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Compact MIMO Antenna with WLAN Band-Notch Characteristics for Portable UWB Systems

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Abstract—A compact multiple input multiple output (MIMO) antenna with WLAN band-notch filtering function for portable wireless ultra-wideband (UWB) systems is proposed in this paper. The overall size of the antenna is $26 \times 40 \times 0.8\,\mathrm{mm}^3$, and it is fabricated on a low-cost FR4 substrate. The antenna comprises two identical planar monopole antenna elements, namely PM1 and PM2, which are fed by a 50-ohm coplanar waveguide. The PM1 and PM2 are positioned perpendicular to each other to minimize the mutual coupling between them. To further reduce the mutual coupling and to increase the impedance bandwidth, a long rectangular strip is protruded from the ground plane between the PM1 and PM2. To create the band-notch characteristics at WLAN band from 5 to 5.9 GHz, an inverted U-shaped slot is etched on the feed line. The simulated and measured results show that the proposed antenna achieves good impedance bandwidth ($S_{11} \leq -10\,\mathrm{dB}$) from 2.2 to 11.4 GHz and mutual coupling (S_{21}) of $< -20\,\mathrm{dB}$. The measured peak gain of 2.4 to 7.5 dBi and radiation efficiency above 90% are obtained except at notch band. The measured envelope correlation coefficient (ECC) of 0.008 in the whole operating band and omnidirectional radiation characteristics demonstrate that the proposed MIMO antenna is a suitable candidate for portable UWB systems.

1. INTRODUCTION

The current and future wireless communication systems like 4G and 5G demand for higher data rates, enhanced quality of service, and coexistence with existing communication systems. Since the Federal Communications Commission (FCC) officially assigned unlicensed spectrum from 3.1 to 10.6 GHz as ultra-wideband (UWB) for commercial applications in 2002 [1], the UWB technology has gained much attention due to its inherent advantages (higher data rates, low power, low cost, and improved quality of service) and applications (wireless personal area networks, vehicular radar systems, and imaging systems). However, frequency interference with other communication systems and multipath fading are the important problems that should be solved well for UWB systems.

Ultra-wideband is a promising technology for short-distance high-speed data communications with a very low power requirement. The existing narrowband system such as wireless local area network (WLAN: 5.15–5.825 GHz) may cause frequency interference to UWB systems. Therefore, UWB antenna with integrated frequency notching function at the interfering frequency band is a feasible solution to mitigate the frequency interference.

UWB technology has many applications in wireless communication world, which include wireless personal area networks (WPANs) and wireless body area networks (WBANs). In an indoor communication application, like other wireless communication systems, the UWB system performance is also restricted by multipath fading due to rich scattering environments which cause inter-symbol

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interference. In recent times, digital communication using multiple input multiple output (MIMO) technology has emerged as a breakthrough for a wireless system. The MIMO system employs multiple antennas at the transmitter and receiver. It makes use of rich multipath environment to mitigate multipath fading effect, and it improves the range of communication and system capacity (data rate) without the need for additional bandwidth or transmitted signal power [2, 3]. Hence, the UWB system with MIMO technology is a viable solution to reduce the multipath fading effect and to improve the quality of service, the range of communication and system capacity.

The electromagnetic interaction between the radiating (antenna) elements in multiple antenna or MIMO system is known as mutual coupling. The closely spaced antennas, especially in portable devices, inevitably cause strong mutual coupling between antennas. The mutual coupling is undesirable which causes fluctuations in the input impedance of individual antenna element, i.e., impedance mismatch which degrades radiation efficiency, causes deviations in antenna radiation pattern due to the high correlation between antenna signals and decreases the channel capacity of MIMO system. Since mutual coupling has a considerable impact on MIMO system performance, the reduction of mutual coupling between antennas and enhancement of isolation between ports are imperative. However, placing multiple antennas in a space-limited portable wireless device is a big challenge for antenna designers [4]. Hence, designing a compact UWB-MIMO antenna exhibiting band-notch function and less mutual coupling is very much needed.

Various decoupling structures have been proposed in the past years for WLAN and WiMAX in [5, 6], and for UWB-MIMO systems in [7–10] to minimize mutual coupling and enhance the isolation. Methods include use of U-slots in feed line of the antenna elements [5, 6], placing radiating elements perpendicular to each other and adding two long protruding stubs to ground [7], use of a tree-like structure on the ground plane [8], etching a T-shaped slot and a line slot on the ground [9], or adding a Y-shaped slot on the T-shaped protruded ground plane [10]. However, the UWB-MIMO antennas in [7–10] do not provide band-notch characteristics.

Several investigations were reported earlier to create band notch function at WLAN band for UWB systems. Methods include inserting $\lambda/4$ and $\lambda/2$ slot resonators on the ground plane [11], inserting an open stub in the printed folded monopole [12], etching split-ring resonator (SRR) slots on radiating element [13], protruding two rectangular stubs on the ground plane [14], etching folded U-shaped slots in the feed line of the antenna [15, 16], employing elliptical SRR on the radiating element [17], using C-shaped and Z-shaped slot resonators on the ground [18], and quarter-wave stub connected to the ground [19]. The antenna designs presented in [11–19] exhibit acceptable isolation and notching characteristics, but some designs are not compact enough, and a few are a bit complex. So, the design of a simple and compact band-notched UWB MIMO antenna with low mutual coupling is needed.

A compact UWB MIMO antenna exhibiting band-notch characteristics for portable wireless devices is proposed in this paper. The proposed antenna has dimension of $26 \times 40 \times 0.8\,\mathrm{mm}^3$ which is small compared to the designs presented in [12–14, 17, 19]. The proposed design consists of two identical planar monopole antenna elements (PM1 and PM2) which are excited by a 50-ohm coplanar waveguide. The monopoles PM1 and PM2 are placed perpendicular to each other to reduce the mutual coupling. To further improve the isolation between the antenna ports and increase the impedance bandwidth, a long rectangular strip is protruded from the ground plane between the monopoles. The proposed antenna achieves good impedance bandwidth ($S_{11} \leq -10\,\mathrm{dB}$) from 2.2 to 11.4 GHz and low mutual coupling (S_{21}) of lower than $-20\,\mathrm{dB}$. To create notch-band at 5–5.9 GHz, an inverted U-shaped slot is etched on the feed line. Reasonably good gain, high radiation efficiency, low envelope correlation coefficient (ECC), and good radiation characteristics are obtained by the proposed antenna. The following sections will discuss detailed description of the proposed design.

2. ANTENNA DESIGN

The geometry of the proposed band-notch UWB-MIMO antenna and a photograph of the fabricated antenna are shown in Figs. 1(a) and 1(b). The proposed design is printed on an FR4 substrate having dielectric constant (ε_r) of 4.4, thickness of 0.8 mm, and loss tangent of 0.02. The overall size of the proposed antenna is $L \times W \times h\,\mathrm{mm}^3 = 26 \times 40 \times 0.8\,\mathrm{mm}^3$.

The antenna comprises two identical rectangular planar monopole radiating elements, denoted as

PM1 and PM2 having sizes $L_R \times W_R$ as shown in Fig. 1(a). Both PM1 and PM2 are fed by the 50-ohm coplanar waveguide having dimensions $F_{L1} \times W_F$. The common ground is formed by joining $L_G \times W_G$ and $L_G \times L$ reduced ground planes and is also printed on the same side of the substrate. The planar monopoles PM1 and PM2 are positioned perpendicularly to each other to reduce the mutual coupling between elements and to improve the isolation between antenna ports. A rectangular long strip of size $S_L \times S_W$ is extended from the common ground plane between the monopoles to further enhance isolation and improve the impedance bandwidth of the antenna. The ground strip extends the current path which shifts the first resonance frequency to lower band and blocks the surface currents to minimizes the mutual coupling. An inverted U-slot resonator is placed on the feed line to create a band-notch function at 5–5.9 GHz. Ansoft HFSS v.13 is used to carry out the proposed antenna design, optimization, and simulations. Optimized dimensions of the proposed antenna are given as follows: (unit: mm): $D_1 = 5.1$, $D_2 = 6.1$, $D_3 = 11.2$, $F_{L1} = 9.5$, $F_{L2} = 1.5$, $F_{L3} = 0.4$, $L = 26$, $L_G = 8$, $L_R = 10$, $S_L = 18$, $S_W = 1$, $W = 40$, $W_F = 1.8$, $W_G = 3.2$, $W_R = 11$, $U_1 = 7.8$, $U_2 = 0.4$, and $U_W = 0.3$.

Figs. 2(a) and 2(b) show the simulated S-parameters such as S_{11} and S_{21} of Antenna 1 (UWB-

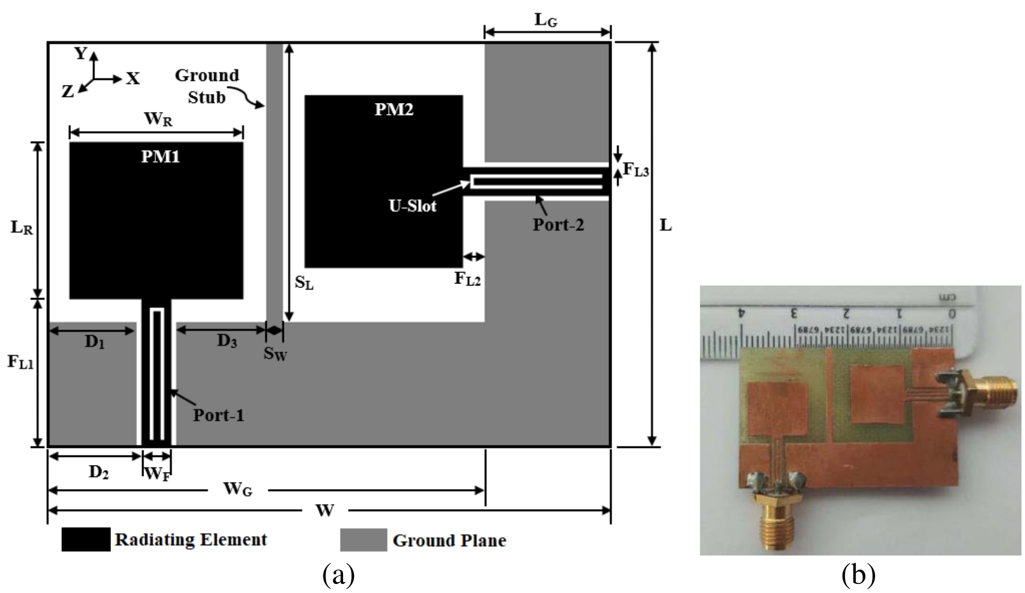


Figure 1. (a) Geometry of the proposed antenna, and (b) fabricated antenna.

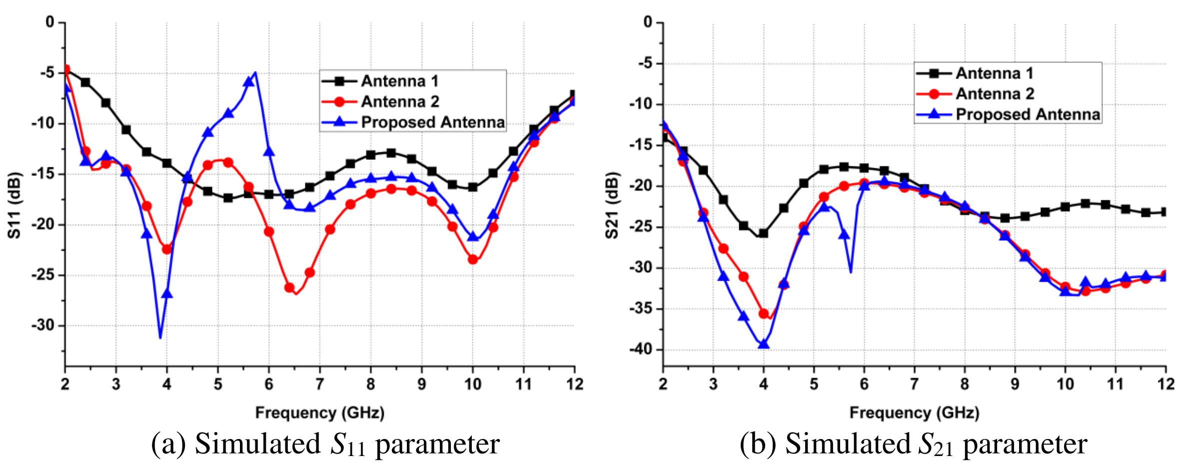


Figure 2. Simulated S-parameters.

MIMO antenna without ground strip), Antenna 2 (UWB-MIMO with a ground strip), and the proposed antenna. It can be observed from Fig. 2(a) that the proposed UWB-MIMO antenna operates from 2.2 to 11.4 GHz with good impedance bandwidth except at notch band from 5 to 5.9 GHz. From Fig. 2(b), it is evident that the mutual coupling of less than −20 dB is obtained over the entire UWB.

3. STUDY OF MIMO ANTENNA

In this section, the effects of the ground strip with different lengths (S_L) and widths (S_W) on the MIMO antenna in terms of impedance bandwidth (S_{11}) and mutual coupling (S_{21}) are studied. Effects of the inverted U-shaped slot resonator with variable slot lengths (U_1) and slot widths (U_W) on the MIMO antenna are also discussed.

3.1. Effects of Ground Strip

Since the ground and radiating elements have smaller dimensions, the flow of surface currents on the ground plane and near-field radiation leads to poor impedance matching and high mutual coupling, which restricts the performance of MIMO antenna. The UWB-MIMO antennas without and with ground strip are shown in Figs. 3(a) and 3(b), respectively. The effects of the ground strip on impedance bandwidth and mutual coupling between the MIMO antenna elements are plotted in Figs. 4(a) and 4(b). It can be seen from Fig. 4(a) that the MIMO antenna without ground strip (Antenna 1) has the first resonance at about 5 GHz with a lower cutoff frequency of 3.2 GHz and mutual coupling (S_{21}) of less than −17 dB between the PM1 and PM2 as plotted in Fig. 4(b). From Fig. 4(c), without a ground strip, huge amounts of surface currents enter port 2 through the common ground plane when port 1 is excited which represents the low isolation between the antenna ports. However, with ground strip between the PM1 and PM2 (Antenna 2), the first resonance is generated at 2.5 GHz with a lower cutoff frequency of 2.3 GHz and provides good impedance bandwidth from 2.3 to 11.4 GHz as depicted in Fig. 4(a). From Fig. 4(b), the mutual coupling of lower than −20 dB between the antenna elements is observed throughout the UWB which is less than −17 dB. In addition, the flow of surface currents is effectively suppressed by the ground strip, and thus less amount of current is leaked into port 2 when port 1 is excited as displayed in Fig. 4(c). The ground strip can work as a reflecting surface so that the direction of surface currents is diverted, and thus the distance between the ports is increased. Hence, the isolation between the MIMO antenna ports is significantly enhanced. Therefore, the ground strip between the MIMO antenna elements will improve impedance matching characteristics and minimize the mutual coupling of the MIMO antenna.

The MIMO antenna is also studied by varying the ground strip length S_L and width S_W, plotted in Figs. 5(a) to 5(d). It can be observed from Figs. 5(a) to 5(d) that the total length and width of the ground strip have more effect on the impedance bandwidth ($|S_{11}| < -10$ dB) than the isolation or mutual coupling. In this paper, the ground strip length $S_L = 18$ mm and width $S_W = 1$ mm are adopted.

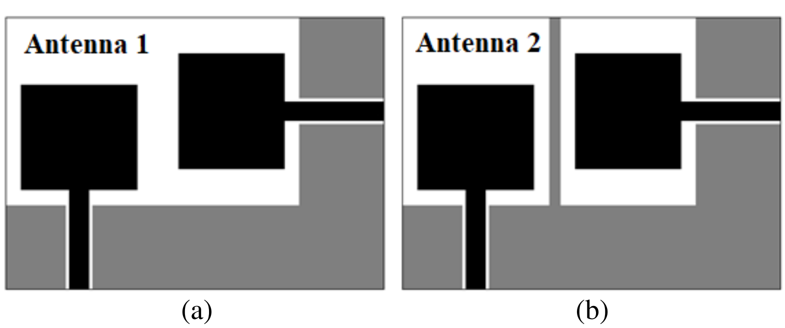


Figure 3. (a) UWB-MIMO antenna without a ground strip (Antenna 1), (b) UWB-MIMO antenna with a ground strip (Antenna 2).

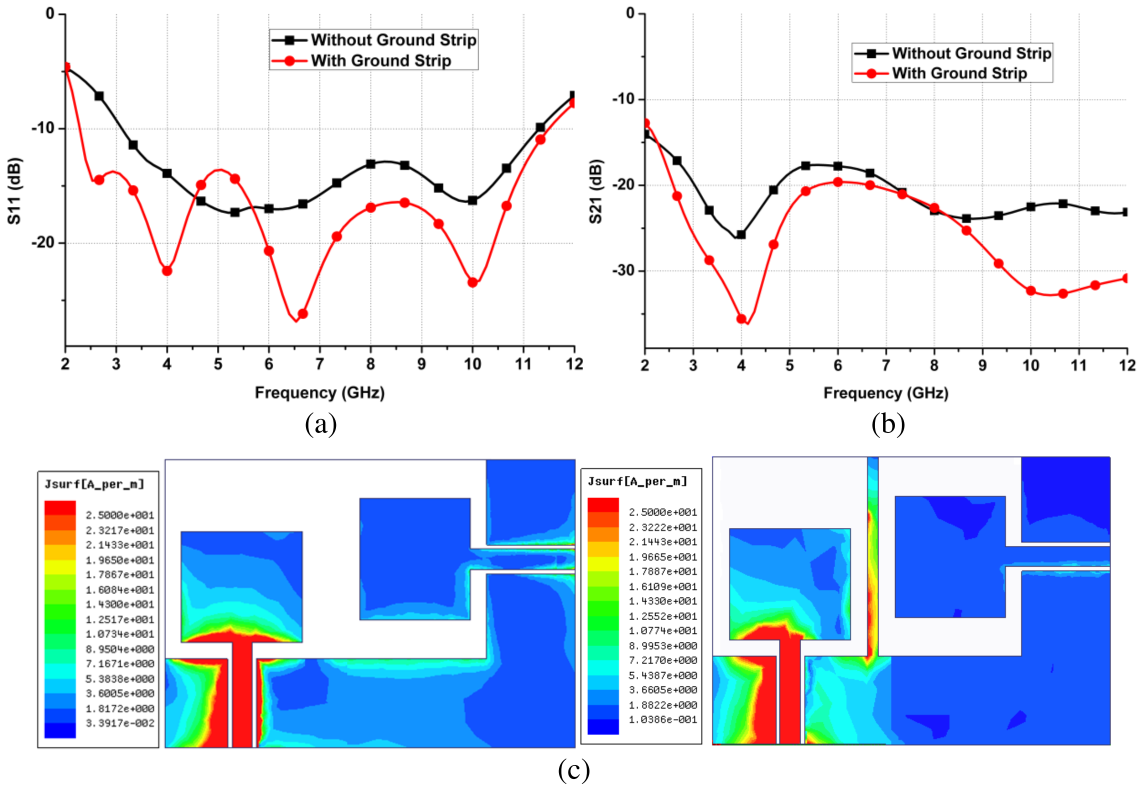


Figure 4. (a) S_{11} without and with a ground strip, (b) S_{21} without and with a ground strip, (c) surface current distribution at 3.8 GHz when port 1 excited without and with a ground strip.

3.2. Effects of an Inverted U-Slot

To create band-notch filtering function for UWB systems, slots of various shapes or split-ring resonators or strips can be used on or next to the feed line or the radiating element or the ground plane as reported in [11–18]. The slot or SRR or strip can act as a band-notch resonator. The notch band center frequency is controlled by the length of the resonator, and notch band bandwidth is controlled by the width of the resonator. By proper selection of resonator length and width, the desired notch band can be generated. The total length of the resonator should be $\lambda/2$ or $\lambda/4$ to create band-notch, where λ is the guided wavelength ($\lambda = \frac{c}{f_{notch} \cdot \sqrt{\varepsilon_{eff}}}$). In this paper, an inverted U-shaped slot is used as a band-notch resonator and is etched on the feed line of Antenna 2 which forms the proposed band-notch UWB-MIMO antenna as shown in Fig. 6(a) through 6(c).

In this work, the length of the U-shaped resonator is calculated using Equation (1) [11].

$$L_N = \frac{c}{2 f_N \sqrt{\varepsilon_{eff}}} \approx \frac{\lambda}{2}, \tag{1}$$

where L_N denotes the total length of U-slot, c the speed of light, f_N the notch center frequency, and $\varepsilon_{eff} = (\varepsilon_r + 1)/2$ the effective dielectric constant. When $f_N = 5.7$ GHz and $\varepsilon_r = 4.4$, the calculated length of the U-slot resonator using Equation (1) is 16.01 mm. The simulated or designed total length of the inverted U-slot resonator is 16 mm and determined by using Equation (2).

$$L_{U\text{-}Slot} = 2U_1 + U_2 \approx \frac{\lambda}{2}. \tag{2}$$

Good agreement between the calculated (theoretical) length and simulated (practical) length is observed. Figs. 7(a) to 7(c) show S_{11}, S_{21} and surface currents without and with inverted U-slot resonator.

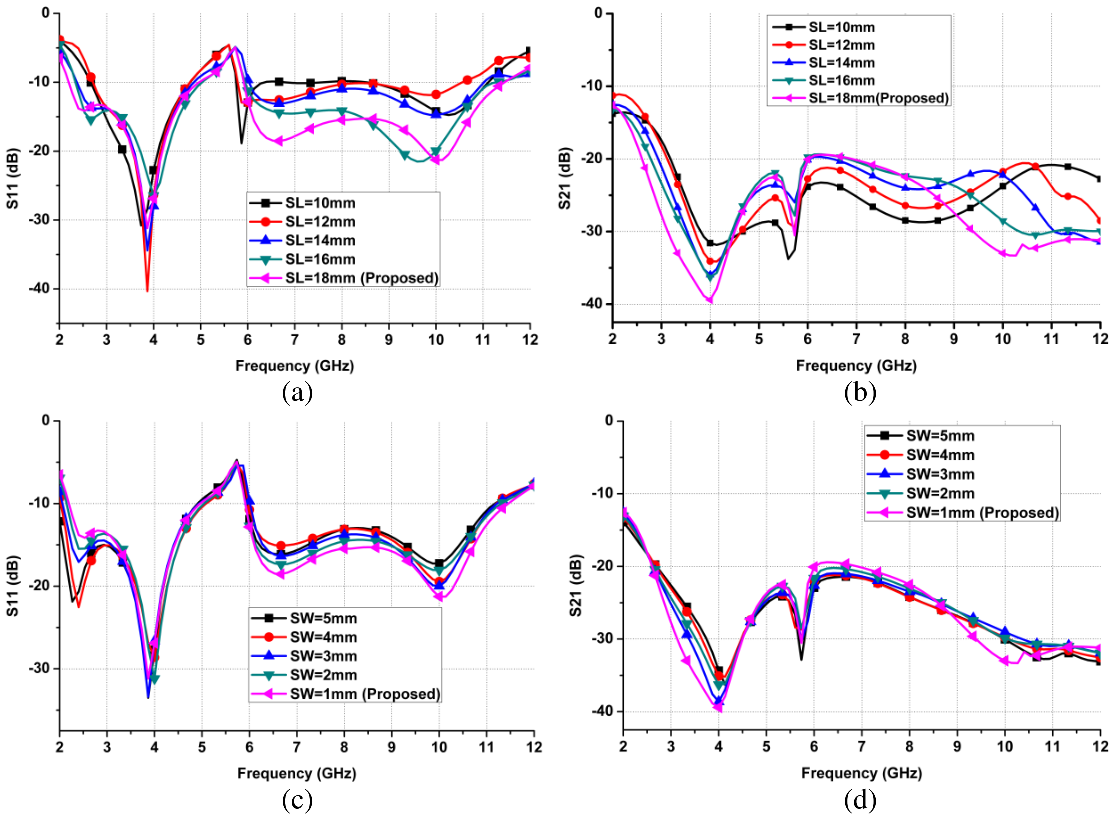


Figure 5. (a) S_{11} for different strip lengths S_L, (b) S_{21} different strip lengths S_L, (c) S_{11} for different strip widths S_W, (d) S_{21} for different strip widths S_W.

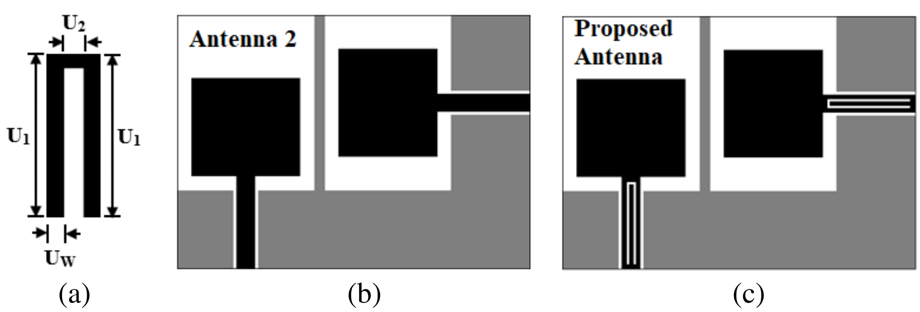


Figure 6. (a) an inverted U-slot resonator, (b) UWB-MIMO antenna with ground strip (Antenna 2), (c) proposed band-notched UWB-MIMO antenna.

As seen in Fig. 7(a), the proposed antenna works from 2.2 to 11.4 GHz with good impedance bandwidth and generates band-notch characteristics from 5 to 5.9 GHz with S_{11} of -5 dB at 5.7 GHz. The mutual coupling of below -20 dB over the entire working band is observed as from Fig. 7(b). It is evident from Fig. 7(c) that at 5.7 GHz, heavy current is concentrated around the slot, so current flow on the radiating elements is blocked and hence no radiation from the antenna. Therefore, notch band from 5 to 5.9 GHz WLAN band is created.

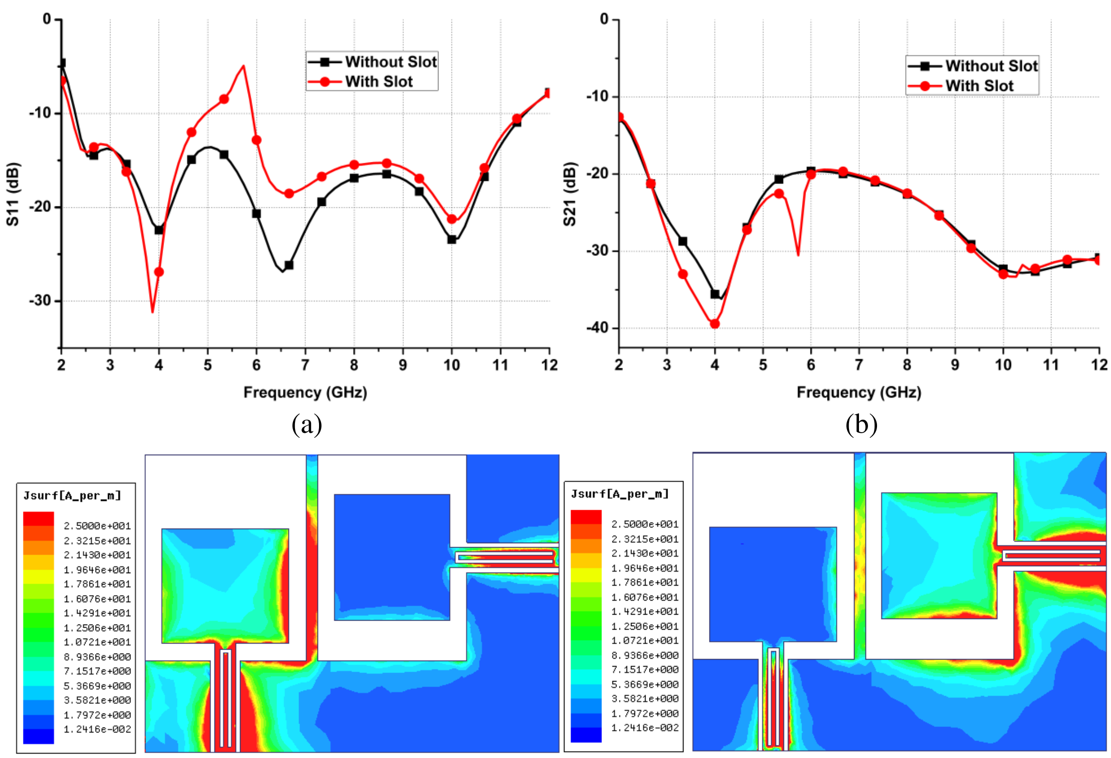
The parametric analysis on the slot length U_1 and slot width U_W is performed to describe the effects of inverted U-slot. Table 1 and Table 2 list the notch bands and their center frequencies for different slot lengths and widths. Figs. 8(a) and 8(b) illustrate S_{11} of the MIMO antenna for different slot lengths U_1 and slot widths U_W, respectively. It is evident from Fig. 8(a) and Table 1 that as the slot

Table 1. The notch bands and notch center frequencies for different slot lengths.

Slot length U_1 (mm)	Notch Band (GHz)	f_N (GHz)
6.8	6.26–6.7	6.5
7.3	5.73–6.4	6.2
7.8 (Proposed)	5.0–5.9	5.7
8.1	4.8–5.7	5.4

Table 2. The notch bands and notch center frequencies for different slot widths.

Slot Width U_W (mm)	Notch Band (GHz)	f_N (GHz)
0.25	5.2–5.7	5.6
0.3 (Proposed)	5.0–5.9	5.7
0.35	4.95–6	5.7
0.4	4.94–6.1	5.7



(c)

Figure 7. (a) S_{11} without and with inverted U-slot, (b) S_{21} without and with inverted U-slot, (c) current distribution at 5.7 GHz when port 1 and port 2 excited.

length U_1 increases from 6.8 mm to 8.1 mm, the center frequency of notch f_N decreases from 6.5 GHz to 5.4 GHz, and notch band is shifted from (6.26–6.7) GHz to (4.8–5.7) GHz. The required band notch from 5 to 5.9 GHz is generated for U_1 of 7.8 mm which is used in this work. Form Fig. 8(b) and Table 2, it can be observed that increasing the slot width U_W from 0.25 mm to 0.4 mm, the notch bandwidth is increased from (5.2–5.7) GHz to (4.94–6.1) GHz with notch center frequency f_N at 5.7 GHz. The slot

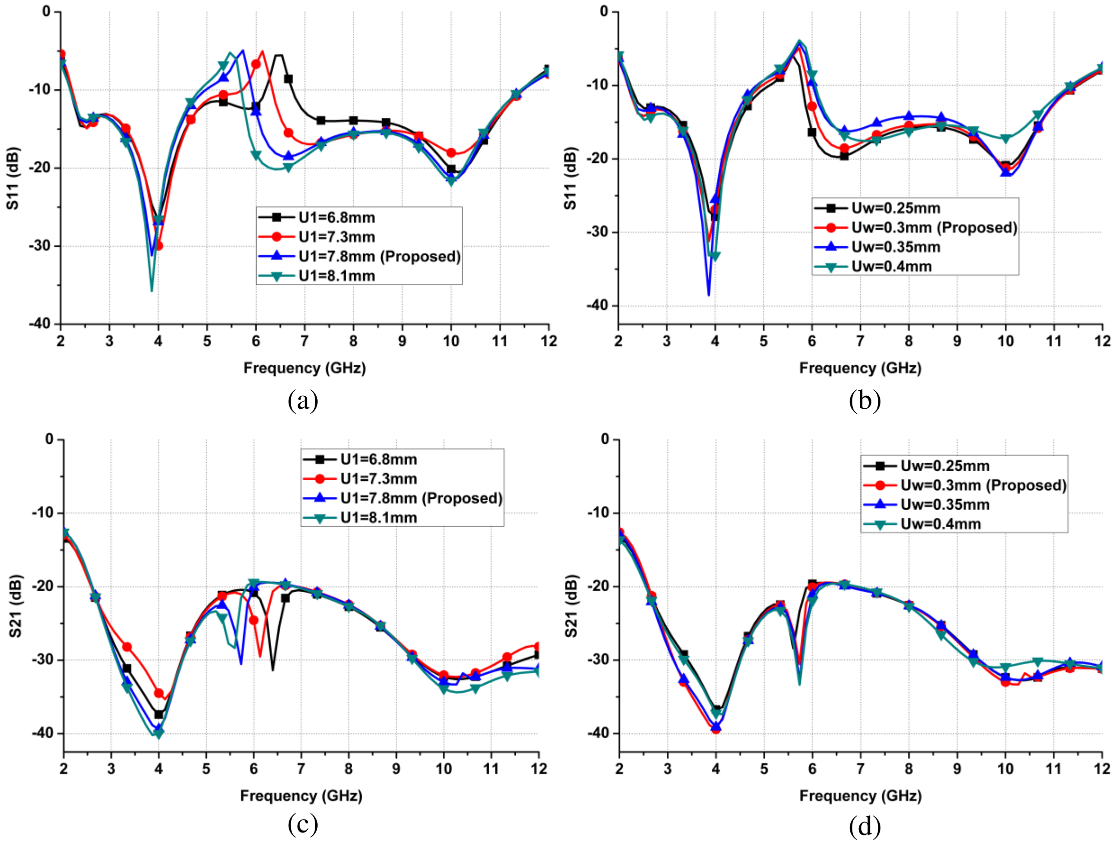


Figure 8. S_{11} for (a) various slot lengths, (b) various slot widths; and S_{21} for (c) various slot lengths, (d) various slot widths.

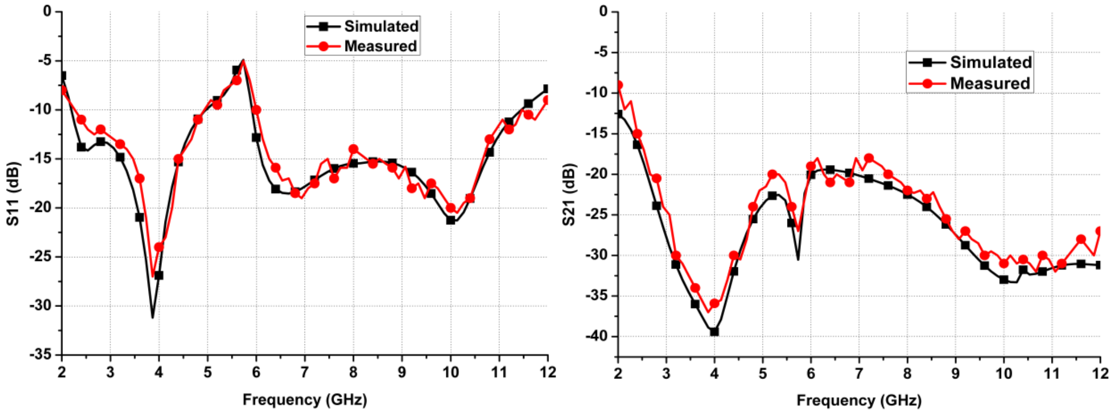
width U_W of 0.3 mm is chosen in this proposed design to get the desired band notch from 5 to 5.9 GHz.

Figures 8(c) and 8(d) show effects of the inverted U-slot resonator on S_{21} of the MIMO antenna for various slot lengths and widths. It is clear from Figs. 8(c) and 8(d) that variation in the slot length U_1 and width U_W has a negligible effect on the mutual coupling of MIMO antenna.

4. RESULTS AND DISCUSSION

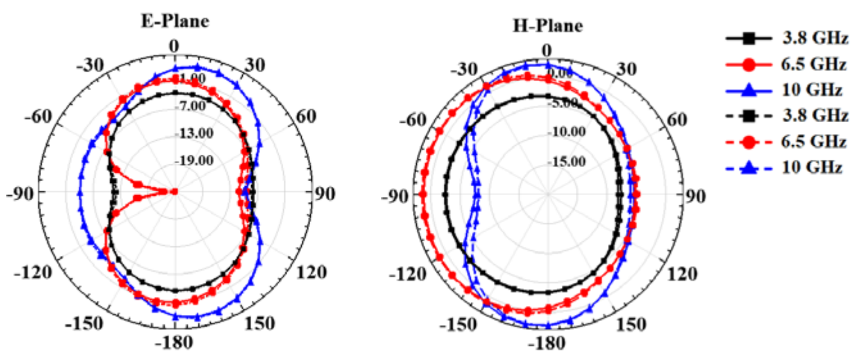
The fabricated antenna with the optimized dimensions mentioned in Section 2 is depicted in Fig. 1(b). S_{11} and S_{21} parameters of the proposed design are measured using Agilent N5224A PNA network analyzer. Comparisons between the simulated and measured S_{11} and S_{21} parameters are illustrated in Figs. 9(a) and 9(b). The proposed antenna offers good impedance bandwidth ($|S_{11}| < -10\,\text{dB}$) from 2.2 to 11.4 GHz with band notch at 5–5.9 GHz as demonstrated in Fig. 9(a). Hence, the frequency interference from WLAN band can be effectively suppressed by the proposed UWB-MIMO antenna. From Fig. 9(b), it is found that the simulated and measured mutual coupling (S_{21}) values are about -20 dB in the operating band except at a few frequencies around 6.2 and 7.2 GHz (-16 dB) demonstrating good isolation between the ports. At 6.2 and 7.2 GHz, S_{21} is -16 dB. Good agreement between the simulated and measured S-parameters is identified from Fig. 9 except for some deviations due to fabrication and soldering imperfections, losses in dielectrics and conductors, effects of SMA connector, and measurement tolerances.

2-D radiation patterns of the proposed UWB-MIMO antenna are measured in an anechoic chamber. The simulated and measured radiation patterns of the proposed antenna on the E-plane and H-plane at 3.8, 6.5, and 10 GHz when port 1 is excited and port 2 terminated with 50-ohm load, and vice-versa are shown in Figs. 10(a) and 10(b). Good agreement between the simulated and measure 2-D radiation

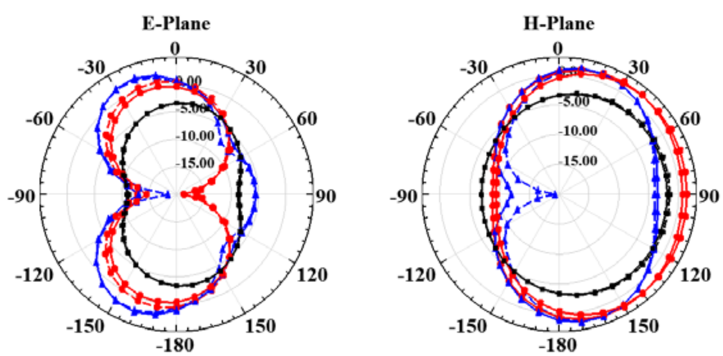


(a) (b)

Figure 9. The simulated and measured results: (a) S_{11}-parameter, (b) S_{21}-parameter.



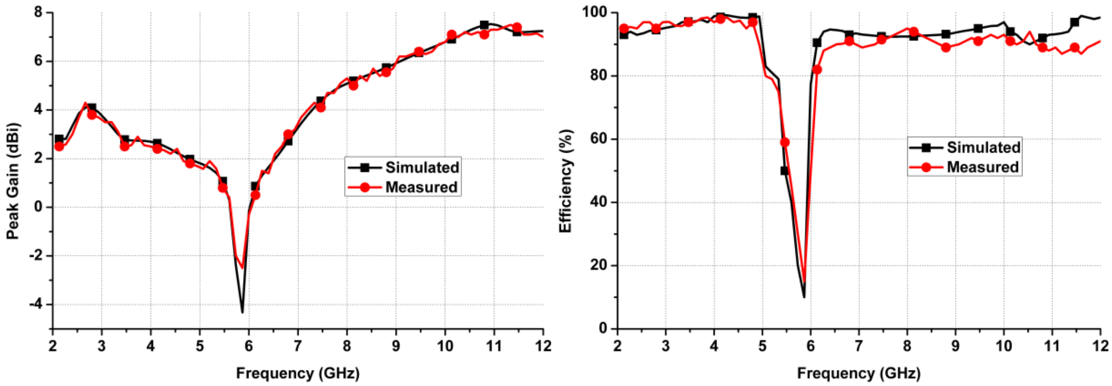
(a) simulated and measured when port 1 excited



(b) simulated and measured when port 2 excited

Figure 10. Simulated (solid line) and measured (dashed line) radiation patterns.

patterns is observed. At 3.8 and 6.5 GHz frequencies, PM1 and PM2 have quite omnidirectional radiation patterns in H-planes, i.e., the XZ plane and YZ plane, respectively. However, at 10 GHz because of the higher-order resonances, the radiation patterns in the H-planes are less omnidirectional. At 6.5 and 10 GHz, PM1 and PM2 have dumbbell-shaped or bidirectional patterns in the E-planes, i.e., the YZ plane and XZ plane, respectively. However, at 3.8 GHz, PM1 and PM2 do not have "dumb-bell" shaped patterns in the E-planes, because, the strip on the ground plane changes the current distributions. It can be seen from Fig. 10 that the proposed antenna provides omnidirectional radiations in H-plane which is essential for portable wireless devices to receive signals from all directions. It is also found that



(a) (b)

Figure 11. Simulated and measured (a) peak gain, (b) radiation efficiency.

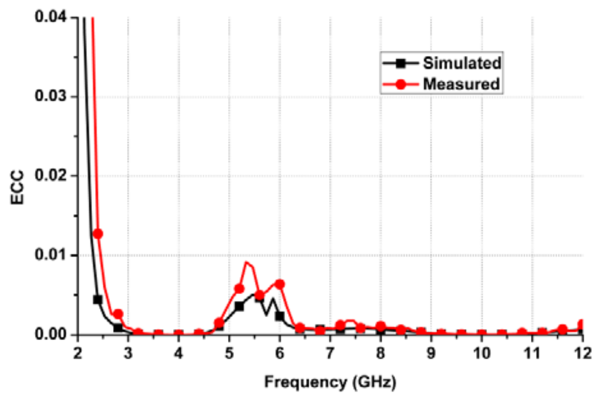


Figure 12. Simulated and measured ECC.

H-plane patterns of port 1 and port 2 are nearly mirror images demonstrating good pattern diversity.

The simulated and measured peak gains of the proposed design are plotted in Fig. 11(a). The peak gain of 2.4 to 7.5 dBi in the operating band is observed excepting at the notch band. At the notch band, the measured peak gain falls to −2.2 dBi. Fig. 11(b) shows the simulated and measured radiation efficiency plots of the proposed antenna. The radiation efficiency of above 90% is found across the UWB except at 5–5.9 GHz notch band. At notch band, the efficiency drops to 12%. It is evident from Figs. 11(a) and 11(b) that the proposed antenna can avoid the frequency interference from WLAN band more efficiently.

Along with radiation patterns, envelope correlation coefficient (ECC) is also an important parameter to study the MIMO antenna diversity and is calculated using S-parameters with Equation (3) of a two-port MIMO antenna system reported by Blanch et al. [20]. Fig. 12 shows the simulated and measured ECCs of the proposed antenna.

$$ECC = \frac{\left|S_{11}^{*}S_{12} + S_{21}^{*}S_{22}\right|^2}{\left(1-\left(\left|S_{11}\right|^2+\left|S_{21}\right|^2\right)\right)\left(1-\left(\left|S_{22}\right|^2+\left|S_{12}\right|^2\right)\right)}, \tag{3}$$

The simulated ECC is about 0.005, and measured ECC is below 0.008 from 2.2 to 11.4 GHz. The deviation between simulated and measured ECC is identified due to the fabrication and measured tolerances. The results demonstrate that the proposed antenna is a suitable candidate for portable UWB-MIMO systems.

Table 3 shows the antenna overall size comparison of existing UWB-MIMO antennas with the proposed antenna. It can be seen that the overall size of the antenna is small compared to the existing

Table 3. Comparison of overall size of existing designs with the proposed antenna.

Ref. No.	Antenna overall size (mm^3)	Bandwidth (GHz)	Mutual coupling, $\lvert S_{21}\rvert$ (dB)	Peak gain (dBi)	ECC	No. of notched-bands
[12]	$55 \times 100 \times 0.8 = 4400$	1.92–10.6	< -17.2	4.96	< 0.18	1
[13]	$43 \times 48 \times 0.8 = 1832.2$	2.5–12	< -15	3	< 0.005	1
[14]	$22 \times 36 \times 1.6 = 1267.2$	3.1–11	< -15	2–3	< 0.1	1
[17]	$29 \times 38 \times 1.6 = 1102$	2.5–19	< -21.5	4	< 0.01	1
[19]	$23 \times 39.8 \times 1.524 = 1395$	2–12	< -20	4–6	NA	1
Pro. Ant.	$26 \times 40 \times 0.8 = 832$	2.2–11.4	< -20	2.4–7.5	< 0.008	1

designs. In addition, the proposed antenna performance in terms of impedance bandwidth, mutual coupling, peak gain, and ECC is also reasonably good.

5. CONCLUSION

In this paper, a compact MIMO antenna with band-notch characteristic at WLAN band is proposed for portable wireless ultra-wideband systems. The proposed MIMO antenna consists of two rectangular monopoles which are excited by 50-ohm coplanar waveguide feed. The monopoles PM1 and PM2 are arranged perpendicularly to reduce to mutual coupling. A rectangular strip is extended from the ground plane to improve the impedance matching characteristics and to further reduce the mutual coupling or enhance the isolation. An inverted U-shaped slot is used on the feed line to realize the band-notch filtering function for suppressing the frequency interference from 5 to 5.9 GHz WLAN band. The proposed antenna has been simulated, and the effects of strip and slot are also studied. The measured results show that the proposed antenna offers good impedance bandwidth ($S_{11} \leq -10\,\text{dB}$) from 2.2 to 11.4 GHz and mutual coupling (S_{21}) of $< -20\,\text{dB}$. Moreover, the favorable gain and radiation efficiency except at designed notch band, low ECC in the whole operating band, and omnidirectional radiation characteristics demonstrate that the proposed MIMO antenna is an appropriate candidate for portable UWB systems.

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