I. INTRODUCTION

The Federal Communications Commission (FCC) has for the first time authorized ultra-wideband (UWB) range from 3.1 to 10.6 GHz in 2002 [1]. UWB requires very low transmittance power, achieves very high data rates and is not in a line of sight. Despite various advantages, UWB also have drawbacks like interference with existing narrow bands and multipath fading. Various techniques have been used to overcome interference problems [2–5], and multiple-input and multiple-output (MIMO) antennas have been used on both transmitting and receiving sides to reduce multipath fading [6–9]. The intent of the present research work is to study miniaturized MIMO antennas with the help of slits etched into the radiators. The overall size of the proposed antenna is 15 mm × 25 mm × 1.6 mm. The reflection coefficients are less than −10 dB between 3–10.9 GHz, except the bands WiMAX (3.2–3.7 GHz) and WLAN (5–6 GHz); similarly, measured and simulated transmission coefficients are less than −20 dB across the entire band of UWB. The envelope correlation coefficient (ECC) is less than 0.02 and the diversity gain is greater than 9.9 dB. The gain, ECC, radiation pattern, multiplexing efficiency, diversity gain and various other parameters are discussed and evaluated in detail.

Key Words: Envelope Correlation Coefficient, Gain, Impedance Bandwidth, MIMO, UWB.

Abstract

In this article, compact a multiple-input and multiple-output (MIMO) system with flag-shaped radiators and a mountain-shaped ground plane is presented. Isolation is enhanced with the help of a decoupling stub placed between radiators, where two bands are stopped with the help of slits etched into the radiators. The overall size of the proposed antenna is 15 mm × 25 mm × 1.6 mm. The reflection coefficients are less than −10 dB between 3–10.9 GHz, except the bands WiMAX (3.2–3.7 GHz) and WLAN (5–6 GHz); similarly, measured and simulated transmission coefficients are less than −20 dB across the entire band of UWB. The envelope correlation coefficient (ECC) is less than 0.02 and the diversity gain is greater than 9.9 dB. The gain, ECC, radiation pattern, multiplexing efficiency, diversity gain and various other parameters are discussed and evaluated in detail.

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was 64 mm × 45 mm × 1.6 mm. Haq and Koziel [14] designed a MIMO antenna with decoupling stub, where the transmission coefficient was less than -20 dB and the ECC was less than 0.005; the dimension of the antenna was 25 mm × 32 mm.

Li et al. [15] presented a Vivaldi MIMO antenna with dual-stopped bands, where the size of the antenna was 26 mm × 26 mm, the isolation was greater than 16 dB and the ECC was less than 0.02 [15]. Kumar et al. [16] designed an octagonal-shaped MIMO antenna with dual-stop bands; the dimension of the antenna was 19 mm × 30 mm × 0.8 mm, isolation was greater than 18 dB and the ECC was less than 0.13 [16]. Chattha et al. [17] designed a MIMO antenna with a dimension of 23 mm × 26 mm × 0.8 mm with a single-stopped band of WLAN; the isolation was greater than 20 dB and the ECC was less than 0.06. In the study by Babu and Anuradha [18], the authors designed a large rectangular antenna with the dimensions 60 mm × 35 mm, a transmission coefficient less than -16.53 dB and an ECC less than 0.04. In [19], the authors designed a dual-notched band MIMO antenna with the dimensions 40 mm × 20 mm and isolation greater than 15 dB. In [20], the authors designed a circular-shaped MIMO antenna with EBG structure for isolation, where the overall dimension of the antenna was 27.2 mm × 46 mm, the isolation was greater than 18 dB and the ECC was less than 0.018. In the study by Khan and Khattak [21], the authors proposed a MIMO antenna with a T-shaped decoupling stub and dual-stop band of WiMAX and WLAN; the dimension of the antenna was 18 mm × 36 mm, the isolation was greater than 20 dB and the ECC was less than 0.05. Overall, the above designs are large in size, have low isolation and add additional complexity to the antenna structures. A detailed comparison among the proposed designs within the existing literature is shown in Table 1.

In the current paper, a dual-notched band MIMO antenna that is compact in size is presented, where the decoupling stub is used to achieve a low transmission coefficient. The overall size of the antenna is 15 mm × 25 mm × 1.6 mm. Two slits are etched in the radiating patch to stop the bands of WiMAX and WLAN. The proposed antenna has high isolation, compact size and good diversity performance compared with the designs in the cited literature.

II. ANTENNA DESIGN CONFIGURATION

1. Antenna Design

The proposed antenna is printed on low cost FR4 dielectric substrate with a height of 1.6 mm, relative permittivity of 4.4 and loss tangent of 0.02. The proposed design consists of two similarly structured radiating patches, a mountain-shaped ground plane and a T-shape decoupling stub. The overall dimensions of the proposed design are 15 mm × 25 mm × 1.6 mm. The top and bottom views of the designed MIMO antenna are depicted in Fig. 1 and their |S| parameters are illustrated in Fig. 2.

The width of the radiating patch (w) is 7.7 mm, the outer and inner lengths of the radiating patch are 9.5 mm and 3.5 mm, denoted respectively by l_o and l_i. The space between the two radiating elements is 9.6 mm. The length and width of the feed line are 7.5 mm and 1.4 mm, respectively. The ground plane consists of two half-circular discs and decoupling stubs. The radius of the half circular disc is 6 mm, and the length and width of the decoupling stub are 15 mm and 3 mm, respectively.

Various other design parameters are summarized in Table 2.

| Study | Size (mm) | Isolation (dB) | ECC | Diversity gain (dB) |
|-------|-----------|---------------|-----|---------------------|
| Zhao et al. [10] | 26 × 28 | >15 | <0.08 | >9.5 |
| Liu et al. [11] | 22 × 36 | >15 | <0.1 | - |
| Li et al. [12] | 35 × 68 | >20 | <0.035 | - |
| Jaglan et al. [13] | 64 × 45 | >15 | <0.02 | - |
| Haq and Koziel [14] | 25 × 32 | >20 | <0.005 | >9.9 |
| Li et al. [15] | 26 × 26 | >16 | <0.02 | - |
| Kumar et al. [16] | 19 × 30 | >18 | <0.13 | - |
| Chattha et al. [17] | 23 × 26 | >20 | <0.06 | - |
| Babu and Anuradha [18] | 60 × 35 | >16.53 | <0.04 | 9.99 |
| Mathur and Dwari [19] | 40 × 20 | >15 | <0.3 | - |
| Dabas et al. [20] | 27.2 × 46 | >18 | <0.018 | >9.9 |
| Khan and Khattak [21] | 18 × 36 | >20 | <0.05 | >9.8 |
| Lee et al. [22] | 90 × 50 | >15 | <0.08 | - |
| Lim et al. [23] | 70 × 48 | >15 | <0.08 | - |
| Kumar et al. [26] | 36 × 36 | >18 | <0.06 | >9.95 |
| Biswal and Das [27] | 30 × 30 | >20 | <0.013 | >9.51 |
| Kang et al. [28] | 38.5 × 38.5 | >15 | <0.02 | - |
| Rajkumar et al. [29] | 40 × 40 | >20 | <0.04 | - |
| Proposed | 15 × 25 | >20 | <0.02 | >9.9 |

Table 1. Comparison among proposed designs with literature cited

2. Decoupling Stub

Mutual coupling is a basic problem in MIMO antenna systems. The deployment of multiple antennas across small dis-
stances causes strong mutual coupling, and placing MIMO antennas spanning large distances necessitates increased antenna size; a decoupling stub is designed to overcome this problem. In the presented MIMO system, the T-shaped decoupling stub is designed for high isolation. The decoupling stub is evaluated in various steps, as shown in Fig. 3, and their $|S|$-parameters are illustrated in Fig. 4. As shown in Fig. 4, the mutual coupling of

![Diagram](image_url)

**Table 2: Design dimension parameters of presented MIMO antenna**

| Parameter | Value (mm) | Parameter | Value (mm) |
|-----------|------------|-----------|------------|
| $W$       | 25         | $l_2$     | 9.5        |
| $L$       | 15         | $w_4$     | 7.7        |
| $l_3$     | 7.5        | $e_1$     | 3          |
| $w_3$     | 1.4        | $e_2$     | 18         |
| $l_4$     | 3.5        | $l_4$     | 12         |
| $l_5$     | 6.1        | $w_5$     | 3          |
| $l_6$     | 8          | $r_2$     | 6          |
| $S_1$     | 4.3        | $S_6$     | 1.1        |
| $S_2$     | 1.7        | $S_7$     | 2.5        |
| $S_3$     | 3          | $S_8$     | 1.2        |
| $S_4$     | 1.7        | $S_9$     | 3.6        |
| $S_5$     | 2.3        | $S_{10}$  | 1.8        |

![Table](image_url)

![Figure 1](image_url)

**Fig. 1.** Design of proposed MIMO-UWB antenna: (a) top view, (b) bottom view, and (c) perspective view.

![Figure 2](image_url)

**Fig. 2.** Simulated $|S|$-parameters of presented MIMO antenna.

![Figure 3](image_url)

**Fig. 3.** Evaluation steps of decoupling stub in MIMO antenna: (a) without decoupling stub, (b) with I-shaped decoupling stub, and (c) with T-shaped decoupling stub.
a MIMO antenna without a decoupling stub and an I-shaped decoupling stub are much higher than with the proposed T-shaped decoupling stub.

Surface current distribution at 3.5 GHz and 5.5 GHz is shown in Fig. 5. Port1 is excited to examine surface current distribution with and without decoupling stub. In Fig. 5, without the decoupling stub, strong transmission between ports is noted; this occurred because a portion of the current was transmitted from Port1 to Port2 due to the small space between the radiating elements. The decoupling stub was added to utilize most of the current on left side of the stub and to isolate the other port.

3. Stop Band Characteristics

The frequency range of UWB is between 3.1 GHz and 10.6 GHz, but there are also some narrow bands, such as WiMAX and WLAN, that interfere with UWB communication. The slits are etched in radiating elements to stop such narrow bands. The total length of slot1 is 13 mm (slot1 = S1 + S2 + S3 + S4 + S5) and the total length of slot2 is 10.2 mm (slot2 = S6 + S7 + S8 + S9 + S10); the detail values of the dimension of the slots are summarized in Table 2. The lengths of the slots are dependent on the relative permittivity of the substrate and the center frequency of the stop band. The lengths of the slots are determined from Eq. (1) [30].

$$L_{slot1} = L_{slot2} = \frac{c}{4f_n \sqrt{(\varepsilon_r + 1)/2}}$$  \hspace{1cm} (1)

$\varepsilon_r$ is relative permittivity, $f_n$ is notch frequency and $c$ is speed of light. The evaluation steps of the notch characteristics are depicted in Fig. 6, and their $|S|$-parameters are illustrated in Fig. 7. slot1 is used to stop the band of WiMAX and slot2 is used to

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Fig. 4. Isolations of decoupling stub in presented MIMO antenna.

Fig. 5. Surface current distribution of MIMO antenna at: (a) 3.5 GHz with decoupling stub, (b) 3.5 GHz without decoupling stub, (c) 5.5 GHz with decoupling stub, and (d) 5.5 GHz without decoupling stub.

Fig. 6. Evaluation steps of notch characteristics in MIMO antenna: (a) MIMO Ant1, (b) MIMO Ant2, (c) MIMO Ant3, and (d) MIMO Ant4 (proposed design).

Fig. 7. Reflection coefficients of design evaluation steps of notch characteristics in proposed MIMO antenna.
stop the band of WLAN, which are justified through Fig. 7. The MIMO Ant1 is a simple UWB antenna ranging from 3 GHz to 10.9 GHz, while the MIMO Ant2 stops the band of WiMAX, the MIMO Ant3 stops the band of WLAN, and the MIMO Ant4 stops both the bands; this is all shown through Fig. 7.

4. Parametric Analysis

The parametric analysis was accomplished by observing the variations in reflection coefficients and isolations with the variation in different parts of the antenna such as radius of the ground plane ($r_g$), width of the decoupling stub ($w_s$), the length and width of the radiating patch ($l_3$) and the width of the feed ($w_f$). The ground plane and decoupling stub have two main functions: providing impedance matching and reducing mutual coupling.

The parametric analysis of ground plane is depicted in Fig. 8. The reflection coefficient is relatively better in the entire UWB for $r_g = 6$ mm. The mismatch losses have been increased in the 4–5 GHz frequency band and above 9 GHz for $r_g = 5$ mm; similarly mismatched losses occur over the entire UWB for $r_g = 7$ mm. The isolations are nearly same up to 8 GHz but are degraded after 8 GHz for both smaller and larger values of $r_g$. When the width of the decoupling stub ($w_s$) varies from 2–4 mm, variations in the reflection coefficients and isolations are observed; this is shown in Fig. 9. Relatively better response over the entire UWB band is observed for $w_s = 3$ mm. The impedance matching is poor beyond 9 GHz, and similarly, isolations are degraded beyond 6 GHz for both smaller and larger values of ($w_s$).

The parametric analysis of the radiating patch is depicted in Fig. 10. Isolation is nearly the same for all values of $l_3$, but reflection coefficients are drastically affected if $l_3$ is increased or decreased by 2 mm. The reflection coefficient is poor between 4–8 GHz for $l_3 = 6$ mm, and there is a poor reflection coefficient beyond 7 GHz for $l_3 = 10$ mm. The parametric analysis of the feed line is depicted in Fig. 11. The reflection coefficient is relatively better across the entire UWB for $w_f = 1.4$ mm. Isolation is nearly the same for all values of feed width ($w_f$). The mismatched losses increase across the 6–9 GHz frequency band for $w_f = 1.2$ mm; similarly mismatched losses occur across the 4–5 GHz for $w_f = 1.6$ mm.

III. RESULTS AND DISCUSSION

The proposed MIMO antenna is printed on FR4 substrate and simulated in CST Microwave Studio. The prototype of the proposed design is depicted in Fig. 12, and the measured and simulated $|S|$-parameters are illustrated in Fig. 13. The latter figure outlines the fact that both measured and simulated reflection coefficients are less than $-10$ dB between 3–10.9 GHz,
except in the cases where the bands of WiMAX (3.2–3.7 GHz) and WLAN (5–6 GHz) covered the entire UWB communication. Similarly, the measured and simulated isolation is greater than 20 dB across the entire band of UWB; both measured and simulated results are nearly same and show significant agreement. The measured and simulated E-plane ($YZ, \phi = 90$) and H-plane ($XZ, \phi = 0$) radiation patterns at various frequencies are illustrated in Fig. 14. From Fig. 14, it is justified that the radiation pattern at 4.5 GHz in both yz-Plane and xz-Plane are omni-directional radiation pattern, the radiation pattern at 7.5 GHz are also form nearly omni-directional radiation pattern in both yz-Plane and xz-Plane; the radiation patterns are stable in both planes on given frequencies.

Diversity performance is evaluated in terms of the ECC, diversity gains and multiplexing efficiency. Ideally, the ECC is equal to zero; practically, an ECC < 0.5 may be acceptable. Diversity gains and ECC are calculated using Eqs. (2) and (3) [31].

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

$$\text{DG} = 10\sqrt{1 - (\text{ECC})^2}$$  \(\text{(3)}\)

The measured and simulated ECC is depicted in Fig. 15. The ECC is 0.02 at notched frequency and almost zero at resonance frequencies. Similarly, the diversity gain is 9.9 dB at notched frequencies and almost equal to 10 dB at resonance frequencies (shown in Fig. 16). Peak gain and multiplexing efficiencies are depicted in Fig. 17; measured and simulated peak gains are
MIMO communication systems. The designed antenna can be used for UWB-ISM/mobile applications. The ECC is nearly same and much lower at notched frequencies when compared with other frequencies. Similarly, multiplexing efficiency was $-10$ dB at notched frequencies and varies between $-4$ dB and $-2$ dB on other frequencies (shown in Fig. 17).

IV. CONCLUSION

In this paper, a compact and new design of a MIMO system is presented. Isolation is achieved with the help of a T-shaped decoupling stub; dual bands of WiMAX (3.2–3.7 GHz) and WLAN (5–6 GHz) are stopped with the help of slits in the radiators. The antenna is printed on FR4 substrate and optimized and simulated in CST Microwave Studio. The ECC is less than 0.02, and the diversity gain is greater than 9.9 dB. The peak gain, ECC, multiplexing efficiency, diversity gain and radiation pattern show that the designed antenna can be used for UWB-MIMO communication systems.

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