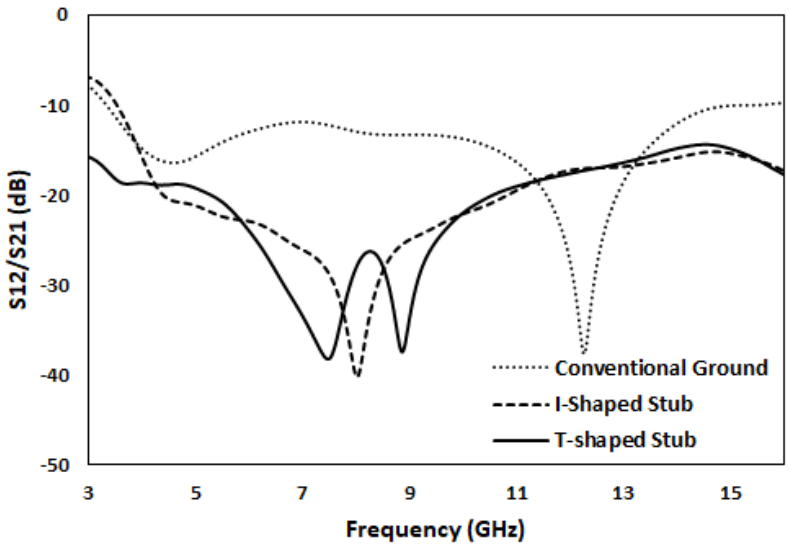


Figure 4. S-parameters results against frequency for different stub structures.

The antenna with the conventional ground is investigated, and the mutual coupling between the antennas is near -10 dB in most of the UWB region. To improve the results further, the conventional ground is modified to a I-shaped stub. The results at lower frequencies are not reasonable, and further modification to T-shaped stub is needed which maximizes the isolation of the antenna. In Figure 4, the results for antennas with the conventional ground, I-shaped and T-shaped stubs are shown. The proposed T-shaped stub results are much better than the conventional ground and I-shaped stub.

The mutual coupling of the presented antenna is -15 dB from 3 to 5 GHz and < -18 dB for the complete UWB onward as clear from Figure 4. To analyze the suggested antenna further, surface current distributions for several frequencies are summarized in Figure 5. The effectiveness of the presented antenna is examined at various frequencies after exciting port 1. Port 2 of the presented antenna is terminated. It is clear from Figure 5 that in the conventional ground plane, a strong surface current is captured between the two ports thus results in weak isolation between two components. To control this surface current, a T-shaped decoupling structure is settled between the radiating elements. After introducing the T-shaped decoupling structure, the greater portion of the surface current concentrates at port 1, and coupled current to the port 2 is minimized. Hence, maximum isolation between the two radiating elements is secured. It is worth considering that the enhanced isolation between the radiating components is always desirable.

Another important parameter for MIMO for the evaluation of antenna performance is ECC

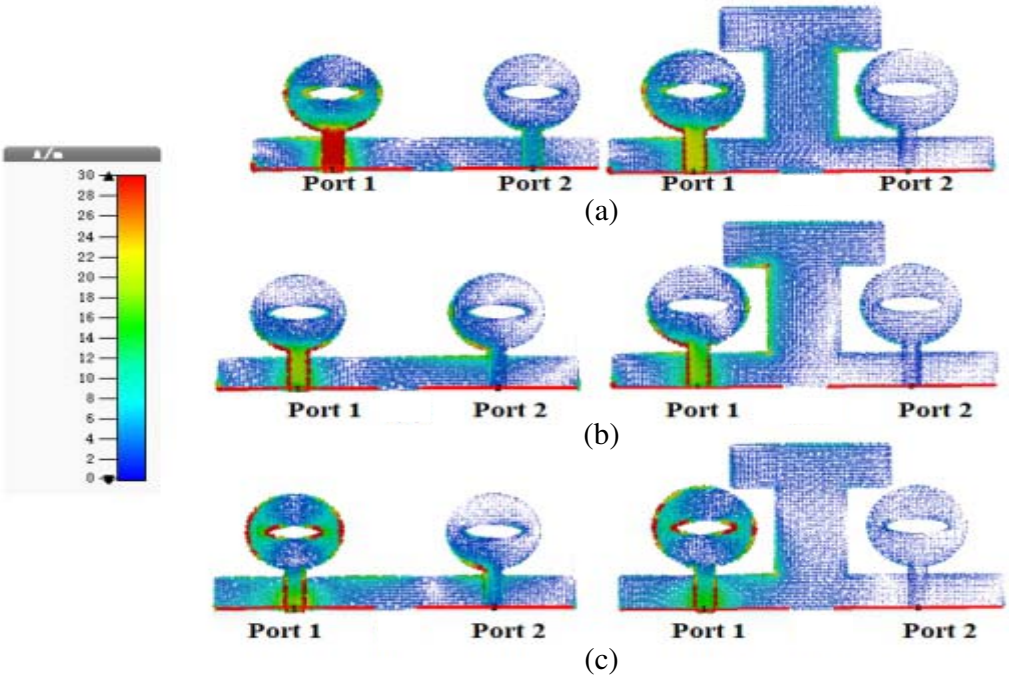


Figure 5. Surface current distribution for T-shaped stub ground and conventional ground for various frequencies (a) 3.5, (b) 6 and (c) 9.

evaluated from Equation (1) [32].

$$\mathrm{ECC} = \frac{|S_{11}^{*}S_{12} + S_{21}^{*}S_{22}|}{\left(1 - |S_{11}|^2 - |S_{21}|^2\right)\left(1 - |S_{22}|^2 - |S_{12}|^2\right)} \tag{1}$$

The proposed antenna ECC < 0.01 is computed using S-parameters. Another necessary parameter for evaluation of antenna performance is Diversity Gain (DG). It is calculated from Equation (2) by using ECC [33].

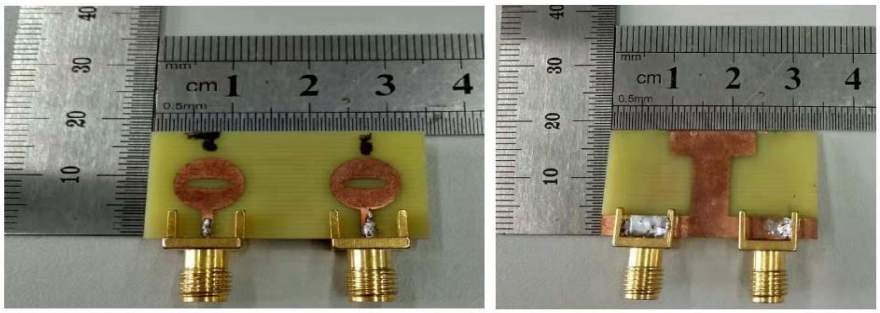
$$\mathrm{DG} = 10\sqrt{1 - (\mathrm{ECC})^2} \tag{2}$$

3. ANTENNA RESULTS AND DISCUSSIONS

The substrate of the presented antenna (1.6 mm thick FR4 substrate) easily available commercially has dielectric constant 4.4 and loss tangent 0.02. For the analysis and simulation of presented antenna, CST Microwave Studio is used. The front and back sides of the fabricated antenna are shown in Figure 6.

3.1. Reflection Coefficient

For the validation of the proposed UWB MIMO antenna, a further prototype based on the dimension parameters is fabricated, and Agilent Network Analyzer (VNA) is used to measure S-parameters results of the presented antenna. Figure 7 verifies that measured and simulated S-parameters of the presented antenna (S_{11}/S_{22} is ≤ -10 dB) and $S_{12}/S_{21} < -15$ dB from 3.1 to 5 GHz and < -18 dB onwards. All the measured results obtained from the fabricated structure show a good contract with the simulated data. The slight changes are due to material impurities and fabrication faults that occur during the process.



(a) (b)

Figure 6. Fabricated design of the proposed antenna: (a) Front side and (b) backside.

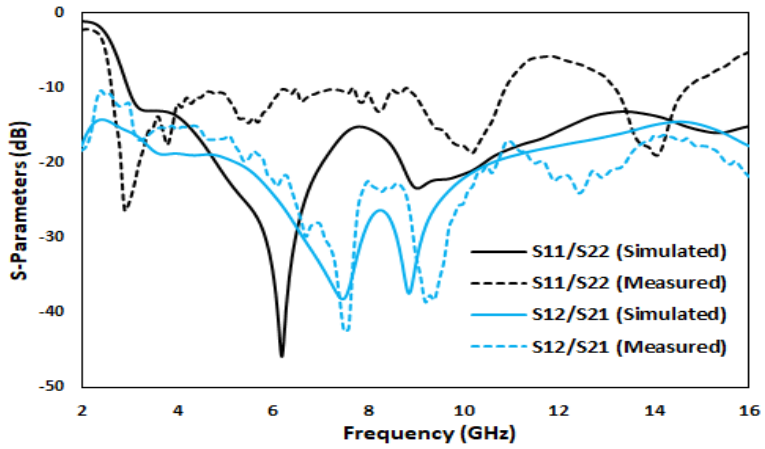
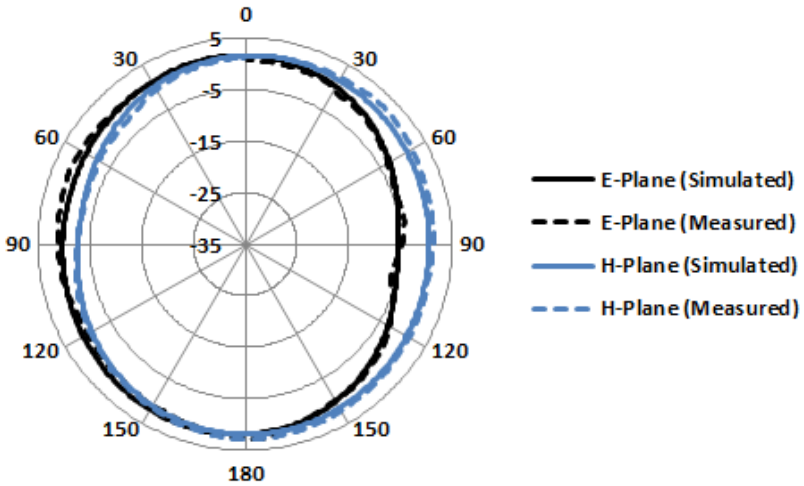


Figure 7. Measured and simulated S-parameters of proposed UWB MIMO antenna.

3.2. Radiation Pattern, Efficiency and Gain

The radiation performances of the presented antenna are studied at various frequencies. From Figure 8, it is found that the presented antenna results at these frequencies are nearly omnidirectional. Port 1 of



(a)

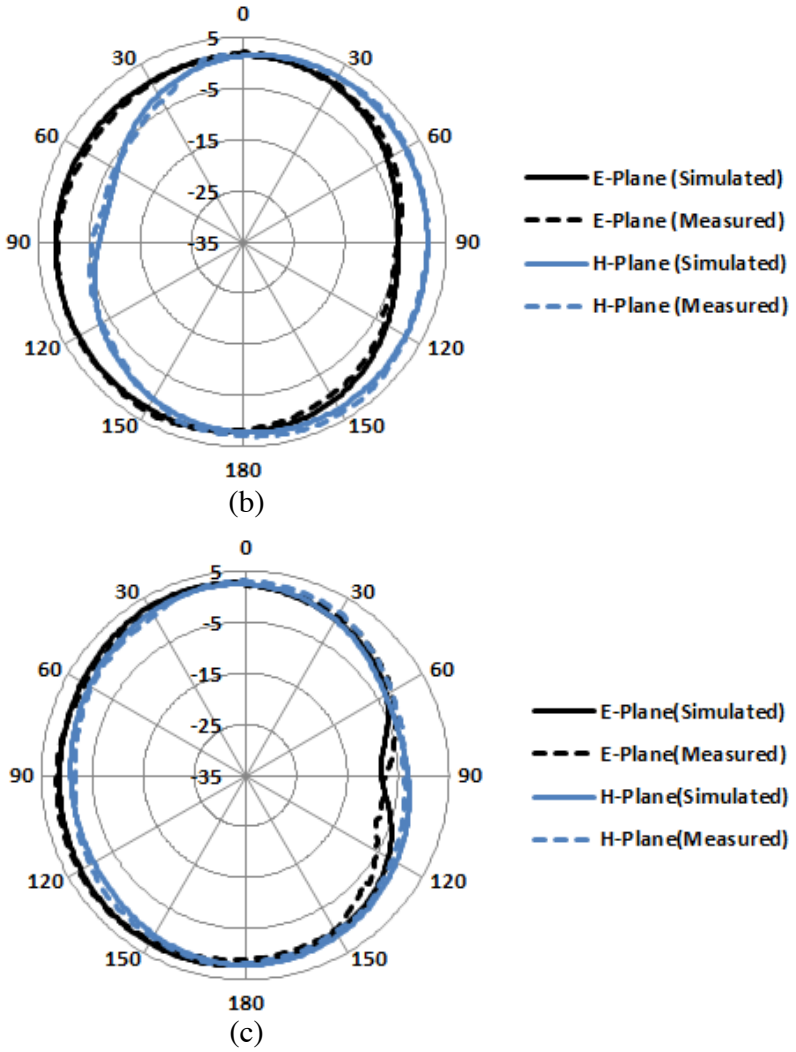


Figure 8. Radiation patterns of presented MIMO antenna at (a) 3.5, (b) 6 and (c) 9 (GHz).

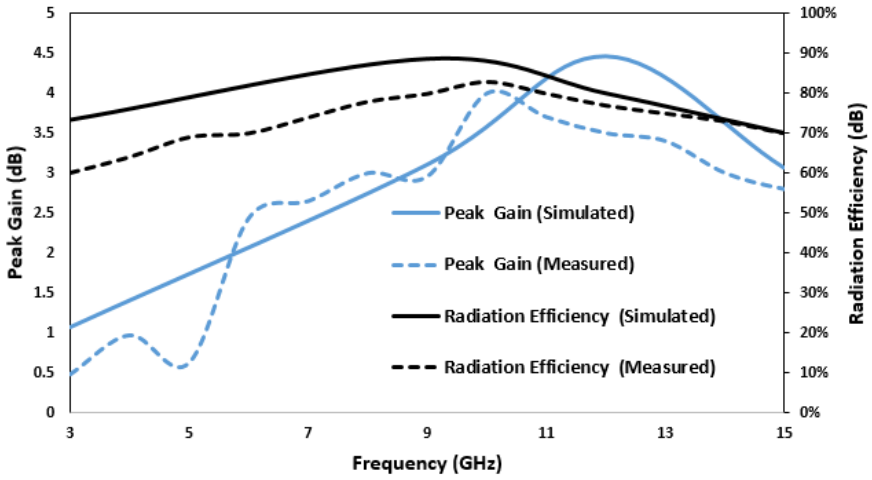


Figure 9. Radiation efficiency and peak gain of the presented antenna.

the antenna is excited for these results, and port 2 is terminated. For an identical antenna, the radiation pattern for other ports is same and mirror images with 90° rotation.

The peak gain of our presented antenna is started from 0.9 dB to 4 dB as shown in Figure 9 and increased linearly for the whole UWB range. As frequency increases, the gain increases. It is because at a higher frequency the patch dimensions become larger than the corresponding wavelength which results in the enhancement of gain [34–36]. The proposed antenna efficiency is greater than 60% to 83% in the UWB range as clear from Figure 9.

3.3. Antenna Diversity Performance Analysis

To examine the accuracy of the presented UWB MIMO antenna in terms of diversity performances. It is very essential that the antenna must have very low ECC. In general, the desired value for ECC is below 0.5. The ECC of presented UWB MIMO antenna is well below 0.01 for the entire UWB range.

Figure 10 shows that our results are in the acceptable range. Another necessary parameter for the evaluation of antenna performance is DG. DG of the proposed antenna is greater than 9.96 dB as clear from Figure 10.

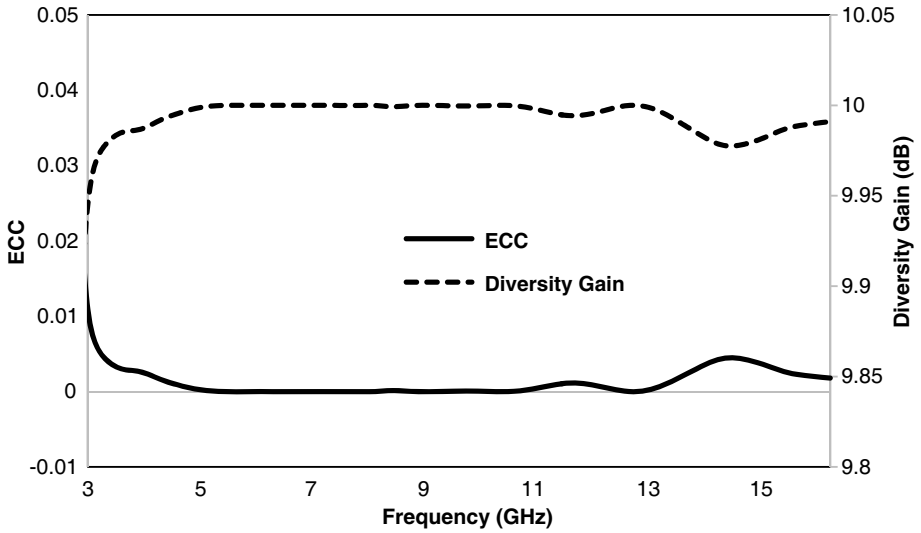


Figure 10. ECC and DG of the presented antenna.

4. CONCLUSIONS

A compact MIMO antenna with enhanced bandwidth and weak mutual coupling is discussed and proposed for UWB applications. The presented MIMO antenna bandwidth covers the entire UWB (3.1–11) GHz. A T-shaped stub is introduced to minimize mutual coupling between the radiating components. The mutual coupling of the proposed antenna is < -15 dB from 3.1 to 5 GHz and < -18 dB from 5 GHz to 11 GHz, diversity Gain > 9.96 dB, and ECC < 0.01. These advantages of the proposed MIMO antenna specify that it is a decent candidate for UWB applications.

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REFERENCES

1. Federal Communication Commission, "First report and order revision of Part 15 of the Commission's rules regarding ultra-wideband transmission system," Washington, DC, USA, 2002.
2. Liang, C., R. Su, P. Gao, and P. Wang, "Compact printed MIMO antenna with 6.1 GHz notched band for ultra wide applications," *Progress In Electromagnetics Research Letters*, Vol. 76, 77–83, 2018.
3. Parchin, N. O., H. J. Basherlou, Y. I. Al-Yasir, A. M. Abdul Khaliq, and R. A. Abd-AlHamid, "Ultra wideband diversity MIMO antenna system for future mobile handsets," *Sensors*, Vol. 20, No. 8, 2371, 2020.
4. Zhang, J. Y., F. Zhang, W. P. Tian, and Y. L. Luo, "ACS-fed UWB-MIMO antenna with shared radiator," *Electronics Letters*, Vol. 51, No. 17, 1301–1302, 2015.
5. Roshna, T. K., U. Deepak, V. R. Sajitha, K. Vasudeven, and P. Mohan, "A compact UWB MIMO antenna with reflector to enhance isolation," *IEEE Transactions on Antennas and Propagation*, Vol. 63, No. 4, 1873–1877, 2015.
6. Liu, L., S. W. Cheung, and T. I. Yuk, "Compact MIMO antenna for portable devices in UWB applications," *IEEE Transactions on Antennas and Propagation*, Vol. 61, No. 8, 4257–4264, 2013.
7. Azim, R., M. T. Islam, and N. Misran, "Compact tapered-shape slot antenna for UWB applications," *IEEE Antennas and Wireless Propagation Letters*, Vol. 10, 1190–1193, 2011.
8. Gautam, A. K., R. Chandel, and B. K. Kanaujia, "A CPW-fed hexagonal shape mono pole like UWB antenna," *Microwave and Optical Technology Letters*, Vol. 55, No. 11, 2582–2587, 2013.
9. Dikmen, C. M., S. Cimen, and G. Çakir, "Planar octagonal-shaped uwb antenna with reduced radar cross section," *IEEE Transactions on Antennas and Propagation*, Vol. 62, No. 6, 2946–2953, 2014.
10. Lin, C. C., "Compact bow-tie quasi-self-complementary antenna for UWB applications," *IEEE Antennas and Wireless Propagation Letters*, Vol. 11, 987–989, 2012.
11. Alsath, M. G. N. and M. Kanagsabai, "Compact UWB monopole antenna for automotive communications," *IEEE Transactions on Antennas and Propagation*, Vol. 63, No. 9, 4204–4208, 2015.
12. Nadeem, I. and D. Y. Choi, "Study on mutual coupling reduction technique for MIMO antennas," *IEEE Access*, Vol. 7, 563–586, 2019.
13. Li, Q., A. P. Feresidis, M. Mavridou, and P. S. Hall, "Miniaturized double-layer EBG structures for broadband mutual coupling reduction between UWB mono poles," *IEEE Transactions on Antennas and Propagation*, Vol. 63, No. 3, 1168–1171, 2015.
14. Zhang, S. and G. F. Pedersen, "Mutual coupling reduction for UWB MIMO antennas with awide band neutralization line," *IEEE Antennas and Wireless Propagation Letters*, Vol. 15, 166–169, 2016.
15. Iqbal, A., U. A. Saraereh, A. W. Ahmed, and S. Bashir, "Mutual coupling reduction using F-shaped stubs in UWB-MIMO antenna," *IEEE Access*, Vol. 6, 2755–2759, 2018.
16. Zhu, X., X. Yang, Q. Song, and B. Lui, "Compact UWB-MIMO antenna with metamaterial FSS decoupling structure," *EURASIP Journal on Wireless Communications*, Vol. 115, 2017.
17. Kang, L., H. Li, X. Wang, and X. Shi, "Compact offset microstrip-fed MIMO antenna for band-notched UWB applications," *IEEE Antennas and Wireless Propagation Letters*, Vol. 14, 1754–1757, 2015.
18. Liu, L., S. W. Cheung, and T. I. Yuk, "Compact MIMO antenna for portable UWB applications with band-notched characteristic," *IEEE Transactions on Antennas and Propagation*, Vol. 63, No. 5, 1917–1924, 2015.
19. Khan, M. S., A. D. Capobianco, S. M. Asif, D. E. Anagnostou, R. M. Shubair, and B. D. Braaten, "A compact CSRR enabled UWB diversity antenna," *IEEE Antennas and Wireless Propagation Letters*, Vol. 16, 808–812, 2016.

20. Dhar, S. K. and M. S. Sharawi, "A UWB semi ring MIMO antenna with isolation enhancement," *Microwave and Optical Technology Letters*, Vol. 57, No. 8, 1941–1946, 2015.
21. Srivastava, G. and A. Mohan, "Compact dual-polarized UWB diversit yantenna," *Microwave and Optical Technology Letters*, Vol. 57, No. 12, 2951–2955, 2015.
22. Deng, J. Y., L. X. Guo, and X. L. Liu, "An ultrawideband MIMO Antenna with a high isolation," *IEEE Antennas and Wireless Propagation Letters*, Vol. 15, 182–185, 2016.
23. Kumar, J., "Compact MIMO antenna," *Microwave and Optical Technology Letters*, Vol. 58, No. 6, 1294–1298, 2016.
24. Zhu, J., B. Feng, B. Peng, S. Li, and L. Deng, "Compact CPW UWB diversity slot antenna with dual band-notched characteristics," *Microwave and Optical Technology Letters*, Vol. 58, No. 4, 989–994, 2016.
25. Zhu, J., B. Feng, B. Peng, L. Deng, and S. Li, "A dual notched band MIMO slot antenna system with Y-shaped defected ground structure for UWB applications," *Microwave and Optical Technology Letters*, Vol. 58, No. 3, 626–630, 2016.
26. Li, W., Y. Hei, P. M. Grubb, X. Shi, and R. T. Chen, "Compact inkjet printed flexible MIMO antenna for UWB applications," *IEEE Access*, Vol. 6, 50290–50298, 2018.
27. Mathur, R. and S. Dwari, "Compact planar reconfigurable UWB-MIMO antenna with on demand worldwide interoperability for microwave access wireless local area network rejection," *IET Microwaves, Antennas & Propagation*, Vol. 13, No. 10, 1684–1689, 2019.
28. Mondal, S., K. Mandal, and P. P. Sarkar, "Design of MIMO antenna for ultra wideband applications," *IETE Journal of Research*, Vol. 64, No. 4, 497–502, 2018.
29. Srivastava, G., B. K. Kanuijia, and R. Paulus, "UWB MIMO antenna with common radiator," *International Journal of Microwave and Wireless Technologies*, Vol. 9, No. 3, 573–580, 2017.
30. Mathur, R. and S. Dwari, "Compact CPW-fed ultrawideband MIMO antenna using hexagonal ring monopole antenna elements," *AEÜ International Journal of Electronics and Communications*, Vol. 93, 1–6, 2018.
31. Purohit, P., B. K. Shukla, and D. K. Raghuvanshi, "A novel design of hybrid open slot antenna with parasitic element for wideband applications," *Progress In Electromagnetics Research C*, Vol. 90, 95–107, 2019.
32. Khan, M. I. and M. I. Khattak, "Designing and analyzing a modern MIMO-UWB antenna with a novel stub for stop band characteristics and reduced mutual coupling," *Microwave and Optical Technology Letters*, 1–6, 2020.
33. Khan, M. I., M. I. Khattak, S. U. Rahman, A. B. Qazi, A. A. Telba, and A. Sebak, "Design and investigation of modern UWB-MIMO antenna with optimized isolation," *Micromachines*, Vol. 11, No. 24, 432, 2020.
34. Kumar, R. and S. Gaikwad, "On the design of nano-arm fractal antenna for UWB wireless applications," *Journal of Microwaves, Optoelectronics and Electromagnetic Applications*, Vol. 12, No. 1, 158–171, 2013.
35. Singhal, S. and A. K. Singh, "CPW-fed hexagonal Sierpinski super wideband fractal antenna," *IET Microwaves, Antennas & Propagation*, Vol. 10, No. 15, 1701–1707, 2016.
36. Rahman, S. U., Q. Cao, H. Ullah, and H. Khalil, "Compact design of trapezoid shape monopole antenna for SWB application," *Microwave and Optical Technology Letters*, Vol. 61, No. 3, 1931–1937, 2019.