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A Compact Notched UWB MIMO Antenna with Enhanced Performance

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Abstract—This paper investigates the performance of compact triple band-notched Multiple Input Multiple Output (MIMO) antenna for Ultra-Wideband (UWB) communication. Open-ended quarter wavelength slots are inserted on the radiators. These slots are used to obtain notch bands at WiMAX/C band, WLAN band and the X-band Satellite Communication System that ranges in 3.3–4.2 GHz, 5–6 GHz, and 7.2–8.6 GHz, respectively. An I-shaped stub extends from the ground surface to minimize mutual coupling among radiating elements. Mutual coupling and Envelope Correlation Coefficient are found less than -15 dB and 0.2, respectively. The diversity characteristics like Mean Effective Gain Ratio and Total Active Reflection Coefficient are found around 1 dB and less than -10.5 dB respectively. The radiation efficiency of the radiator is more than 80% over the entire UWB frequency range. The proposed antenna is designed with the overall dimensions of $23 \times 40 \times 1.6\,\mathrm{mm}^3$.

1. INTRODUCTION

High data rates and better Quality of Service (QoS) are the main concerns of future wireless communication systems. In April 2002, the FCC approved ultra-wideband (UWB) that lies within 3.1 to 10.6 GHz for the commercial use [1]. The use of UWB technology is encouraged in wireless communication, as it is one of the most favorable techniques for improving data rate. UWB technology has attracted considerable attention because of its features like extremely less power consumption, increased data rate, and inexpensive [2]. It is used in many applications such as high accuracy radar, sensor data collection, imaging, and indoor position systems.

Ultra-wideband is a trending technology for short range and low power communication. However, some narrowband applications cause interference in UWB frequency range such as WiMAX/C Band, WLAN Band, and X-Band that lie in 3.3–4.2 GHz, 5–6 GHz, and 7.2–8.6 GHz, respectively [1]. To minimize this interference, a UWB antenna with multiband rejection is needed. Band rejection characteristic can be achieved in UWB antennas by using different shapes of slots. These slots are etched in the patch to produce triple band notches for the elimination of interference, for example, an arc-shaped slot [3], multiple fractal-shaped slots [4], vertical H-shaped slot [5], two round shaped slots of half wavelength in the antenna element [6], three semi-circle half-wavelength slots [7], and three straight rectangular strips with open-ends [8]. Further, to attain notches an arc slit on the ground and a fractal arc slit on the radiating patch can be used [9]. Different shapes of stubs like fork-shaped or short stub [10] on radiator, by using Electromagnetic Band Gap (EBG) structures [11], can also discard the interfering band. Band rejection resonators like capacitively loaded loop [12], electric ring [13], and stepped impedance resonator-defected ground structure [14] are also reported in the literature.

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Signal fading is the key concern for UWB system in the multipath environment. It can be fixed by UWB MIMO antenna which provides improved channel capacity. UWB MIMO antennas have issue of mutual coupling between radiating elements. High electromagnetic coupling among antenna elements affects system performance. Mutual coupling can be minimized by Defective Ground Structures (DGS) [15] such as in dumb-bell shape [16] and U-shape [17]. Another method to achieve better isolation is to extend the ground like a T-shaped strip [18]. In the literature, researchers have also used meander line resonator [19], split ring resonators [20], neutralization line [21], polarization diversity [22, 23], and decoupling strips [24] to improve the mutual coupling between the antenna elements.

Various researchers have discussed dual and triple notched bands characteristics with UWB MIMO antenna [25]. After surveying different techniques [26, 27], it is realized that achieving band notch UWB MIMO antenna with compact size remains a challenge.

A miniaturized triple band notched UWB MIMO antenna is proposed in this work. An I-shaped stub is used to decrease the mutual coupling amid radiating elements. Open-end quarter wavelength slots are used to attain band notches in interfering bands. The tested results indicate that the suggested antenna has an excellent low mutual coupling and impedance matching.

2. PROPOSED UWB MIMO ANTENNA WITH TRIPLE NOTCHES

2.1. Design and Analysis

Dimensions of the suggested antenna are presented in Fig. 1. It has identical patch antenna elements with modified ground plane. Flame Retardant (FR)-4 substrate has dielectric constant (ε_r), substrate height, and loss tangent of 4.4, 1.6 mm, and 0.02, respectively. The dimension of the suggested antenna is $23 \times 40 \times 1.6\,\text{mm}^3$. A 50-ohm microstrip line excites the antenna elements. An I-shaped stub is connected with ground plane to reduce mutual coupling. Further, three open-end quarter wavelength slots denoted as twisted quarter wavelength open end slot (slot-1), inverted L-shaped open end slot (slot-2), and rectangular slot (Slot-3) are inserted on the radiator. These slots are used to achieve band-notches at WiMAX/C Band, WLAN Band, and X-band Satellite Communication band. Slot 1 and slot 2 are twisted to achieve a compact size of the radiating patch. Fig. 2 presents the fabricated antenna. Fig. 3 illustrates the stepwise design of the proposed antenna. Antenna A is a UWB antenna without any notch. Once the UWB antenna is achieved, it is further modified to Antenna B using slot 1 so as to eliminate interference from WiMAX/C band. Slot 2 and slot 3 are inserted to the radiating surface to suppress interference from WLAN Band and X Band, respectively. Design and simulations for the suggested antenna are performed by Ansoft HFSS v.13 software. Dimension of the antenna is given in Table 1.

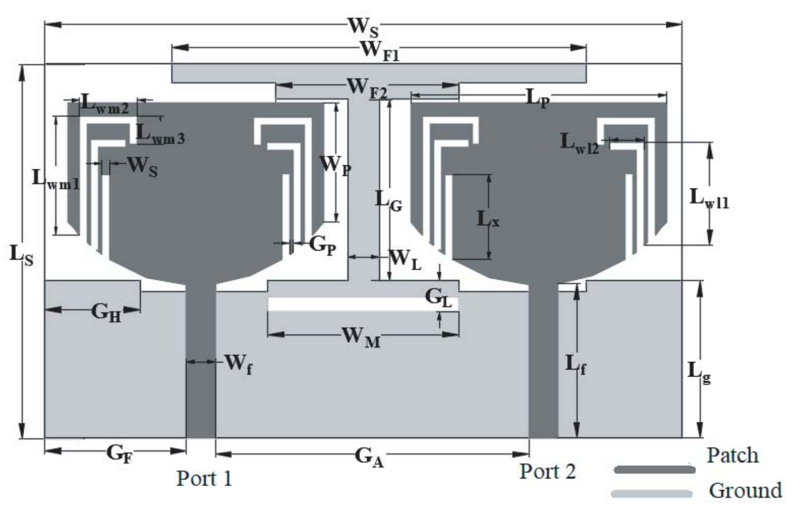


Figure 1. Design of suggested antenna.

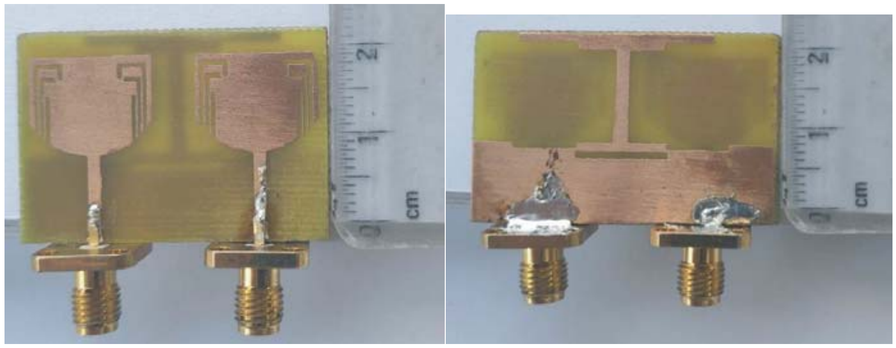


Figure 2. (a) Top view, (b) bottom view of fabricated UWB MIMO antenna.

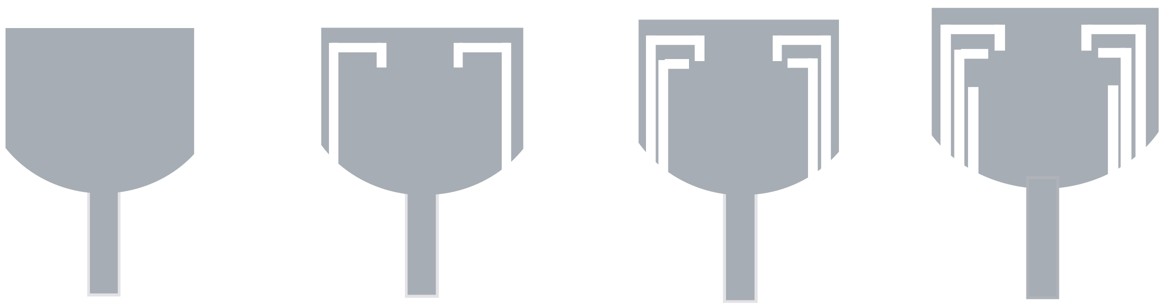


Figure 3. Stepwise expansion of single element UWB antenna (top view).

Table 1. Parameters of suggested antenna.

Parameters	L_S	W_S	L_g	L_f	W_f	L_{wm1}	L_{wm2}	L_{wm3}
Unit (mm)	23	40	9.3	9.7	2.6	8	3	2
Parameters	L_{wl2}	W_g	L_x	w_s	G_A	G_F	W_M	L_G
Unit (mm)	1.3	0.2	6	0.5	19.7	8.9	12	11.5
Parameters	G_H	W_{F1}	W_{F2}	G_P	L_{wl1}	G_W	W_L	L_P
Unit (mm)	6	26	16	2	7	0.7	2	7.5

2.2. Effect of Open End Slots on Single Element of Proposed Antenna

By inserting open-end slots in the radiator, triple band-notches are achieved. These open-end quarter wavelength slots introduce impedance mismatch [28]. By varying the dimension of the slots, one can adjust notch bands.

In Fig. 4, VSWR variations of all intermediate antennas along with the suggested antenna are observed. Impedance bandwidth of the designed UWB MIMO antenna lies in 2 to 11 GHz range. It is verified that each slot is responsible for notch generation in its band. Fig. 5 shows the tested results of VSWR variation with frequency.

The total length (L_{Wimax}) of slot-1 is given as

$$L_{\text{Wimax}} = L_{wm1} + L_{wm2} + L_{wm3} \tag{1}$$

Slot-2 is inserted in the patch to get band-notch function at WLAN at center frequency 5.5 GHz, and

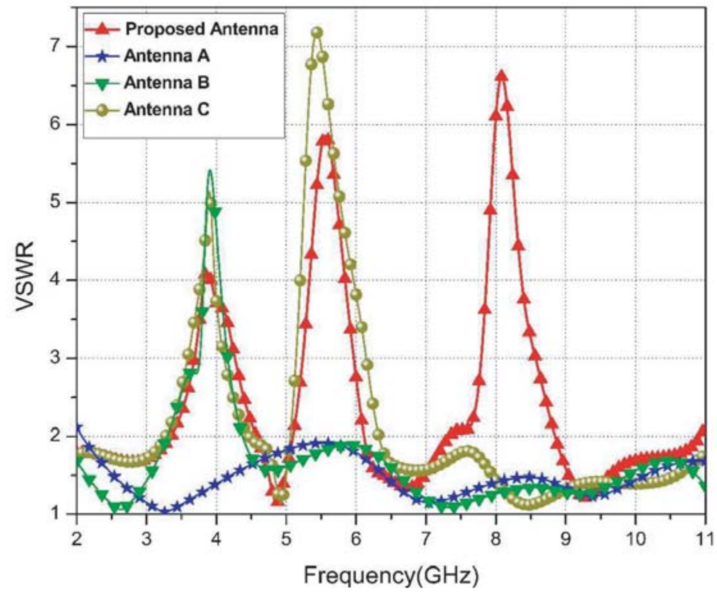


Figure 4. VSWR of various antenna.

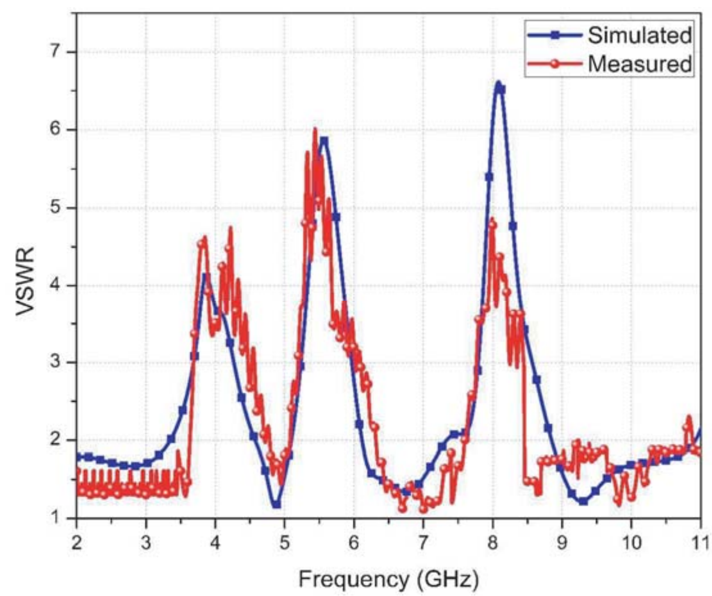


Figure 5. Measured and simulated VSWR.

the total length (L_{wlan}) of slot-2 can be given as

$$L_{\text{wlan}} = L_{wl1} + L_{wl2} \tag{2}$$

$$L_{\text{xband}} = L_x \tag{3}$$

The whole length of slot 1, slot 2, and slot 3 [29–31] is calculated by a given formula

$$L_{\text{slot}} = \frac{c}{4f\sqrt{\varepsilon_{eff}}} \tag{4}$$

where ε_{eff} represents the effective dielectric constant. The effective dielectric constant is calculated by using ε_r of the substrate:

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} \tag{5}$$

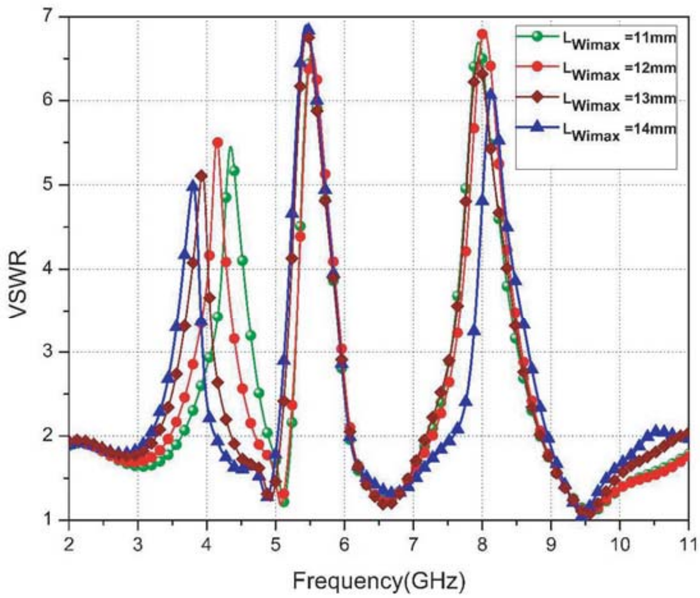


Figure 6. Variation of WiMAX length.

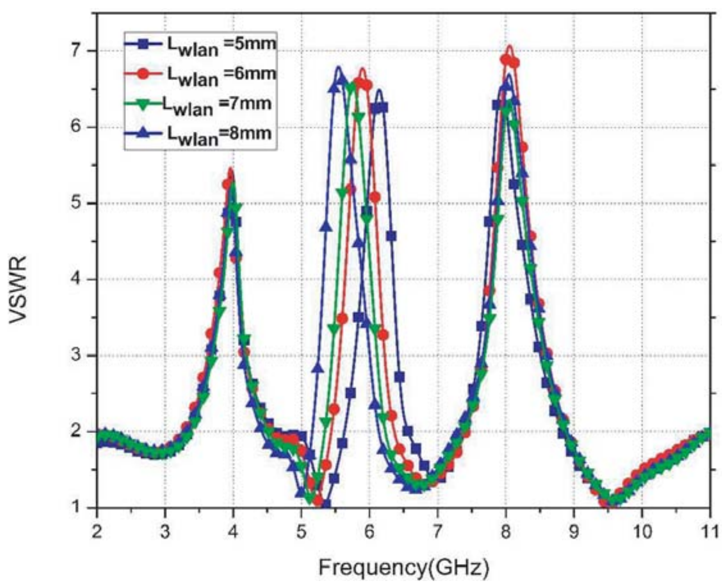


Figure 7. Variation of WLAN length.

The calculated ε_{eff} is 2.7. Therefore, the length of slot 1 (L_{wimax}) is 13 mm. Fig. 6 indicates the VSWR for the change of length L_{wimax}, while keeping parameters constant. It can be seen from Fig. 6 that the center notched frequency shifts towards 3.8 GHz from 4.3 GHz, as the length increases from 11 mm to 14 mm.

The intended length of slot 2 (L_{wlan},) for the WLAN band is 8.3 mm. Fig. 7 indicates the VSWR with change of length L_{wlan}, while keeping other parameters constant. As the length increases from 5 mm to 8 mm, the center notched frequency shifts from 6.2 GHz to 5.5 GHz. For X band, the calculated length of slot 3 (L_{xband}) is 6 mm.

Figure 8 illustrates the VSWR for the change of length L_x, while keeping other parameters constant. As the length increases from 6 mm to 9 mm, the center notched frequency shifts from 8 GHz to 6.9 GHz.

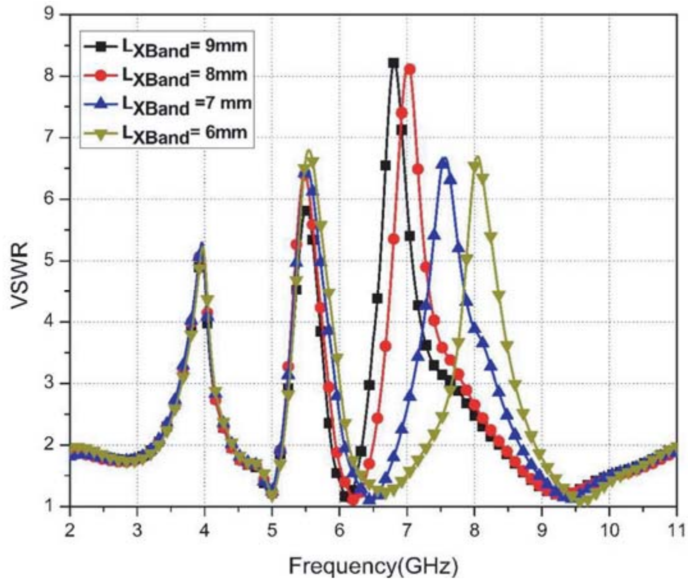


Figure 8. Variation of X band length.

It can be observed from Figs. 6, 7, and 8 that tuning a particular slot length does not disturb the other notch frequency. Therefore, coupling among slots is very little and can be tuned individually.

2.3. Effect of Variation of Ground Plane of Suggested Antenna

The suggested antenna performance also depends on the ground plane. Due to modified ground plane, the isolation is enhanced. Fig. 9 illustrates stepwise expansion of UWB MIMO antenna ground plane design. Antenna D in Fig. 9 is selected for the proposed MIMO antenna design so as to have triple band notches. Further, Fig. 10 shows mutual coupling variations with different ground plane shapes. It is observed from Fig. 10 that the best performance can be obtained using ground plane D. Fig. 11 illustrates the measured results of mutual coupling.

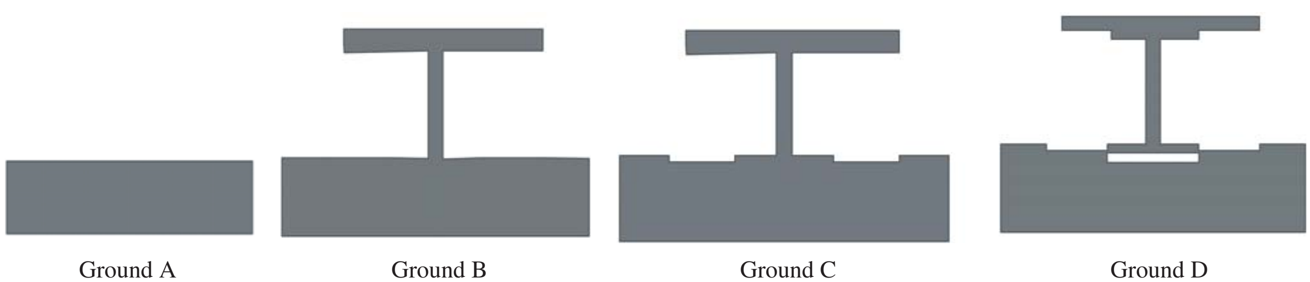


Figure 9. Expansion of ground plane of proposed UWB MIMO antenna.

Figs. 12(a), (b), and (c) depict that the currents are focused on slot 1, slot 2, and slot 3 of the radiator, respectively. Here, in all the three cases, the currents along the slot are in opposite directions. Hence, currents will cancel out, and no radiation takes place. Therefore, VSWR is greater than 2 at these frequencies.

Figures 13(a), (b) and (c) depict simulated and tested radiation pattern plots at different frequencies.

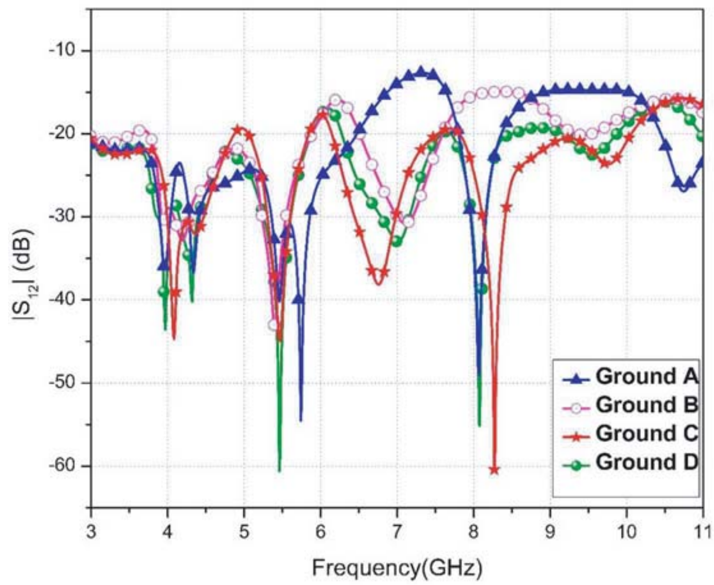


Figure 10. Mutual coupling in dissimilar ground plane.

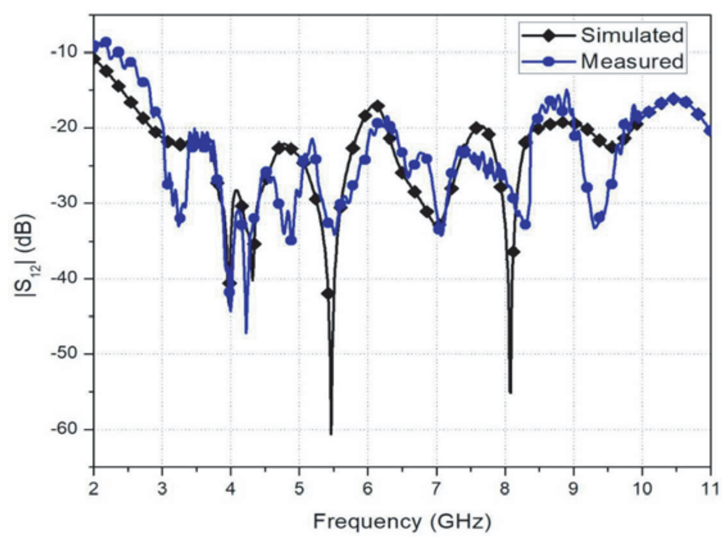
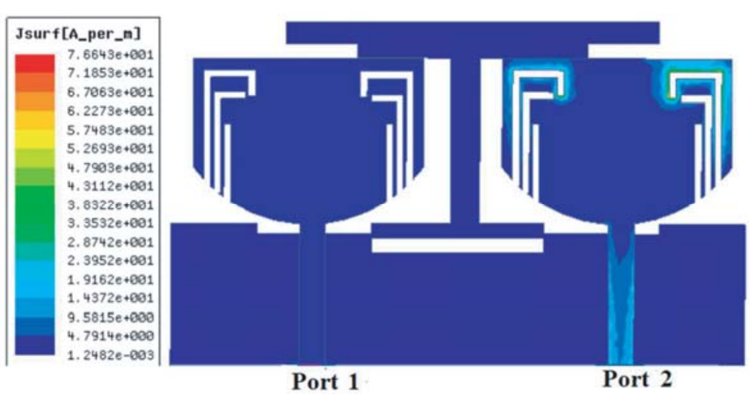
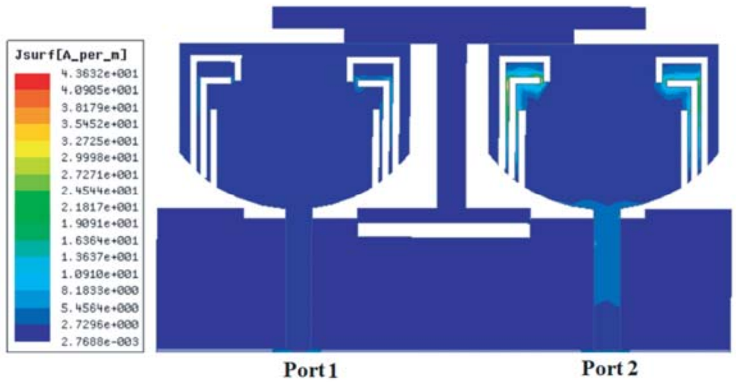


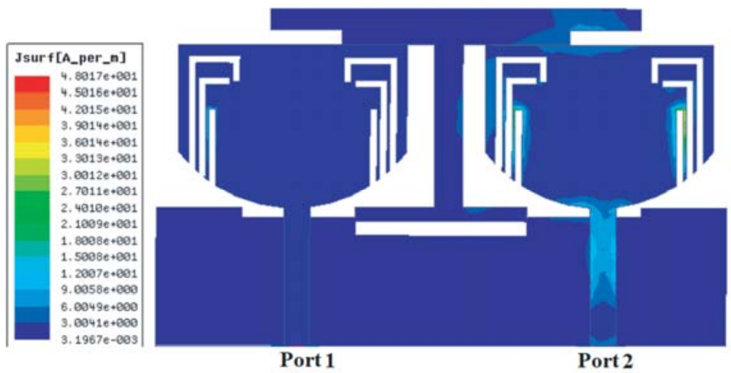
Figure 11. Measured and simulated mutual coupling.



(a)



(b)



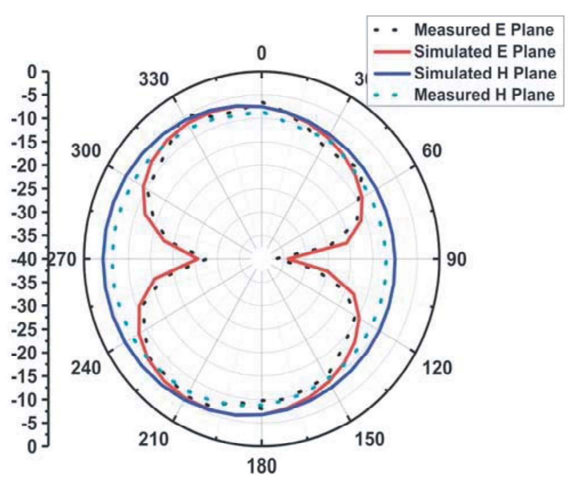
(c)

Figure 12. Simulated distribution of surface current (a) 3.7 GHz, (b) 5.5 GHz, (c) 7.5 GHz.

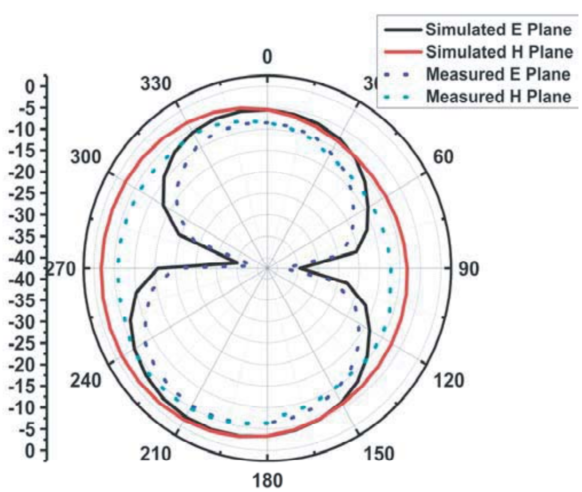
3. RESULTS AND DISCUSSION

3.1. Proposed Notched UWB MIMO Antenna Performance

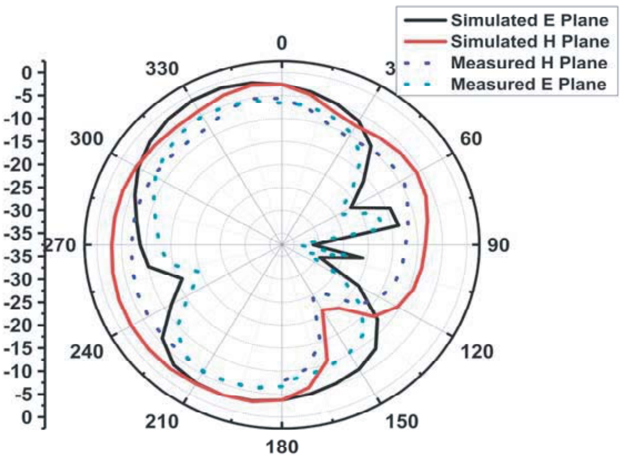
The suggested MIMO antenna performance parameters can be calculated using Envelope Correlation Coefficient (ECC), Total Active Reflection Coefficient (TARC), Diversity Gain (DG), radiation



(a)



(b)



(c)

Figure 13. Tested and simulated radiation pattern plot of the presented antenna (a) 3 GHz, (b) 5 GHz and (c) 9.5 GHz.

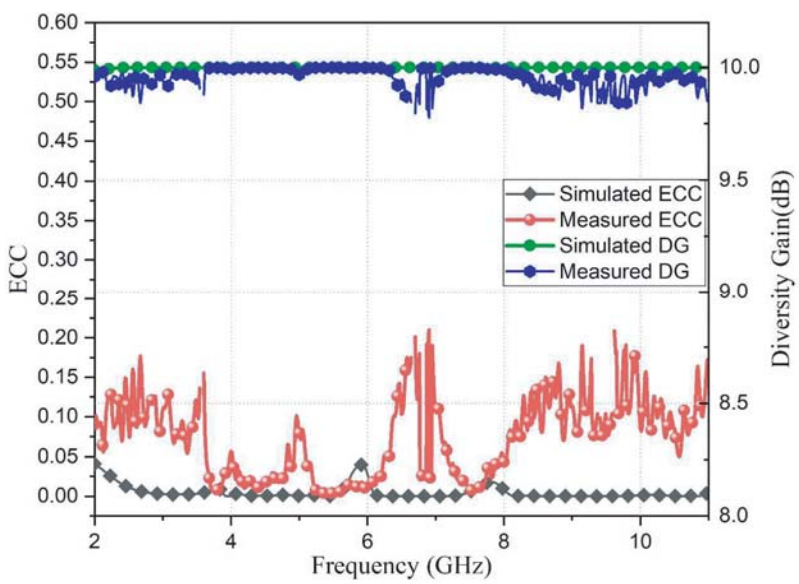


Figure 14. Measured and simulated variation of ECC and DG with frequency.

efficiency, and Mean Effective Gain (MEG). ECC can be measured in terms of mutual coupling and the amount of correlation among antenna elements. The ECC [32] in terms of S parameters is calculated as

$$\text{ECC} = \frac{|S_{11}^* S_{12} + S_{21}^* S_{22}|^2}{\left(1 - |S_{11}|^2 - |S_{21}|^2\right)\left(1 - |S_{22}|^2 - |S_{12}|^2\right)} \tag{6}$$

For uncorrelated diversity antenna, the ideal value of ECC should be zero, but its practical limit is < 0.5 [33]. The measured and simulated variations of ECC and DG with frequencyare shown in Fig. 14. In MIMO system, the effect of nearby antenna elements is visible in terms of mutual coupling [34]. Mutual coupling can disturb the entire operating bandwidth and efficiency of the antenna. As return loss is used to account performance of single antenna element, similarly TARC accounts for the overall MIMO antenna system performance. TARC [34, 35] for two-port MIMO antenna system is expressed

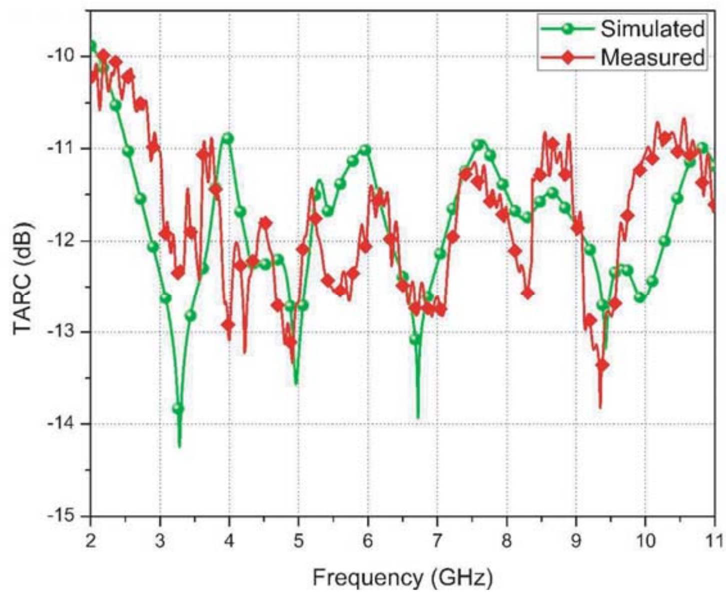


Figure 15. TARC variation with frequency.

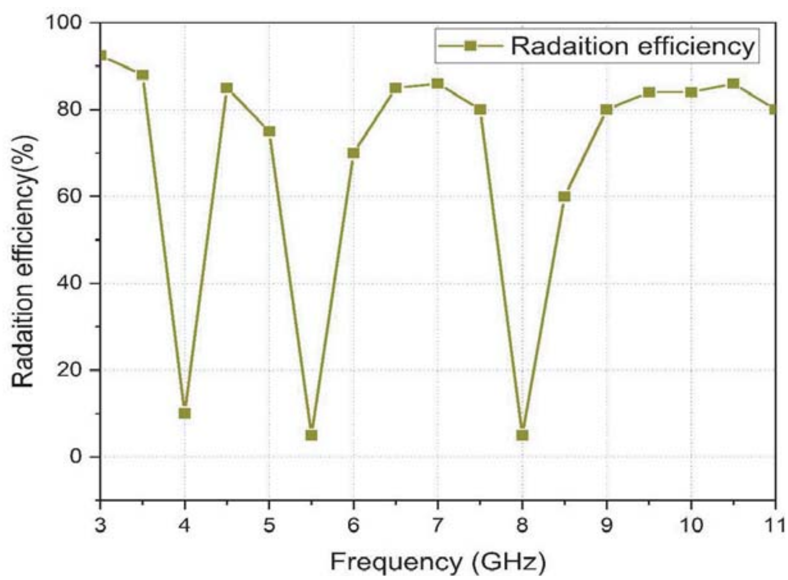


Figure 16. Radiation efficiency plot of suggested antenna.

as:

$$\mathrm{TARC} = \sqrt{\frac{(S_{11} + S_{12})^2 + (S_{21} + S_{22})^2}{2}} \tag{7}$$

The value of TARC for MIMO system should be $< 0\,\mathrm{dB}$ [35]. Fig. 15 depicts the simulated and tested results of TARC, which is found less than $-10\,\mathrm{dB}$. Diversity Gain [36, 37] of suggested antenna is calculated as:

$$\mathrm{DG} = 10\sqrt{1 - \mathrm{ECC}^2} \tag{8}$$

Figure 16 indicates the radiation efficiency of the suggested antenna. With the compact size and high isolation, radiation efficiency for UWB MIMO is around 80% in operation band of suggested antenna.

$$\mathrm{MEG}_i = 0.5\left[1 - \sum_{j=1}^{N} |S_{ij}|^2\right] \tag{9}$$

The mean effective gain [38] is calculated using following equation. So, MEG_i and MEG_j are calculated as

$$\mathrm{MEG}_i = 0.5\left[1 - |S_{11}|^2 - |S_{12}|^2\right] \tag{10}$$

$$\mathrm{MEG}_j = 0.5\left[1 - |S_{21}|^2 - |S_{22}|^2\right] \tag{11}$$

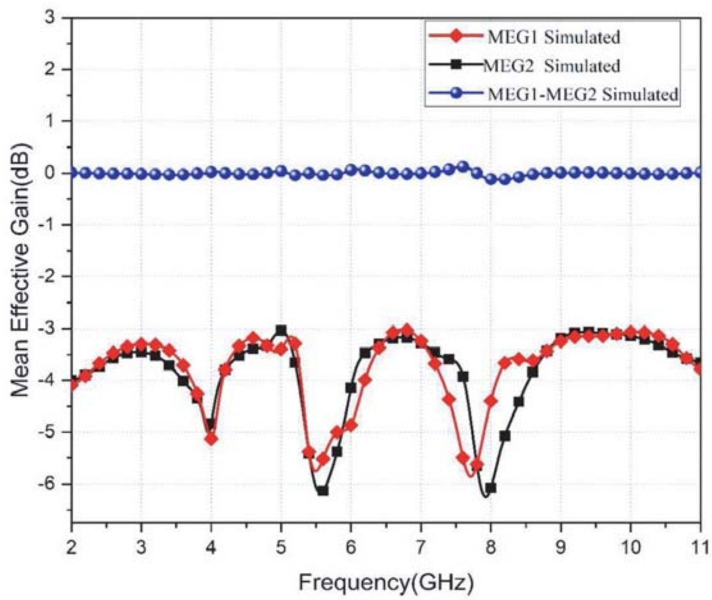


Figure 17. MEGs of two antenna elements.

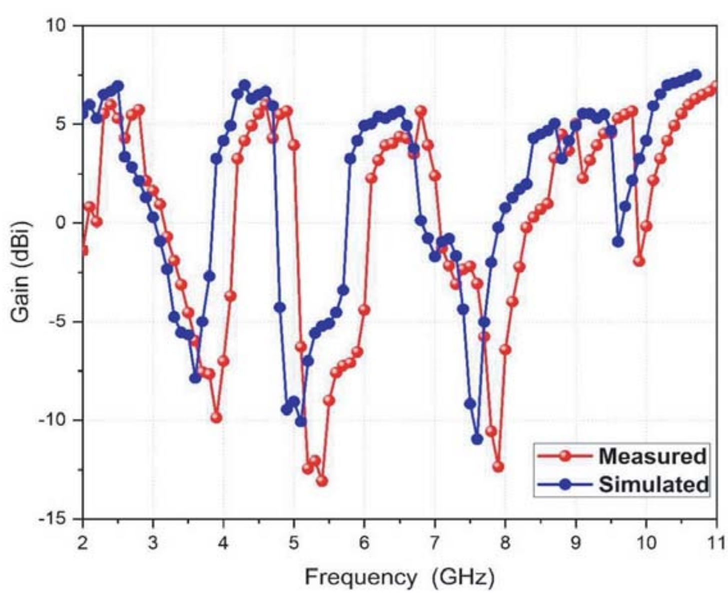


Figure 18. Tested gain.

Table 2. Comparison of suggested antenna with different antenna design.

Reference	Dimensions mm × mm	Notched band (GHz)	No. of Notches	Bandwidth (GHz)	Isolation (dB)	Radiation Efficiency
[36]	18 × 21	3.3–3.7, 5.15–6 & 7.8–8.4	3	2.9–20	−22	75%–85%
[39]	64 × 45	3.3–3.6, 5–6 & 7.1–7.9	3	2–10.6	−17	80%
[40]	58 × 45	3.3–3.6 & 5–6	2	2.3–10.6	−15	-
[41]	50 × 50	3.3–3.6, 5.15–5.35 & 5.725–5.825	3	2.76–10.75	−15	Better than 68%
[42]	48 × 48	5.1–6.0	1	2.5–12	−18	-
[43]	38.5 × 38.5	5.03–5.97	1	3.08–11.8	−15	Above 75%
[44]	30 × 60	3.3–3.8, 5.25–5.825 & 7.7–8.5	3	2.8–11	−20	80%
[45]	40 × 40	5.1–5.8 & 7.9–8.4	2	3.4–12	−15	-
[46]	34 × 49	5.1–5.8	1	3.1–10.6	−18	-
[47]	26.75 × 41.5	3.3–3.7, 3.7–4.2, & 5.15–5.85	3	3.1–11.5	−15	75%
[48]	22 × 26	5.4–5.86 & 7.6–8.4	2	3.1–11.8	−20	85%
Suggested Antenna	**23 × 40**	**3.3–4.2, 5–6 & 7.2–8.6**	**3**	**2–11**	**−17**	**Around 80%**

where i and j denote antenna elements 1 and 2, respectively. Fig. 17 shows the different MEGs for the suggested antenna. We can see that MEG is in between desired limits [38] for the whole range of UWB system.

$$|\mathrm{MEG}_i - \mathrm{MEG}_j| < 3\,\mathrm{dB} \tag{12}$$

Figure 18 represents the tested gain, and it is noticed that the gain decreases at the notched frequencies.

Many MIMO antennas have been discussed in the literature with band notch attributes. Table 2 shows that the suggested antenna has compact size than all other antennas mentioned.

4. CONCLUSION

A multiple band-notched UWB MIMO antenna is designed and fabricated having compact size and high efficiency. The suggested antenna has an operational impedance bandwidth from 2 to 11 GHz (VSWR ≤ 2) excluding three rejection bands: 3.3–4.2 GHz, 5–6 GHz, and 7.2–8.6 GHz. The suggested antenna shows good diversity performance with ECC < 0.2. The ratio of MEG is in between the desired limits, TARC < -10.5 dB, and radiation efficiency is around 80%.

The measured results shows good resemblance to simulated ones.

REFERENCES

1. Wang, S., "A new compact printed triple band-notched UWB antenna," *Progress In Electromagnetics Research Letters*, Vol. 58, 67–72, 2016.
2. Tang, M.-C., H. Wang, T. Deng, and R. W. Ziolkowski, "Compact planar ultrawideband antennas with continuously tunable, independent band-notched filters," *IEEE Transactions on Antennas and Propagation*, Vol. 64, No. 8, 3292–3301, Aug. 2016.

3. Pan, S., G. Luo, B. Ke, and K. Li, "A planar UWB antenna with triple-notched bands using triple-mode stepped impedance resonator," *Progress In Electromagnetics Research Letters*, Vol. 55, 45–52, 2015.
4. Elhabchi, M., M. N. Srifi, and R. Touahni, "A tri-band-notched UWB planar monopole antenna using DGS and semi arc-shaped slot for WIMAX/WLAN/X-band rejection," *Progress In Electromagnetics Research Letters*, Vol. 70, 7–14, 2017.
5. Jaglan, N., S. D. Gupta, B. K. Kanaujia, and S. Srivastava, "Design and development of efficient EBG structures based band notched UWB circular monopole antenna," *Wireless Personal Communication*, 1–27, Springer, May 2017.
6. Ojaroudi, N. and M. Ojaroudi, "Small square monopole antenna having variable frequency band-notch operation for UWB wireless communications," *Microwave and Optical Technology Letters*, Vol. 54, 1994–1998, 2012.
7. Bakariya, P. S., S. Dwari, and M. Sarkar, "Triple band notch UWB printed monopole antenna with enhanced bandwidth," *AEU — International Journal of Electronics and Communications*, Vol. 69, 26–30, 2015.
8. Gorai, A., A. Karmakar, M. Pal, and R. Ghatak, "Multiple fractal-shaped slots-based UWB antenna with triple-band notch functionality," *Journal of Electromagnetic Waves and Applications*, Vol. 27, 2407–2415, 2013.
9. Gorai, A., A. Karmakar, M. Pal, and R. Ghatak, "Multiple fractal-shaped slots-based UWB antenna with triple-band notch functionality," *Journal of Electromagnetic Waves and Applications*, Vol. 27, 2407–2415, 2013.
10. Ali, W. A. E. and R. M. A. Moniem, "Frequency reconfigurable triple band-notched ultra-wideband antenna with compact size," *Progress In Electromagnetics Research C*, Vol. 73, 37–46, 2017.
11. Luo, C.-M., J.-S. Hong, and L.-L. Zhong, "Isolation enhancement of a very compact UWB-MIMO slot antenna with two defected ground structures," *IEEE Antennas and Wireless Propagation Letters*, Vol. 14, 1766–1769, 2015.
12. Zhang, C., J. Zhang, and L. Li, "Triple band-notched UWB antenna based on SIR-DGS and fork-shaped stubs," *Electronics Letters*, Vol. 50, 67–69, 2014.
13. Jaglan, N., S. D. Gupta, E. Thakur, D. Kumar, B. K. Kanaujia, and S. Srivastava, "Triple band notched mushroom and uniplanar EBG structures based UWB MIMO/Diversity antenna with enhanced wide band isolation," *AEU — International Journal of Electronics and Communications*, Vol. 90, 36–44, 2018.
14. Wang, J. H., Y.-Z. Yin, and X. L. Liu, "Triple band-notched ultra wideband (UWB) antenna using a novel modified capacitively loaded loop (CLL) resonator," *Progress In Electromagnetics Research Letters*, Vol. 42, 55–64, 2013.
15. Vendik, I. B., A. Rusakov, K. Kanjanasit, J. Hong, and D. Filonov, "Ultra-wideband (UWB) planar antenna with single-, dual-, and triple-band notched characteristic based on electric ring resonator," *IEEE Antennas and Wireless Propagation Letters*, Vol. 16, 1597–1600, 2017.
16. Tang, M.-C., H. Wang, T. Deng, and R. W. Ziolkowski, "Compact planar ultra-wide band antennas with continuously tunable, independent band-notched filters," *IEEE Transactions on Antennas and Propagation*, Vol. 64, No. 8, 3292–3301, 2016.
17. 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, Mar. 2016.
18. Zhu, F.-G., J.-D. Xu and Q. Xu, "Reduction of mutual coupling between closely-packed antenna elements using defected ground structure," *Electronics Letters*, Vol. 45, 2009.
19. Ghosh, C. K., B. Mandal, and S. K. Parui, "Mutual coupling reduction of a dual-frequency microstrip antenna array by using U-shaped DGS and inverted U-shaped microstrip resonator," *Progress In Electromagnetics Research C*, Vol. 48, 61–68, 2014.
20. Park, J., J. Choi, J. Park, and Y. Kim, "Study of a T-shaped slot with a capacitor for high isolation between MIMO antennas," *IEEE Antennas and Wireless Propagation Letters*, Vol. 11, 1541–1544, 2012.

21. Ghosh, J., S. Ghosal, D. Mitra, and S. R. Bhadra Chaudhuri, "Mutual coupling reduction between closely placed microstrip patch antenna using meander line rsesonator," *Progress In Electromagnetics Research Letters*, Vol. 59, 115–122, 2016.
22. Vendik, I. B., A. Rusakov, K. Kanjanasit, J. Hong, and D. Filonov, "Ultra-wideband (UWB) planar antenna with single-, dual-, and triple-band notched characteristic based on electric ring resonator," *IEEE Antennas and Wireless Propagation Letters*, Vol. 16, 1597–1600, 2017.
23. Zhang, S. and G. F. Pedersen, "Mutual coupling reduction for UWB MIMO antennas with a wideband neutralization line," *IEEE Antennas and Wireless Propagation Letters*, Vol. 15, 166–169, 2016.
24. Mao, C. and Q. Chu, "Compact coradiator UWB-MIMO antenna with dual polarization," *IEEE Transactions on Antennas and Propagation*, Vol. 62, No. 9, 4474–4480, 2014.
25. Chiu, C.-Y., J.-B. Yan, and R. D. Murch, "Compact three-port orthogonally polarized MIMO antennas," *IEEE Antennas and Wireless Propagation Letters*, Vol. 6, 619–622, 2007.
26. Zhang, S., Z. Ying, J. Xiong, and S. He, "Ultrawideband MIMO/diversity antennas with a tree-like structure to enhance wideband isolation," *IEEE Antennas and Wireless Propagation Letters*, Vol. 8, 1279–1282, 2009.
27. Vendik, I. B., A. Rusakov, K. Kanjanasit, J. Hong, and D. Filonov, "Ultra-wideband (UWB) planar antenna with single-, dual-, and triple-band notched characteristic based on electric ring resonator," *IEEE Antennas and Wireless Propagation Letters*, Vol. 16, 1597–1600, 2017.
28. Bakariya, P. S., S. Dwari, and M. Sarkar, "Triple band notch UWB printed monopole antenna with enhanced bandwidth," *AEU — International Journal of Electronics and Communications*, Vol. 69, 26–30, 2015.
29. Ryu, K. S. and A. A. Kishk, "UWB antenna with single or dual band-notches for lower WLAN band and upper WLAN band," *IEEE Transactions on Antennas and Propagation*, Vol. 57, 3942–3950, 2009.
30. Nguyen, D. T., D. H. Lee, and H. C. Park, "Very compact printed triple band-notched UWB antenna with quarter-wavelength slots," *IEEE Antennas and Wireless Propagation Letters*, Vol. 11, 411–414, 2012.
31. Zhang, G.-M., J.-S. Hong, and B.-Z. Wang, "Two novel band-notched UWB slot antennas fed by microstrip line," *Progress In Electromagnetics Research*, Vol. 78, 209–218, 2008.
32. Ramachandran, A., S. Mathew, V. P. Viswanathan, M. Pezholil, and V. Kesavath, "Diversity-based four-port multiple input multiple output antenna loaded with interdigital structure for high isolation," *IET Microwaves, Antennas & Propagation*, Vol. 10, No. 15, 1633–1642, Dec. 2016.
33. Rajagopalan, A., G. Gupta, A. S. Konanur, B. Hughes, and G. Lazzi, "Increasing channel capacity of an ultra-wideband MIMO system using vector antennas," *IEEE Transactions on Antennas and Propagation*, Vol. 55, No. 10, 2880–2887, 2007.
34. Gautam, A. K. and K. Rambabu, "Tapered fed compact UWB MIMO-diversity antenna with dual band-notched characteristics," *IEEE Transactions on Antennas and Propagation*, Vol. 66, No. 4, 1677–1684, 2018.
35. Karaboikis, M. P., V. C. Papamichael, G. F. Tsachtsiris, C. F. Soras, and V. T. Makios, "Integrating compact printed antennas onto small diversity/MIMO terminals," *IEEE Transactions on Antennas and Propagation*, Vol. 56, 2067–2078, 2008.
36. Chandel, R., A. K. Gautam, and K. Rambabu, "Tapered fed compact UWB MIMO-diversity antenna with dual band-notched characteristics," *IEEE Transactions on Antennas and Propagation*, Vol. 66, No. 4, 1677–1684, 2018.
37. Mohammed, H. J., et al., "Design of a uniplanar printed triple band-rejected ultra-wideband antenna using particle swarm optimisation and the fire-fly algorithm," *IET Microwaves, Antennas & Propagation*, Vol. 10, No. 1, 31–37, 2016.
38. 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, 4257–4264, 2013.

39. Jaglan, N., S. D. Gupta, E. Thakur, D. Kumar, B. K. Kanaujia, and S. Srivastava, "Triple band notched mushroom and uniplanar EBG structures based UWB MIMO/diversity antenna with enhanced wide band isolation," *AEU — International Journal of Electronics and Communications*, Vol. 90, 36–44, 2018.
40. Jaglan, N., S. D. Gupta, B. K. Kanaujia, S. Srivastava, and E. Thakur, "Triple band notched DG-CEBG structure based UWB MIMO/diversity antenna," *Progress In Electromagnetics Research C*, Vol. 80, 21–37, 2018.
41. Chacko, B. P., G. Augustin, and T. A. Denidni, "Uniplanar polarisation diversity antenna for ultrawideband systems," *IET Microwaves, Antennas & Propagation*, Vol. 7, 851–857, 2013.
42. Gao, P., S. He, X. Wei, Z. Xu, N. Wang, and Y. Zheng, "Compact printed UWB diversity slot antenna with 5.5-GHz band-notched characteristics," *IEEE Antennas and Wireless Propagation Letters*, Vol. 13, 376–379, 2014.
43. 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.
44. 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, 626–630, 2016.
45. 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, 989–994, 2016.
46. Yoon, H. K., Y. J. Yoon, H. Kim, and C.-H. Lee, "Flexible ultra-wideband polarisation diversity antenna with band-notch function," *IET Microwaves, Antennas & Propagation*, Vol. 5, 1459–1463, 2011.
47. Banerjee, J., A. Karmakar, R. Ghatak, and D. R. Poddar, "Compact CPW-fed UWB MIMO antenna with a novel modified Minkowski fractal defected ground structure (DGS) for high isolation and triple band-notch characteristic," *Journal of Electromagnetic Waves and Applications*, Vol. 31, 1550–1565, 2017.
48. Jetti, C. R. and V. R. Nandanavanam, "Trident-shape strip loaded dual band-notched UWB MIMO antenna for portable device applications," *AEU — International Journal of Electronics and Communications*, Vol. 83, 11–21, 2018.