A Compact MIMO Ultra-Wide Band Antenna with Low Mutual Coupling

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Abstract **─** In this paper, a novel compact multiple-input multiple-output (MIMO) antenna with the size of 26 mm × 60 mm × 1.6 mm for ultra-wide band (UWB) applications is proposed. The proposed MIMO antenna consists of two single UWB antennas and a stub placed between the two antennas to reduce the mutual coupling. The proposed antenna achieves the voltage standing wave ratio (VSWR) less than 2 and more than 86% radiation efficiency over the whole band of interest. Performance of the antenna is examined using both simulation and experiment.

Index Terms **─** MIMO antennas, planar antenna, printed antenna, Ultra-Wide Band (UWB), Ultra-Wide Band antenna.

I. INTRODUCTION

Recently, the Ultra-Wide Band (UWB) communications were proposed to achieve high-rate data transmission over the short range. In order to enhance further the transmission rate and increase the coverage, the combination of the UWB communication systems with the Multiple-Input Multiple-Output (MIMO) transmission schemes has gained considerable attention recently. In such combined UWB-MIMO systems, multiple antennas need to be carefully designed to achieve maximum system performance.

A UWB MIMO antenna often consists of multiple radiation elements placed next to each other. Due to space constrain, the distance between radiation elements is often small, leading to considerably large mutual-coupling between them. This coupling phenomenon is considered as a bottleneck in the MIMO UWB systems and should be minimized to improve the stability and radiation efficiency of the whole system. The design of a UWB MIMO antenna is thus not only related to each element but also reduction of mutual coupling between elements. During the last decade, various UWB MIMO antennas constructed from compact UWB antennas with different structures have been proposed.

In [1], Gopikrishna *et al.* proposed a UWB slot antenna on the dielectric plate FR4 with $\varepsilon_r = 4.4$, $\tan\delta = 0.02$, and the small size of 30 mm × 13.5 mm × 1.6 mm. Another small UWB slot antenna introduced by Kumar and Gogoi [2] has the size of 14.6 mm × 28.1 mm × 0.8 mm. Both the antenna and the ground plane are made by copper with the thickness of 30 μm on the FR4 with dielectric permittivity $\varepsilon_r = 4.4$ and tangent loss $\tan\delta = 0.02$. The antenna can cover the entire spectrum of the UWB band from 2.9 GHz to 11.0 GHz. The antenna designed by Zheng *et al.* [3] has the size of 22 mm × 15 mm × 0.8 mm and $\varepsilon_r = 2.55$, and can work over the frequency range from 3.8 GHz to 11.0 GHz for VSWR < 2.

Recently, some UWB MIMO antennas with two elements using different structures and materials have also been proposed. These MIMO antennas are composed of either identical stepped patch or identical circular-disc monopole elements. Both the planar UWB antennas fed by 50 Ω microstrip line, i.e., stepped patch, and the circular-disc monopole were presented in [4] and [5], respectively. The selection of these antennas to design MIMO antennas can be justified by their good performance, small size and ease of integration. However, these antennas have been redesigned to adapt the changes in substrate and thereafter optimized to reduce their dimension as compared with those presented in [4] and [5].

In [6], Najam *et al.* proposed a MIMO antenna composed of two rounded antennas with radius $R = 12$ mm and dimension of 40 mm × 68 mm × 1.6 mm on FR4 dielectric substrate. In a different work [7], Cheng *et al.* proposed a MIMO antenna which has dimension of 62 mm × 55 mm × 1 mm on dielectrics with $\varepsilon_r = 2.65$ and $\tan\delta = 0.001$. In another design given in [8], Li *et al*. proposed a similar MIMO antenna on dielectrics with ε_r=2.65 but slightly different dimension of

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70 mm × 62 mm × 1 mm and tanδ = 0.002. Although these antennas were shown to have good performance, their dimension is still relatively large which may prevent them from being implemented in small devices. Moreover, mutual coupling was not considered in their designs, which may result in degraded performance.

In this paper, a compact MIMO UWB antenna with thin structure, suitable for general structure of UWB equipment, is proposed. The structure of the antenna elements is fabricated on the FR4 substrate with dielectric permittivity $\varepsilon_r = 4.4$ and loss tangent tanδ = 0.02. As a general design rule, we first calculate and tune the parameters of the antenna elements, set suitable distance between them and select suitable size of the dielectric substrate to achieve the desired voltage standing wave ratio (VSWR $\leq$ 2), omni-directional pattern and antenna gain. In order to minimize the mutual coupling between antennas, a stub is placed between two elements in the MIMO antenna. The prototype was then fabricated and its characteristics were measured and compared with simulation results.

II. DESIGN OF UWB MIMO ANTENNA

A. Antenna structure

The configuration of the proposed UWB MIMO antenna is shown in Fig. 1. It is developed from the slot format UWB antenna in [9].

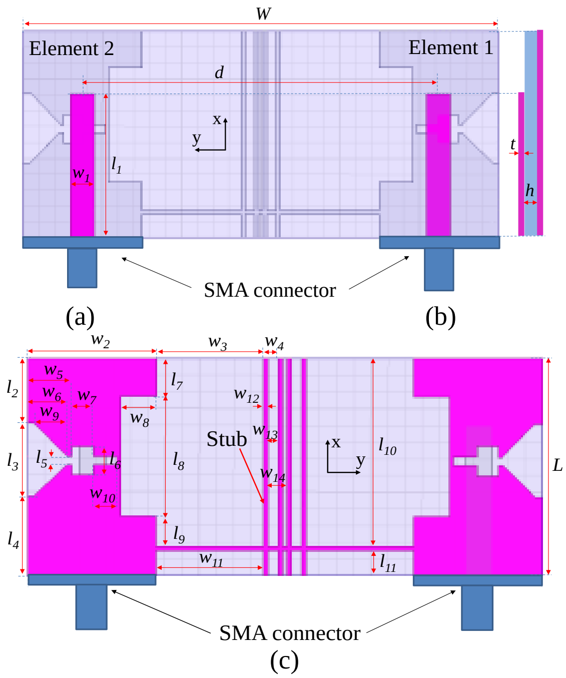


Fig. 1. Configuration of MIMO antenna: (a) top view, (b) side view, and (c) bottom view.

The original antenna has the size of 15 mm × 26 mm ×1.6 mm and consists of a feed line of size l_1 = 18 mm, w_1 = 3 mm. Its rear is a gouged ground plane in order to reduce the antenna size and create multiple resonances to expand the operating bandwidth. The UWB MIMO antenna is built by placing two single antennas at a distance of $d = 0.45\lambda_{max}$ = 45 mm with $\lambda_{max} = c/f_{min}$ and f_{min} is the minimum operating frequency. In order to reduce the small degree of interoperability between the elements of the antenna, a copper stub having an appropriate shape and size is placed in the middle of the two elements. This stub acts as a filter to prevent a certain range of mutual influence between the two elements in the MIMO antenna. The size of the elements in the MIMO antenna is adjusted slightly comapred to [9]. In the MIMO antenna structure, each single antenna still has the size of 15 mm × 26 mm × 1.6 mm but different dimensional parameters of slots. The final design of the UWB MIMO antenna has the size of L = 26 mm, W = 60 mm, and other geometrical parameters as summarized in Table 1.

Table 1: The optimal geometrical parameters (mm)

Parameter	Value	Parameter	Value	Parameter	Value
L	26	l_7	4.6	w_6	4.5
W	60	l_8	14.4	w_7	2.5
t	0.035	l_9	3.5	w_8	4.2
h	1.6	l_{10}	22.5	w_9	3.8
l_1	18	l_{11}	3	w_{10}	3.1
l_2	7.8	w_1	3	w_{11}	12.5
l_3	8.8	w_2	15	w_{12}	0.5
l_4	9.4	w_3	12.5	w_{13}	1.25
l_5	1	w_4	1.75	w_{14}	2
l_6	3.6	w_5	5	d	45

B. Performance evaluation

The Ansoft HFSS software with the finite element method was used to investigate antenna dimensions in order to find the optimal structure for the antenna. Simulations were performed under the condition that both the elements in the MIMO antenna can work concurrently.

The first investigated parameter is the VSWR of the MIMO antenna. In order to reduce the mutual coupling between the two antennas, a copper stub is placed on the plane of the MIMO antenna to separate its two elements. The simulated VSWR of the MIMO UWB antenna with and without stub is shown in Fig. 2. As can be seen from the figure, in case of using the stub the VSWR is smaller than that of the case without stub. The recorded VSWR is less than 2 in the whole frequency range for both antenna elements. In the case without stub, when one antenna is excited it will induce the other causing considerable mutual coupling between the two elements due to limited spacing. When the stub is present, the excited antenna will induce the stub before the other antenna, which reduces induction from one to the other. As a result, the mutual coupling between the two antennas is diminished. However, the induced current on the stub will create a secondary electromagnetic field which in turn will affect both the antenna elements. This will influence not only the mutual coupling between the two antennas but also their VSWR.

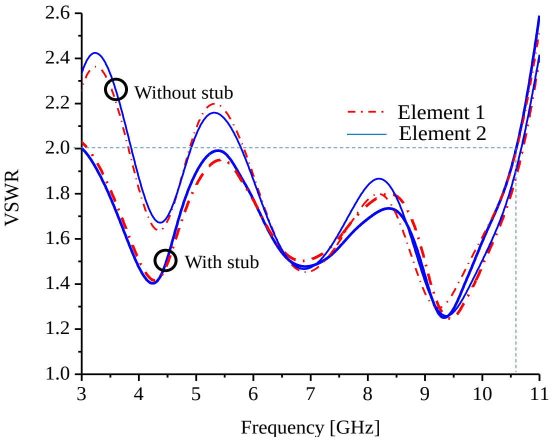


Fig. 2. Simulated VSWR of antenna elements.

The correlation coefficient between two antennas can be determined via *S*-parameters using the following equation [10]:

$$r_e = |r_{12}| = \frac{\left|S_{11}^* S_{12} + S_{21}^* S_{22}\right|^2}{\left(\sqrt{1-|S_{11}|^2-|S_{21}|^2}\right)\left(\sqrt{1-|S_{22}|^2-|S_{12}|^2}\right)}. \qquad (1)$$

In order to ensure that the MIMO antenna can work properly when VSWR is less than 2 (equivalent to the return loss ratios S_{11} and S_{22} are less than 10 dB) it is required that $\rho_e < 0.5$ [11], which is equivalent to the fact that S_{12} and S_{21} are less than -15 dB.

Figure 3 shows the simulated parameters S_{12} and S_{21} of the MIMO antenna for the case with and without the stub. It can be seen from the figure that the two parameters decrease significantly as the frequency increases. For the case with the stub the two parameters S_{12} and S_{21} can achieve the target of less than -15 dB over the whole frequency band of interest. Whereas, if the stub is not used the two parameters can not achieve the target for the frequency less than 3.5 GHz.

Using the simulated results and using (1) we can obtain the correlation coefficient ρ_e for the case using the stub as shown in Fig. 4. It can be seen that the correlation coefficient is less than -22 dB over the whole band of interest with the minimum value of -67 dB. This attainable correlation coefficient guarantees the suitability of the antenna for mobile communications with a minimum acceptable correlation coefficient of 0.5. It is also worth noting that the low correlation coefficient will improve the antenna diversity gain.

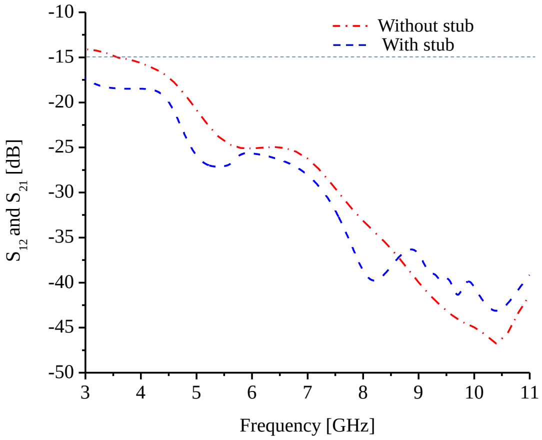


Fig. 3. Simulated parameters S_{12} and S_{21}.

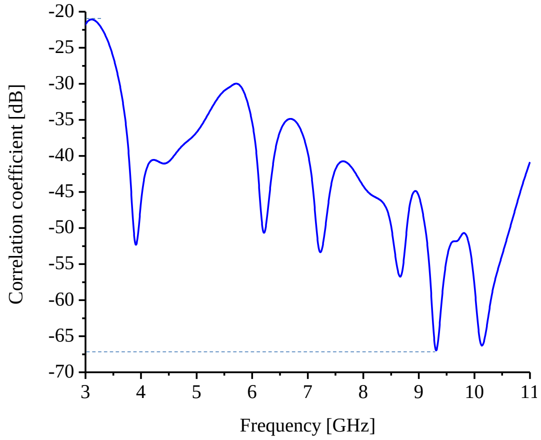


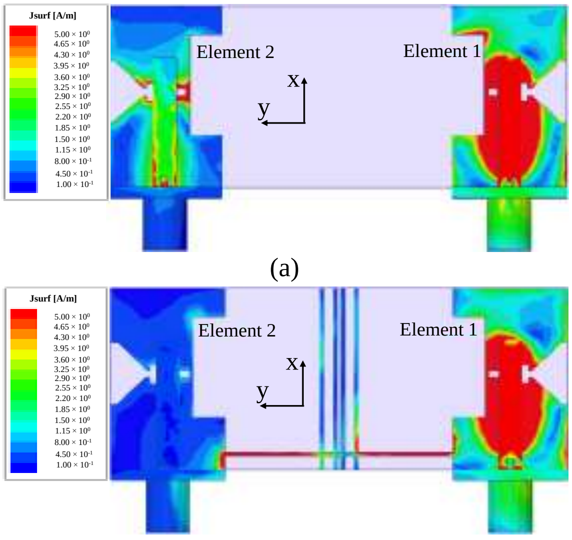
Fig. 4. Simulated antenna envelope correlation coefficient.

To better understand the mutual coupling effect between the two elements in the MIMO antenna, the surface current distribution is plotted in Fig. 5 for the case element 2 is excited while element 1 is not. When the stub is not used it is clear that the current of element 1 significantly induces element 2. However, when the stub is used the current of element 1 will induce mainly on the stub leading to reduced induced current on element 2.

From the above observations, it is clear that the use of the stub can reduce mutual coupling effect between two elements in the proposed MIMO antenna.

Next we will investigate other antenna characteristics. Figure 6 shows the radiation patterns of the proposed antenna when one element is fed while the other is matched by a 50 Ω load impedance. The radiation patterns of the antenna are simulated at the frequencies of 3.1 GHz, 5.0 GHz, 7.0 GHz, 9.0 GHz and 10.6 GHz. In the figure, the dashed-dotted lines denote the radiation patterns in the xz plane while the short dashed line in the yz plane for the case element 1 is excited while element 2 is not (case 1). The patterns for the case element 2 is excited while antenna 1 is not identical to the case 1 but symmetric about the x axis. To simplify the presentation, these patterns are omitted in the figure. The solid lines denote the radiation patterns in the zx plane while the dashed lines in the yz plane for the case both the elements are excited (case 2). It can be seen from the figure that in the yz plane, the radiation patterns of the two elements are different but most of them are axially symmetric. Also, the radiation pattern of each element is almost omni-directional, particularly in the yz plane for the whole band of interest.

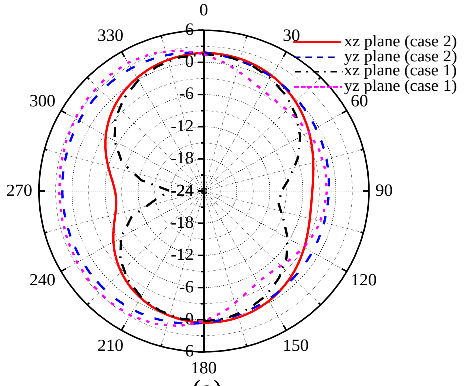
Figure 7 depicts the peak gain of the MIMO antenna within the investigated frequency range (case 2). It is apparent that although the antenna peak gain varies with frequencies, it is still higher than 3.1 dBi within the frequency band of interest. The antenna gain achieves its peak value of 5.4 dBi at the frequency of 10.0 GHz.



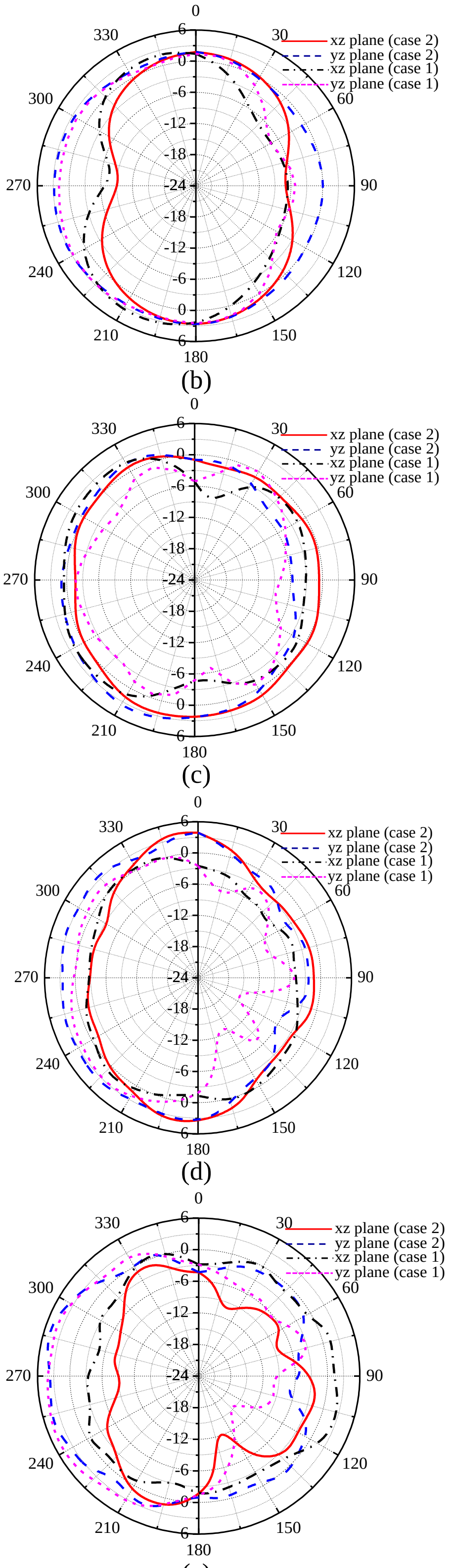
(a)

(b)

Fig. 5. Suface current distribution at 3.5 GHz: (a) without the stub and (b) with the stub.



(a)



(b)

(c)

(d)

(e)

Fig. 6. Radiation patterns of the proposed antenna: (a) 3.1 GHz, (b) 5.0 GHz, (c) 7.0 GHz, (d) 9.0 GHz, and (e) 10.6 GHz.

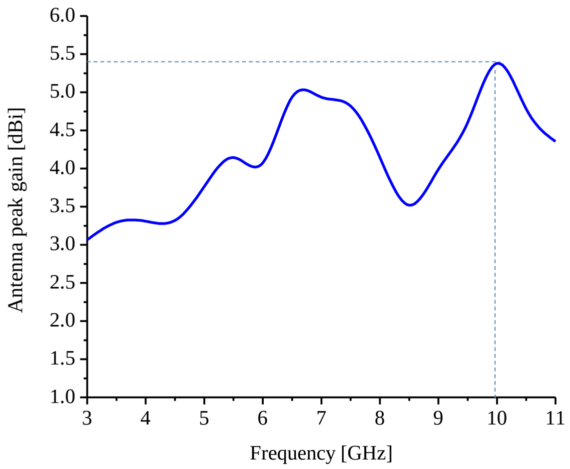


Fig. 7. Antenna peak gain versus frequency.

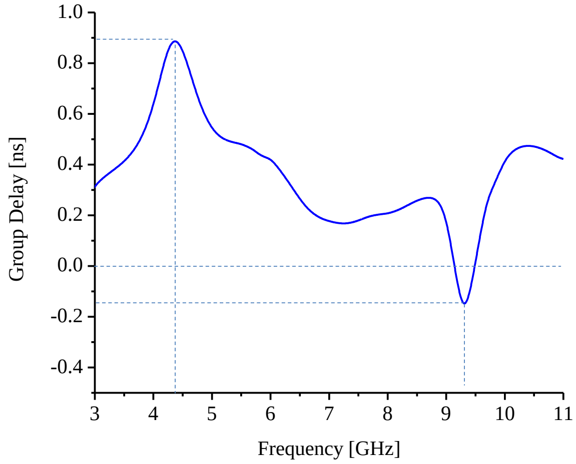


Fig. 8. Simulated group delay.

The group delay of the proposed MIMO antenna is shown in Fig. 8. It can be seen from the figure that the variation of the group delay is less than 1ns, which exhibits good phase linearity within the band of interest. This good group delay characteristic guarantees the suitability of the antenna for UWB applications.

The simulated radiation efficiency is shown in Fig. 9. It can be seen clearly from the figure that the proposed antenna achieves more than 86% efficiency over the band of interest with the maximum value of 96% at 7.25 GHz.

Next, we evaluate the Total Active Reflection Coefficient (TARC) of the proposed MIMO antenna. As TARC also takes the mutual effects into connsideration, it provides a more meaningful measure of the antenna performance than the reflection coefficient. TARC of a 2×2 MIMO antenna can be directly calculated from the scattering matrix elements as follows [12]:

$$\Gamma'_a = \sqrt{\frac{\left|S_{11}+S_{12}e^{j\theta}\right|^2+\left|S_{21}+S_{22}e^{j\theta}\right|^2}{2}}, \qquad (2)$$

where θ represents the random phase. The average TARC with 12 excitation vectors for the MIMO antenna are shown in Fig. 10. As can be seen in the figure, TARC for the case with stub exhibits lower values than for the case without stub at most frequencies.

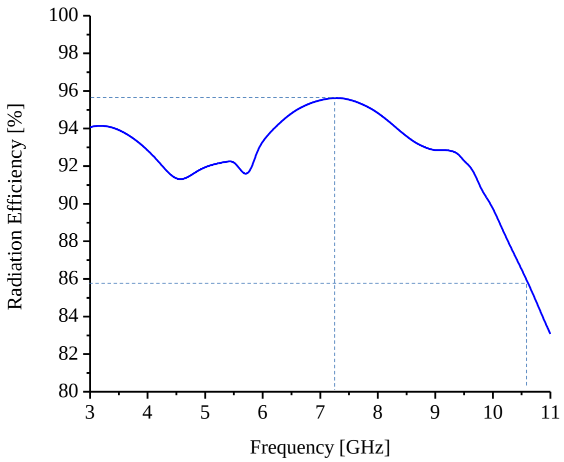


Fig. 9. Simulated radiation efficiency.

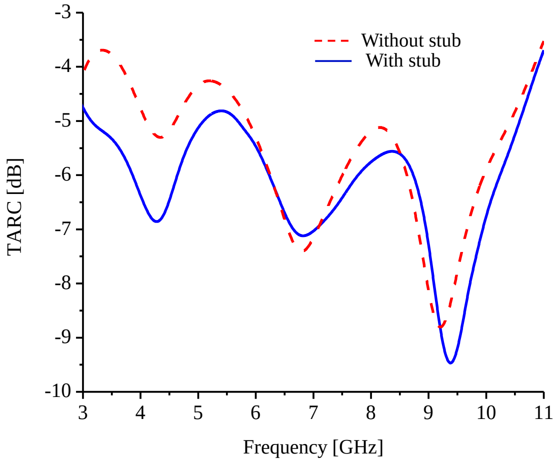
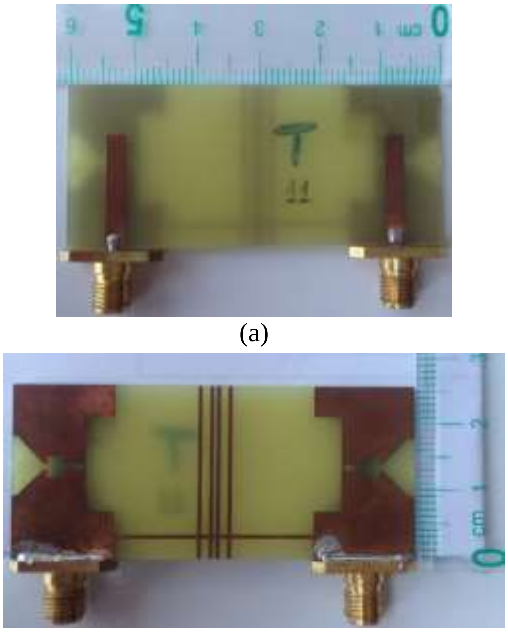


Fig. 10. Calculated TARC for the proposed MIMO antenna.

C. Measured results and discussions

Based on the simulated results, a prototype of the proposed antenna has been fabricated as shown in Fig. 11. The VSWR of the two elements were measured and compared with simulated results in Fig. 12 and Fig. 13. From these figures, it can be seen that both the measured and simulated VSWR are similar. The maximum VSWR recorded for the two antennas are both less than 2, which proves that the proposed antenna satisfies the requirement of VSWR for a MIMO UWB antenna.

When measuring the mutual coupling effect between the two antennas, we note that since the two antenna elements can be considered as a two-port reciprocal network, the two parameters S_{12} and S_{21} are the same. Therefore, it is enough to investigate one, such as S_{12}, of the two parameters. Figure 14 compares the measured and simulated results of S_{12} (and S_{21}). It can be seen from the figure that both the measured and simulated curves have the similar shape and agree pretty well with each other. Moreover, the maximum measured value of S_{12}, and also S_{21}, is less than -20 dB which is similar to other proposed antennas in [6,13,14,16].


(a)

(b)

Fig. 11. Photograph of the fabricated MIMO antenna: (a) front view and (b) bottom view.

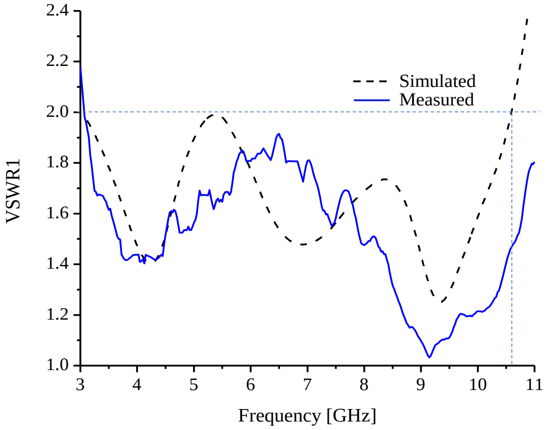


Fig. 12. Measured and simulated VSWR of antenna 1.

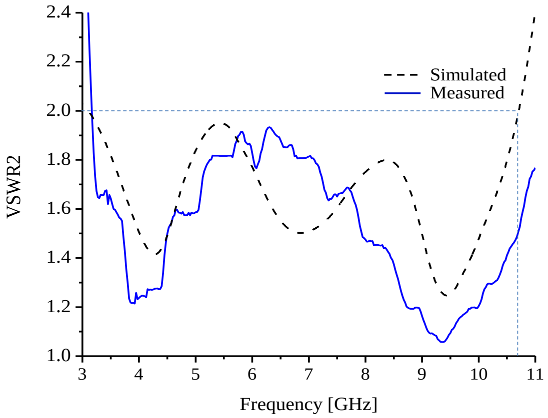


Fig. 13. Measured and simulated VSWR of antenna 2.

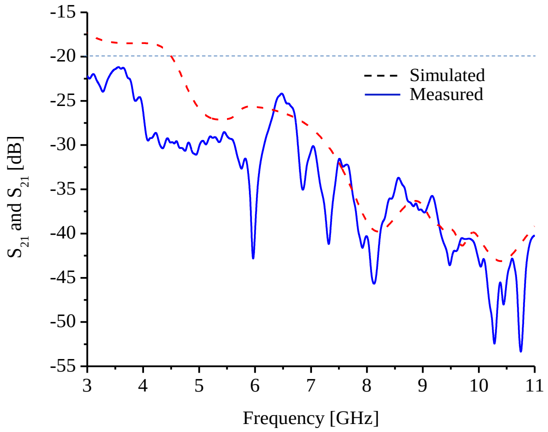


Fig.14. Measured and simulated results of S_{12}.

Table 2 compares our proposed antenna with other relevant UWB MIMO antennas in the literature in terms of antenna size, maximum gain, and parameter S_{12}. Compared with the proposed antennas in [6], [13], [14], [15], [16], our antenna has clearly smaller size while achieving higher maximum gain. In terms of the measured parameter S_{12}, our antenna achieves the same value of less than -20 dB as those in [6], [13], [14], [16] but smaller than that in [15]. This achieved value is far less than the requirement of -15 dB to make our design suitable for a compact and low mutual coupling UWB MIMO antenna.

Table 2: The proposed antenna versus other works

Works	Dimensions (mm)	G_{max} (dBi)	S_{12} (dB)
[6]	40×68×1.6	2.2 dBi	< -20 dB
[13]	43×80×0.8	3.5 dBi	< -20 dB
[14]	30×68×1.6	2.5 dBi	< -20 dB
[15]	38×91	5.3 dBi	< -17 dB
[16]	40×68	2.5 dBi	< -20 dB
Proposed MIMO antenna	26×60×1.6	5.4 dBi	< -20 dB

III. CONCLUSION

In this paper, we have proposed a compact UWB MIMO antenna with low mutual coupling. The antenna structure is simple and easy for fabrication by using printed circuit technology. The proposed antenna has VSWR less than 2 in the whole frequency band of interest from 3.0 GHz to 10.6 GHz, which corresponds to 101.4% of the center frequency. The attainable radiation patterns are almost omni-directional in the whole frequency band. The peak gain achieved by the antenna varies from 3.1 dBi to 5.4 dBi denpending on the frequency with the maximum at 10.0 GHz. The proposed antenna also achieves the maximum radiation efficiency of 96% thanks to the attainable low mutual coupling. The fabricated prototype of the antenna was measured and shown that it meets the requirements for an UWB MIMO antenna.

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