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Miniaturized four-port UWB MIMO antennas with triple-band rejection using single EBG structures

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Research Paper

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Abstract

This research paper introduces a ultra-wideband (UWB) multiple input multiple output (MIMO)/diversity antenna with three rejected bands using one compact electromagnetic band gap (EBG) structure. The suggested EBG structure rejects three bands at WiMAX, WLAN, and the X-band within the passband of the UWB antenna. To achieve compactness in the conventional EBG structure, two via and square slots are introduced. This structure contributes to better impedance matching by using tapered feedline and slots in the radiating patch. To improve the isolation among all four compact UWB monopoles, decoupling strips are extended from the ground plane. Furthermore, the $|S_{21}|$ is below 17 dB in between the antenna elements and the envelope correlation coefficient is below 0.5, which are tolerable values within the UWB range. Furthermore, different MIMO/diversity characteristics are also discussed. An FR-4 substrate with dimensions of $38 \times 45 \times 1.6\ mm^3$ is used for the fabrication of the suggested structure.

Introduction

In the last 20 years, with the growth of wired networks and mobile communication systems, numerous wireless access technologies have been progressed. Latterly, with the growth of smart gadgets like home digital entertainment center, the need for a high transmission rate in wireless technology has fascinated extensive attention. It has been proved that improved data rate can be attained by combining ultra-wideband (UWB) with multiple inputs multiple outputs (MIMO) systems [1]. UWB systems operate from 3.1 to 10.6 GHz, comprise channel capacity, eliminate the fading effect, etc. Therefore, by employing UWB MIMO systems, the fading effect and data rate can be further improved without passive elements. Presently, many researchers mainly focus on miniaturization, broadband, high isolation that improves the enactment of UWB MIMO antennas. Numerous methods developed in the literature to have enhanced impedance matching with compact size. These techniques are multi-session transformers, tapered lines, and distributed impedance matching [2]. Multi-session transformer method is the modified version of the quarter-wave transformer, employing multiple segments of $\lambda/4$ transmission lines linked together [2]. The disadvantage of this technique is that it makes the system complex. In the tapered line technique, the feed line width is exponentially increased or decreased for the impedance matching purpose. Another technique is distributed impedance matching where the structure is modified itself without using any passive element for widening the impedance bandwidth. Other than impedance bandwidth, UWB systems require a band-notched filter to suppress the interference from the narrowband system, such as WiMAX varies from 3.3 to 3.7 GHz, WLAN varies from 5 to 6 GHz, and X-band system varies from 7.2 to 8.4 GHz; therefore, UWB systems do not cause any interference to the other existing narrowband systems [3]. Numerous designs are discussed in the literature such as etch slots of different shapes such as open-end quarter wavelength rectangular slot [4], arc [5], meandered in the patch surface or on the ground surface. Another method to achieve band notch characteristics is by adding stub [6] and parasitic element beside the feed line and rejection resonators like capacitively-loaded loop [7]. The above-discussed method produces poor radiation patterns due to perturbation in the radiating surface or on the ground plane. Lately, multiple band notches are attained by using single electromagnetic band gap (EBG) structures. In [8], three bands are rejected by using three different EBG structures. In [9], two EBG structures obtain three rejected bands at three interfering narrow bands. Further in [10], a single EBG structure obtains triple notches with a size of $9.4 \times 4.5\ mm^2$.

Triple notch UWB MIMO antenna

The final prototype of the structure is depicted in Fig. 1 and the adjusted parameters of the suggested antenna are presented in Table 1. HFSS (v13) is used to design and simulate the suggested antenna. For validation, the proposed antenna is fabricated using the EP 2006 PCB prototype

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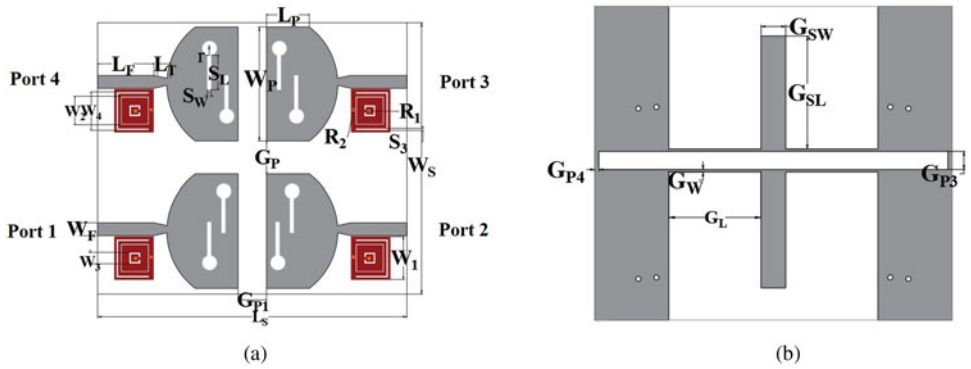


Fig. 1. (a) Layout of the top view of suggested antenna. (b) Layout of the bottom view of suggested antenna.

Table 1. Dimensions of the suggested structure

Parameters	Value (mm)	Parameters	Value (mm)	Parameters	Value (mm)
W_s	38	L_P	6	G_P	4.6
L_s	45	W_P	16	G_{P1}	4
L_1	6	S_3	0.3	R_1	0.3
W_1	6	S_2	0.2	S_L	4.8
S_W	11	L_F	7.9	W_3	1.6
L_T	0.8	W_2	5.4	W_4	4
W_2	5.4	W_F	1.8	G_{P4}	0.52
G_W	0.3	G_L	11.2	G_{P3}	2.2
GS_W	0.3	R_2	0.3	r	1

machine. This four-element UWB antenna is fabricated using FR-4 having ε_r of 4.4 and has a compact size of $38 \times 43 \times 1.6\,mm^3$. Figure 2 presents the prototype of the proposed UWB MIMO antenna. The *S*-parameters are measured using the Agilent N5230C vector network analyzer, and gain and radiation patterns are tested using the microwave shield anechoic chamber, respectively. The values of S_L, S_W, W_P, L_P, and L_T are varied to get a wider bandwidth of 9 GHz (2–11 GHz), which covers the entire frequency range. To generate triple notches, the EBG structure is placed near the feedline of the suggested antenna.

Band gap determination

To further validate the band gap characteristic of EBG structure, the proposed EBG structure 5×4 lattice of EBG structure is simulated using an FR4 substrate with $\varepsilon_r = 4.4$ with the height of 1.6 mm. The bandwidth of the band gap of the EBG structure is computed by using the suspended microstrip transmission line method presented in Fig. 3. In the presence of the EBG periodic structure, the transmission responses (S_{21}) between the two ports are analyzed to obtain the band gap properties. Figure 4 shows three band gaps as 0.4 GHz (3.3–3.7 GHz), 1 GHz (5.15–5.85 GHz), and 1.4 GHz (7.2–8.6 GHz); the minimum S_{21} value is about −37 dB for the triple band gaps.

Equivalent circuit model

The equivalent circuit of the suggested structure is depicted in Fig. 5. The arrangement of inductor (*L*), capacitor (*C*), and resistance (*R*) is used to demonstrate the port of 50 Ω load, feed line, and radiating patch [11]. The fed lines and radiating patch are symbolized by the series and parallel arrangement of *L*1, *C*1, *R*1, and *L*7, *C*7… L*N*, C*N*, respectively. The parallel arrangement of *L*6 and *C*6 use to denote the mutual coupling among ports 1–2, and ports 1–4. Similarly, the parallel arrangement of *L*5 and *C*5 is used to symbolize isolation between ports 1–3. The modified EBG structure is equivalent to three resonant circuits denoted by parallel combination *L*2 and *C*2, *L*3 and *C*3, and *L*4 and *C*4.

Numerical results and discussion

Voltage standing wave ratio (VSWR) and S parameters

Figure 6 illustrates the simulated VSWR curve with and without the EBG structure. From the simulated result, it is observed that the UWB MIMO antenna with EBG structure function in the entire UWB range except for WiMAX, WLAN, and X-band. The VSWR parameter of the suggested antenna is illustrated in Fig. 7 and it show that the VSWR value at rejecting bands is more than 2; therefore, it is clear that no radiation is taking place at the rejecting frequencies 3.5, 5.5, and 7.7 GHz.

However, Fig. 8 shows the tested and simulated VSWR curve of the structure. The difference in the tested and simulated results is because of the various losses like conduction loss, dielectric loss, mismatch loss, SubMiniature version A (SMA) soldering, fabrication error, measurement error, and orientation problems when the proposed structure is connected to the vector network analyzer [12].

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Figure 9 demonstrates the isolation of the suggested antenna. The mutual coupling among the patch antenna is considerably minimized by using T-shaped stubs on the ground plane. A slot is etched on the ground plane to enhance the isolation. It can be seen from Fig. 10 that mutual coupling is below −15 dB for the whole frequency band. The measured curves confirm good resemblance with simulated curves.

Radiation pattern

Figure 11 indicates the simulated and tested radiation plot at 4, 6.3, and 7.6 GHz at both E plane and H plane. It is seen that the suggested structure shows a ring-shaped radiation pattern in the H plane and rotation symmetry at the E plane. Figure 12 illustrates that the gain of the suggested antenna is varied from −9.5 to 7.5 dB for the entire UWB range.

MIMO characteristics

The significant factors to analyze and validate the MIMO characteristics are envelope correlation coefficient (ECC), diversity gain (DG), total active reflection coefficient (TARC) [13], and mean effective gain (MEG) [14]. During the analysis of the MIMO antenna, the ECC is considered as a valuable parameter to evaluate the degree of signal fading or diversity skill of the MIMO antenna. Correlation is commonly used to measure the difference between the radiation patterns. ECC and DG can be determined using S parameters [13] and radiation pattern [14]. The mathematical formula to evaluate the ECC in terms of scattering parameters and radiations pattern can be given by [15]

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

For four elements:

$$ECC(\rho_{12}) = \frac{|S_{11}^* S_{12} + S_{21}^* S_{22}|^2}{(1 - |S_{11}|^2 - |S_{21}|^2)(1 - |S_{22}|^2 - |S_{12}|^2)} \quad (2)$$

$$ECC(\rho_{13}) = \frac{|S_{11}^* S_{13} + S_{31}^* S_{33}|^2}{(1 - |S_{11}|^2 - |S_{31}|^2)(1 - |S_{33}|^2 - |S_{13}|^2)} \quad (3)$$

$$ECC(\rho_{14}) = \frac{|S_{11}^* S_{14} + S_{41}^* S_{44}|^2}{(1 - |S_{11}|^2 - |S_{41}|^2)(1 - |S_{44}|^2 - |S_{14}|^2)} \quad (4)$$

where S_{11}, S_{22}, S_{33}, and S_{44} are the reflection coefficients. S_{12}, S_{21}, S_{31}, S_{13}, S_{41}, and S_{14} are coupling between the ports:

$$ECC = \frac{\left|\int_\Omega [XPR \cdot E_{\theta_i} E_{\theta_j}^* P_\theta + E_{\phi_i} E_{\theta_j}^* P_\phi] d\Omega\right|^2}{\int_\Omega [XPR \cdot E_{\theta_i} E_{\theta_i}^* P_\theta + E_{\phi_i} E_{\phi_i}^* P_\phi] d\Omega X \int_\Omega [XPR \cdot E_{\theta_j} E_{\theta_j}^* P_\theta + E_{\theta_j} E_{\theta_j}^* P_\phi] d\Omega} \quad (5)$$

XPR is the cross-polarization rate of the incident field:

$$XPR = \frac{P_V}{P_H} \quad (6)$$

where P_V and P_H are the average power along elevation (θ) and azimuthal angle (ϕ). DG is an efficient parameter used to measure the enactment level of diversity systems. The DG defined as the slant of the error probability plot of the received SNR DG is related to ECC by the below equation [16]

$$DG = 10\sqrt{1 - ECC^2} \quad (7)$$

The RE and BW of an MIMO antenna are not accurately characterized by return loss. Therefore, rather than using return loss, TARC can be used so that it accounts for both coupling and random signal combination. Thus, TARC delivers a more significant measure of MIMO efficiency.

Figure 13 shows the simulated ECC and DG measured using S parameters. Ideally, ECC must be 0 but practically it should be beneath 0.5 and DG must be around 10 dB. The ECC and DG for different antenna elements are within 0.02 and 9.92 dB, respectively. The radiation efficiency and bandwidth of an MIMO antenna are not accurately characterized by return loss. Therefore, rather than using return loss, TARC can be used so that it accounts for both coupling and random signal combination. TARC is a significant factor that denotes the mutual coupling of the ports. For the four-port UWB MIMO antenna, the TARC can be calculated using below equation [17]:

Figure 14 illustrates the TARC of the suggested antenna. Ideally, for an MIMO system, the TARC should be less than 0

$$TARC = \sqrt{\frac{(S_{11} + S_{12} + S_{13} + S_{14})^2 + (S_{21} + S_{22} + S_{23} + S_{24})^2 + (S_{31} + S_{32} + S_{33} + S_{34})^2 + (S_{41} + S_{42} + S_{43} + S_{44})^2}{4}} \quad (8)$$

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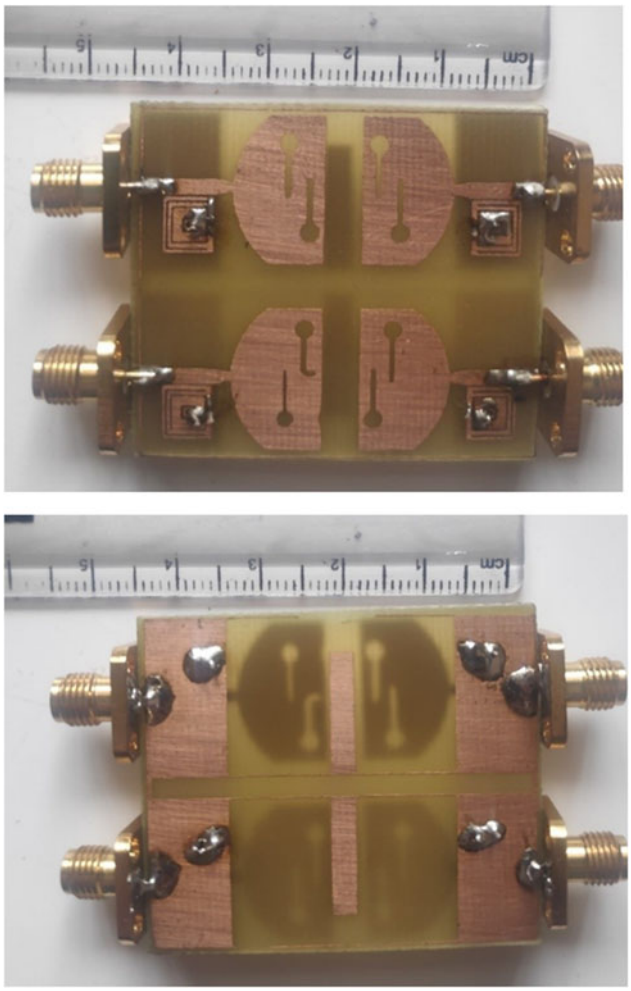


Fig. 2. Prototype of the proposed four-element UWB MIMO antenna.

dB. It is clear from Fig. 14 that the TARC is below −2.5 dB for the complete band with the triple rejected bands.

MEG is one of the significant factors and is defined as the relation given below [18]:

$$MEG_i = 0.5\mu_{irad} = 0.5\left(1 - \sum_{j=1}^{N} |S_{ij}|^2\right) \quad (9)$$

where N is the number of patches and μ_{irad} is the efficiency. In this case $N = 4$:

$$MEG_1 = 0.5[1 - |S_{11}|^2 - |S_{12}|^2 - |S_{13}|^2 - |S_{14}|^2] \quad (10)$$

$$MEG_2 = 0.5[1 - |S_{21}|^2 - |S_{22}|^2 - |S_{23}|^2 - |S_{24}|^2] \quad (11)$$

$$MEG_3 = 0.5[1 - |S_{31}|^2 - |S_{32}|^2 - |S_{33}|^2 - |S_{34}|^2] \quad (12)$$

$$MEG_4 = 0.5[1 - |S_{41}|^2 - |S_{42}|^2 - |S_{43}|^2 - |S_{44}|^2] \quad (13)$$

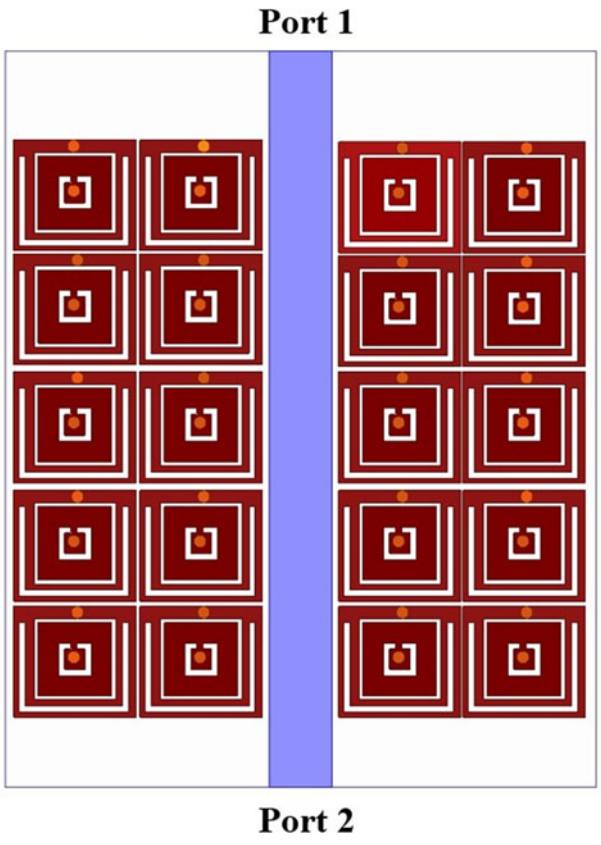


Fig. 3. Transmission line over modified EBG structure.

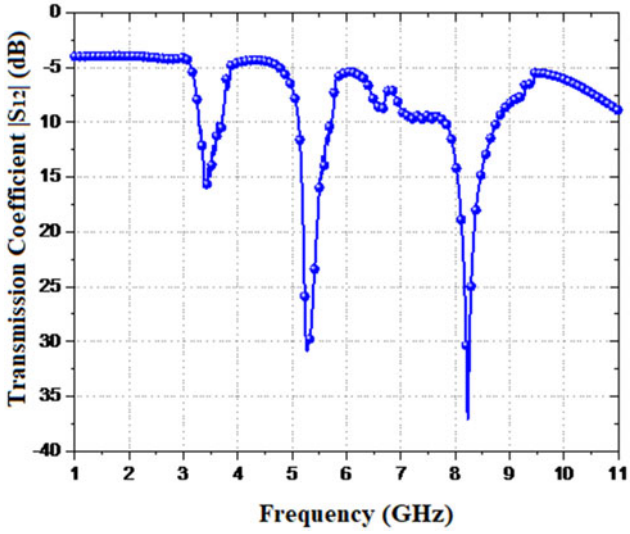


Fig. 4. Transmission coefficient for modified EBG structure.

For better diversity performance, the range of MEG should be $|MEG_i - MEG_j| < -3$ dB. The simulated MEG of the suggested four-port UWB MIMO is shown in Fig. 15. The value of MEG's for all the four elements is within the desired limit. The performance evaluation of the suggested UWB MIMO antenna with those recent antennas in the publication is presented in Table 2.

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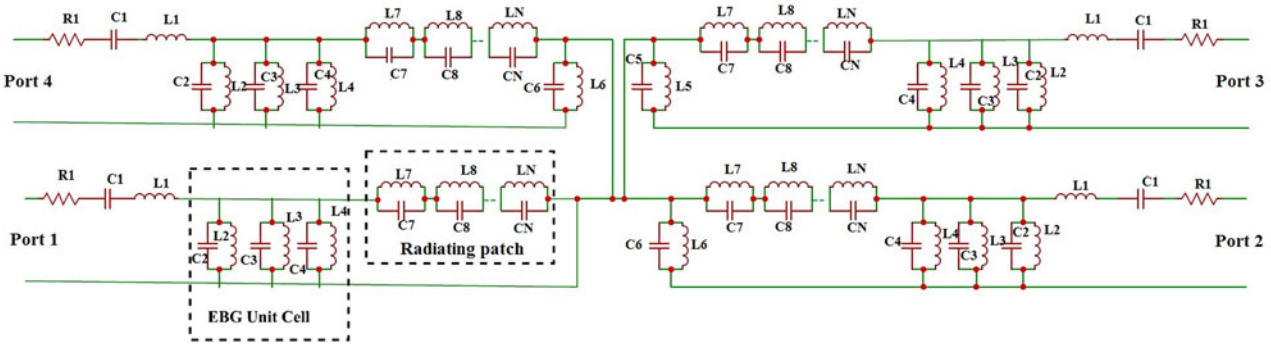


Fig. 5. Equivalent circuit.

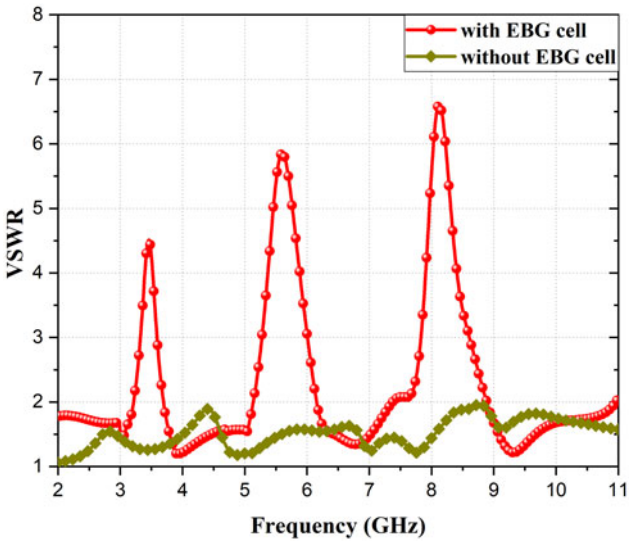


Fig. 6. Deviation of VSWR with frequency.

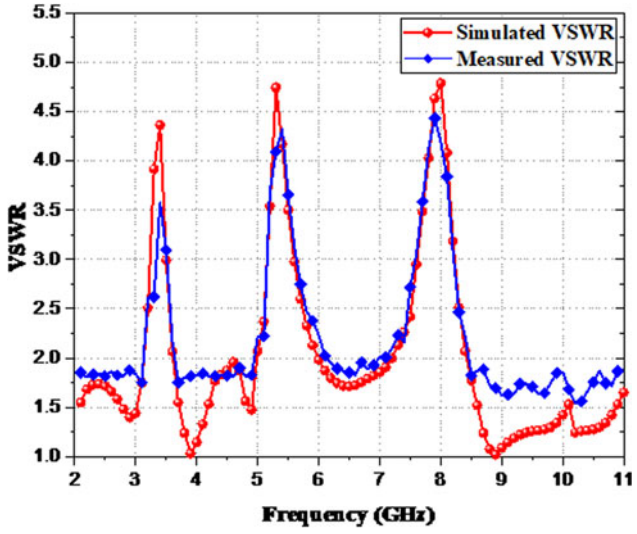


Fig. 8. Variation of measured and simulated VSWR.

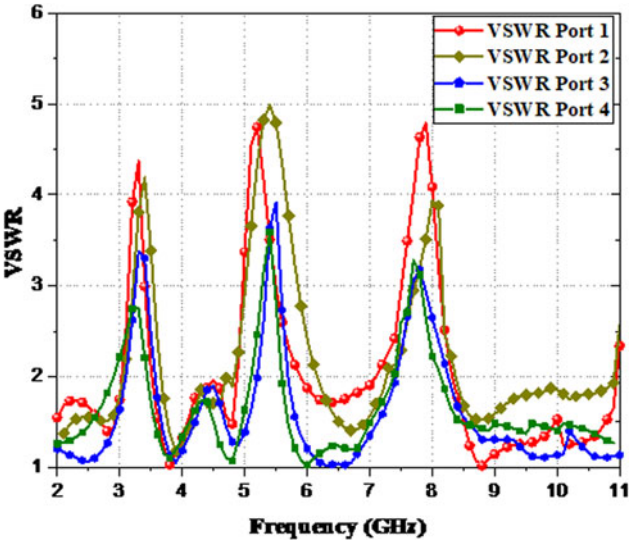


Fig. 7. Variation of VSWR with the frequency of different ports.

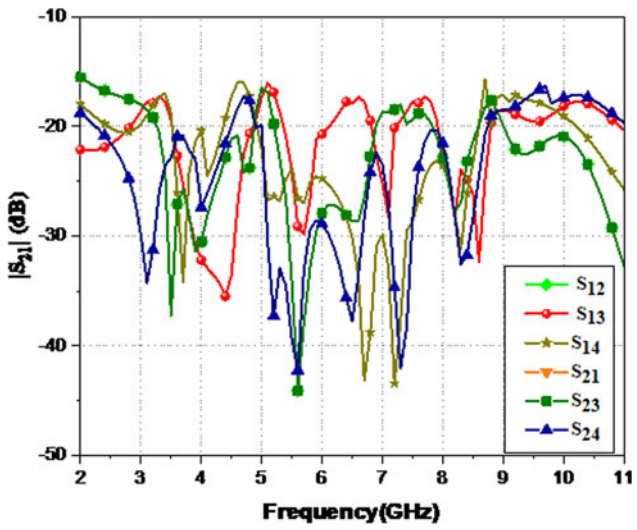


Fig. 9. Deviation of mutual coupling with frequency.

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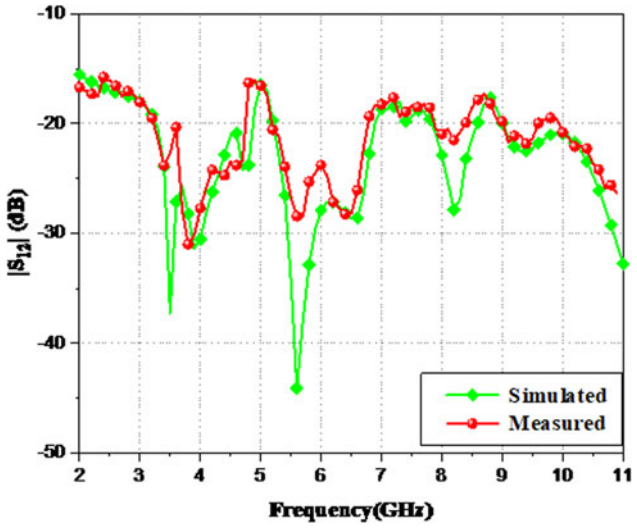


Fig. 10. Variation of mutual coupling with frequency.

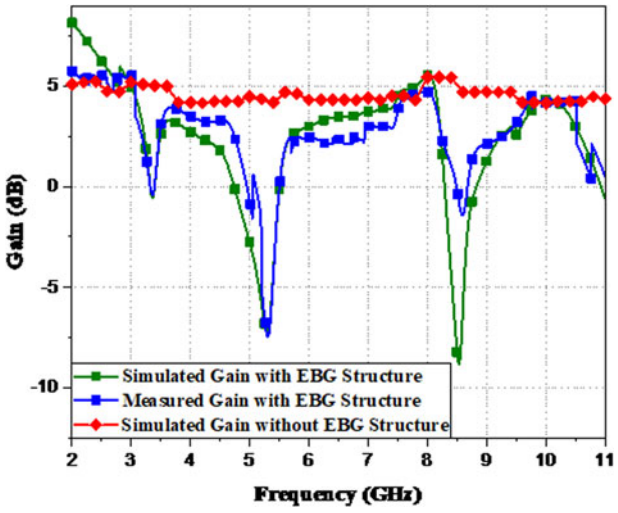


Fig. 12. Deviation of gain with frequency.

Performance comparison of different antennas

Table 2 shows the comparative study of different four-element band-notched UWB antennas. Size of the antenna, number of notches, bandwidth, number of notch structures, and ECC [19, 20] are some of the important parameters considered for the comparison. It can be observed from Table 2 that notch structures given in [21–25, 27–29] provide notches at a single frequency. EBG structures given in [26] provide notches at two different frequencies. The proposed antenna has compact size, better ECC, and precise notches at three different interfering bands. The proposed antenna provides triple-band notch characteristics using a single EBG structure with better diversity characteristics.

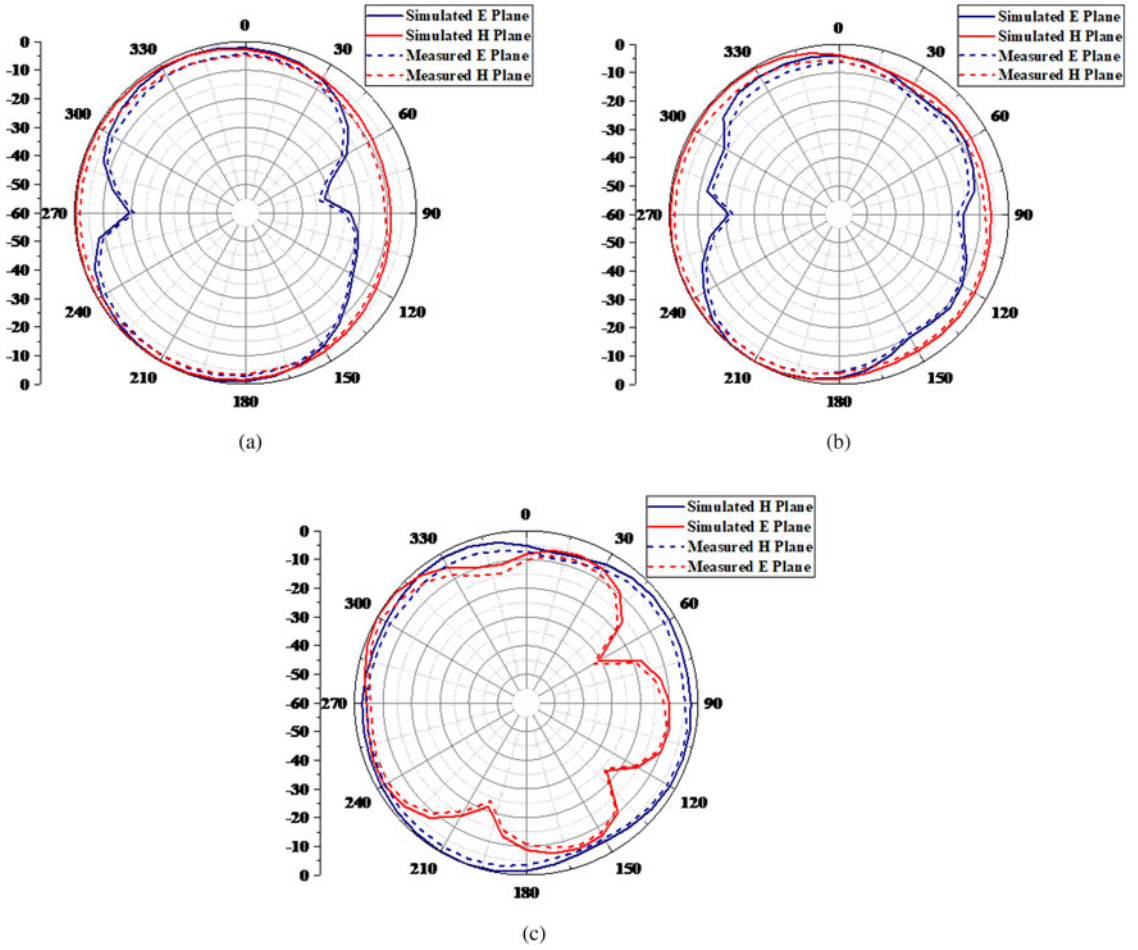


Fig. 11. (a) Normalized radiation plot at 4 GHz. (b) Normalized radiation plot at 6.3 GHz. (c) Normalized radiation plot at 7.6 GHz.

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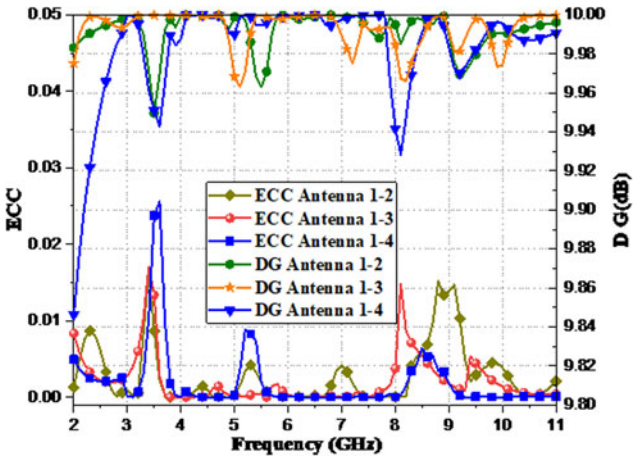


Fig. 13. Deviation of ECC and DG with frequency.

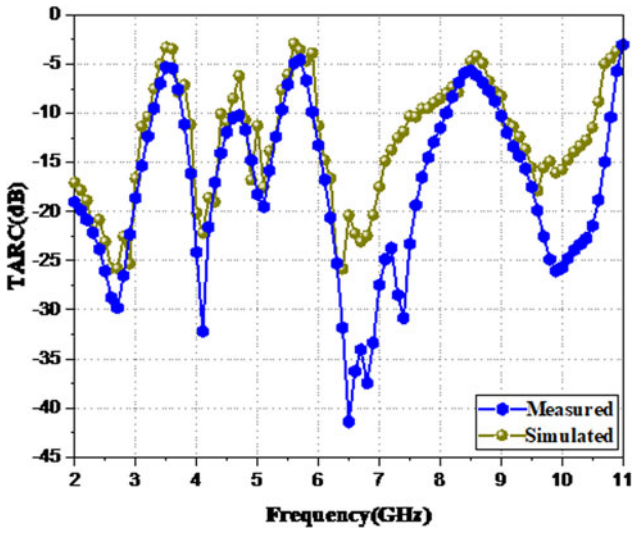


Fig. 14. Variation of TARC with frequency.

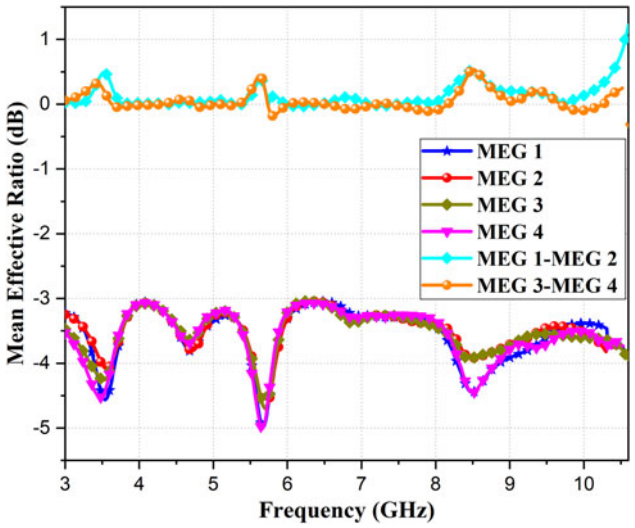


Fig. 15. Variation of MEG with frequency.

Therefore, the proposed antenna can be used as a suitable design for modern wireless communication systems.

Conclusion

In this paper, a miniaturized band-rejected UWB MIMO antenna is designed. A modified EBG unit cell is used to obtain three band-notched characteristics. The novelty of this structure is that the three rejection bands are obtained by using only a modified compact EBG structure with C-shaped slots on its surface. A single EBG structure is used instead of using multiple EBG structures. The tested and simulated scattering parameters, gain, mutual coupling, and radiation patterns were studied and tested. The proposed antenna attains decent diversity performance parameters with ECC < 0.02, TARC < −7.5 dB, and MEG is in the desired limits. The measured result shows a good resemblance.

Table 2. Comparison table of the proposed antenna with other antennas

Ref.	Dimensions (mm^3)	Notched band (GHz)	Isolation	No. of notches	Radiating elements	Bandwidth (GHz)	Notch technique	ECC	No. of notch structures
[21]	63 × 63 × 1.6	3.5, 5.5, 8.5	15	3	4	1.3–40	Complementary split-ring resonator (CSRR)	0.01	3
[22]	58 × 58 × 0.8	3.5, 5.5	18	2	4	3–16	Hexagonal-shaped CSRR	0.07	2
[23]	52 × 52 × 1.6	3.5, 5.5	18	2	4	2–40	L- and C-shaped resonator slits	0.09	2
[24]	81 × 87 × 1.6	3.87–5.94, 7.04–8.7	20	2	4	1–14	L-shaped slot and rectangular stub	0.1	2
[25]	60 × 60 × 1.6	5.36–6.34	17	1	4	2.7–10.68	Mushroom-like EBG	0.3	1
[26]	60 × 60 × 1.6	5.1–5.6, 7.3–9.1	15	2	4	3–16.2	Periodic EBG structure	0.5	1
[27]	44 × 44 × 1.6	5.10–5.95	15	1	4	2.95–10.8	Half-wavelength resonant stub	0.1	1
[28]	39 × 50 × 1.6	5.15–5.35, 5.75–5.825	20	2	4	2–12	LC band-stop resonator	0.1	2
[29]	50 × 25 × 1.6	4.9–6.4	17	1	4	2–12	LC notch filter	0.45	1
This paper	**38 × 45 × 1.6**	**3.3–3.7, 5.15–5.85, 7.9–8.6**	**17**	**3**	**4**	**2–11**	**Modified EBG structure**	**0.01**	**1**

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