Compact multiple-input multiple-output antenna with low correlation for ultra-wide-band applications

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Abstract: A compact multiple-input multiple-output (MIMO) antenna with a small size of 26 × 55 mm^2 and low correlation has been proposed for the ultra-wide-band (UWB) applications operating over a frequency range of 3.1–12.3 GHz at −10 dB. The MIMO antenna consists of two identical elements each of which has a planar radiator with microstrip-fed over half-sized ground plane. The antenna elements are placed orthogonally to achieve a good isolation between the two input ports. The antenna's characteristics such as the bandwidth, isolation, radiation pattern, peak gain and surface current distributions have been investigated. Moreover, diversity performance in terms of envelope correlation coefficient and mean effective gain has been analysed. Furthermore, a parametric study has been carried out to provide more design information. An arrangement with quad-elements has been designed for MIMO operations, as well. The simulation and measurement results show that the proposed antenna has an impedance bandwidth larger than the frequency range of UWB with low correlation and high diversity performance. The proposed MIMO antenna has been compared in detail with the previous works reported elsewhere in terms of antenna size, geometric complexity, bandwidth, mutual coupling and use of additional structure to obtain more isolation. From this point of views, the antenna is more preferable than other suggestions.

1 Introduction

Planar antennas have received much attention for the portable devices because of having some attractive features such as low profile, small size, conformability to mounting host and capability of integration into arrays [1]. However, the planar antennas with regular shapes such as rectangular, circular and triangular are large to place inside the present portable devices. Therefore it is important task to miniaturise the planar antennas. Various modifications have been successfully applied to the antenna's structure in order to reduce the size and improve the radiation performance. The antenna configurations such as inverted F antenna (IFA) [2], planar IFA [3], co-planar waveguide-fed antenna [4] and defected ground antenna [5] have increasingly found usage in the portable devices since they provide high performance and compact designs. On the other hand, analytically analysing and designing these kinds of antennas require great efforts because of having irregular shapes. Computation electromagnetic (CEM) algorithms [6] incorporated into computer based software can be alternative to accomplish this issue.

Ultra-wide-band (UWB) systems have become popular because of allowing signal transmission in a large bandwidth with a low energy level [7–11]. Planar antennas are good candidates for the systems that operate in a wide frequency range of UWB since they are capable of meeting the demand of UWB operation. UWB systems are commonly used for high data rate transmission, multimedia streaming, radar imaging and cancer sensing etc. [10]. Especially, UWB systems have been more studied since federal communications commission (FCC) approved the unlicensed use of the frequency range from 3.1 to 10.6 GHz for applications requiring low power emitted [11]. To further increase data throughput and alleviate the multipath fading, multiple-input multiple-output (MIMO) systems have been considered for UWB systems [12]

MIMO systems that utilise multiple antenna elements have been received a growing amount of interests because of overcoming the limited channel capacity of conventional systems [13]. Thanks to MIMO systems, data throughput is increased with introducing spatially multiplexing [14] whereas multipath fading is reduced by providing the diversity [15]. MIMO systems are able to simultaneously transmit multiple signals through spatially parallel isolated channels. However, designing MIMO antennas for the portable devices is a challenging task because the antenna elements need to be located closed to each other in a small place. This circumstance inevitably results in a significant mutual coupling between antenna elements, and thus degrades the diversity performance. Design of MIMO antenna with small size and low correlation is crucial for the portable devices. Furthermore, maintaining low correlation over frequency range of UWB is more difficult than that of narrow-band.

In the literature, many studies have been conducted for UWB MIMO antenna varying in size, geometry and isolation level [16–29]. A detailed comparison against each other [16–29] has been tabulated in Section 5. Hereby, some highlighted features related to those suggested antennas have been expressed. Two identical monopole elements in different arrangements with additional structures [16–19] and without any additional structures [20–27] have been formed for the MIMO antennas. The additional structures including strips and/or slots are generally loaded to the main antenna elements to achieve low correlation. However, the additional structures may give rise to a complicated and large design. On the other hand, antennas designed in [28, 29] have two arbitrary elements which are not identical. The antenna designs suggested in [19, 29], respectively, operate over 2.8–8.0 and 3.1–5.15 GHz frequency ranges which are not satisfied UWB operation requirement.

In this study, a small MIMO antenna with overall size of 26 × 55 mm^2 operating in the UWB between 3.1 and 12.3 GHz which

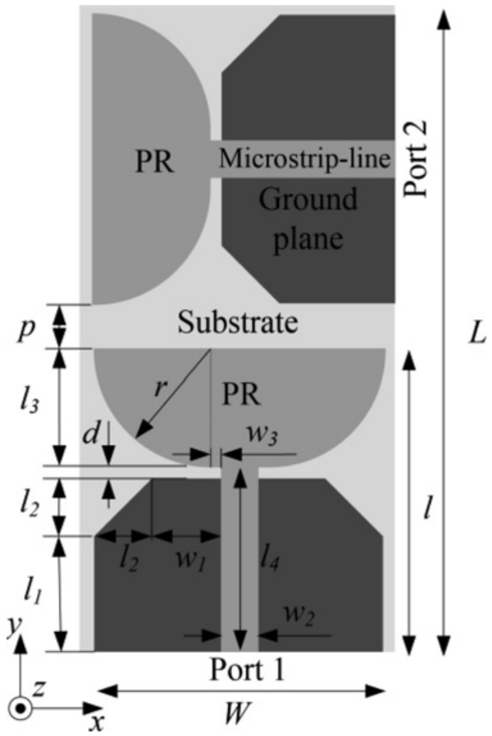


Fig. 1 *Geometry of the proposed MIMO antenna*

Table 1 Dimensions of MIMO antenna (mm)

L	l	l_1	l_2	l_3	l_4	W	w_1	w_2	w_3	d	p	r
55	26	10	5	10	16	25	6	3	1	1	4	10

satisfies the requirements of FCC has been designed for the portable devices. The antenna configuration consists of two identical elements, and each element has a planar radiator (PR) with a microstrip-fed. The antenna has been designed by means of an electromagnetic design and verification platform IE3D™ [30]. The MIMO/diversity performance has been analysed in terms of bandwidth, mutual coupling, radiation patterns, gain, surface current distributions, envelope correlation coefficient (ECC) and mean effective gain (MEG). Furthermore, a parametric study has been performed to investigate the effect of the geometry on the *s*–parameters and an arrangement with quad-elements has been also designed for MIMO operation. Although the antenna elements are located close to each other, a good isolation between the two input ports has been obtained without using any additional structure because of being orthogonal to each other. Then, a prototype of the designed antenna has been fabricated by using the material of FR4 with thickness of 1.6 mm. Consequently, the MIMO antenna has more satisfactory results of small size, geometric simplicity, large bandwidth and low correlation as compared with other configurations reported elsewhere [16–29].

The remainders of the paper are organised as follows: The Section 2 briefly describes the antenna structure. In the Section 3, design procedure, including simulation, parametric study and array design are presented. The Section 4 outlines the antenna fabrication process. In the Section 5, performance analysis and a comparison with previous designs are carried out. Finally, conclusion is expressed in the Section 6.

2 MIMO antenna structure

The geometry of the proposed MIMO antenna is given in Fig. 1 and its physical parameters are shown in Table 1. The MIMO array consists of two identical antenna elements. Each element consists of a PR with microstrip-fed and an half-sized ground plane. The PR and ground plane are printed on FR4 substrate with dielectric permittivity of 4.4 and thickness of 1.6 mm. The two lower corners of the PR are circularly trimmed to provide large impedance bandwidth. The PR is fed by a 50 Ω microstrip-line with a dimension of $w_2 \times l_4$ and has ground plane having a size of $W \times (l_1 + l_2)$ printed on back side of the substrate. The upper corners of the ground plane are triangularly clipped with a length of l_2 for getting the better impedance matching.

3 Design procedure

3.1 Simulation process

The simulations were carried out by means of the CEM simulator IE3D™ based on method of moment [31] to design and optimise the proposed MIMO antenna. The antenna was designed by the rule of thumb, and then antenna's dimensions were fine-tuned with

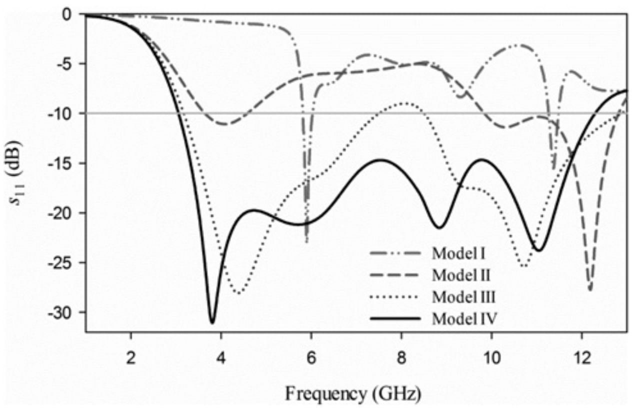


Fig. 3 *Simulated s_{11} parameters of Model I, II, III and IV*

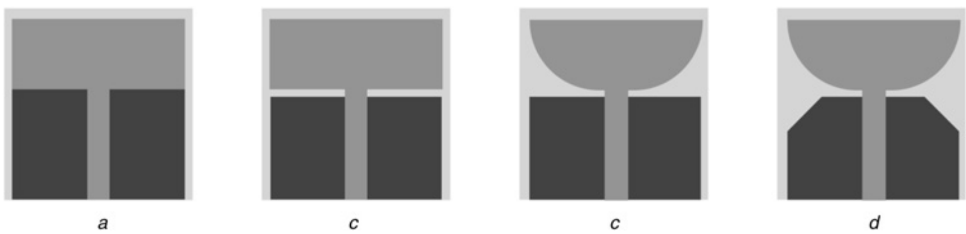


Fig. 2 *MIMO antenna element with different geometries*

a Model I
b Model II
c Model III
d Model IV

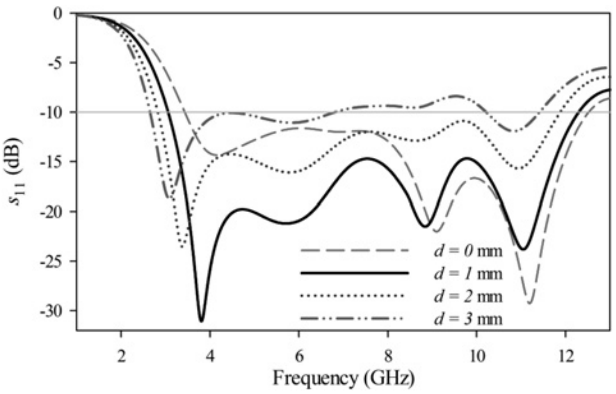


Fig. 4 *Simulated s_{11} parameters for different values of d*

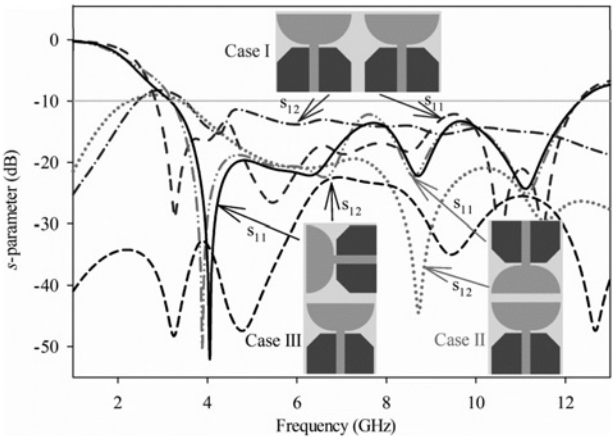


Fig. 5 *Simulated s–parameters for different arrangements of dual-elements MIMO antenna*

the aid of genetic algorithm (GA) [32] built–in optimisation module of the IE3D™. At the design stage, simple shaped monopole antennas have been aimed to ensure ease of antenna fabrication, the GA utilised the objective function of |*s*–parameter| <−10 dB to find the best dimensions. In simulations, the microstrip lines were supposed to 50 Ω probe fed with 1 V wave source and the mesh lines per wavelength ratio were set to be 20 in limit of 13 GHz.

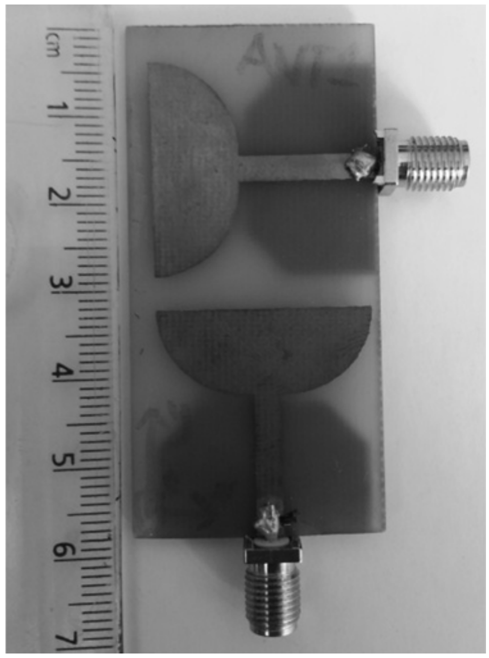


Fig. 7 *Photograph of prototyped MIMO antenna*

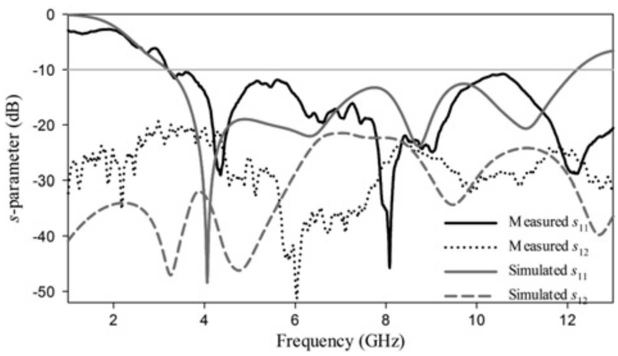
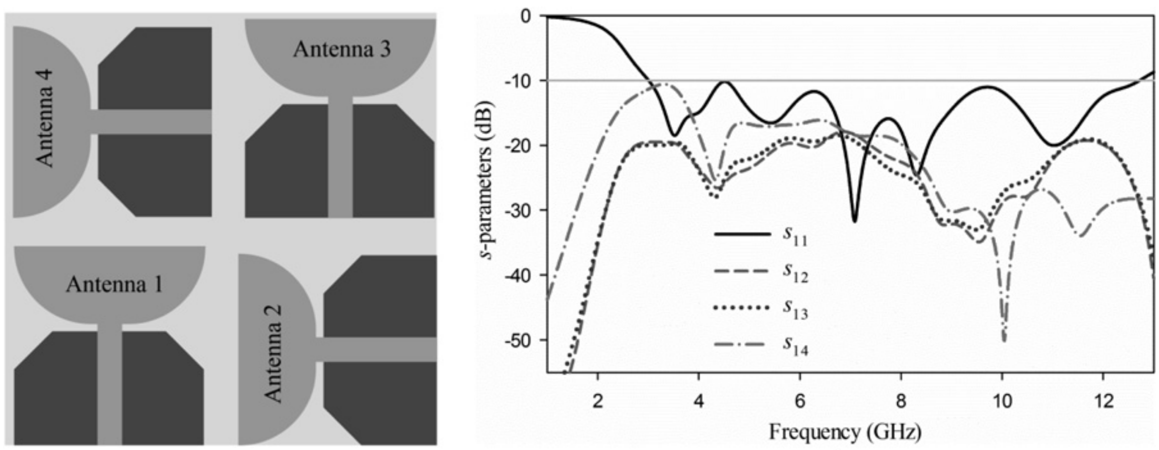


Fig. 8 *Simulated and measured s–parameters of prototyped MIMO antenna*



a

b

Fig. 6 *Quad-elements MIMO structure*

a Antenna arrangement
b Simulated *s* –parameters

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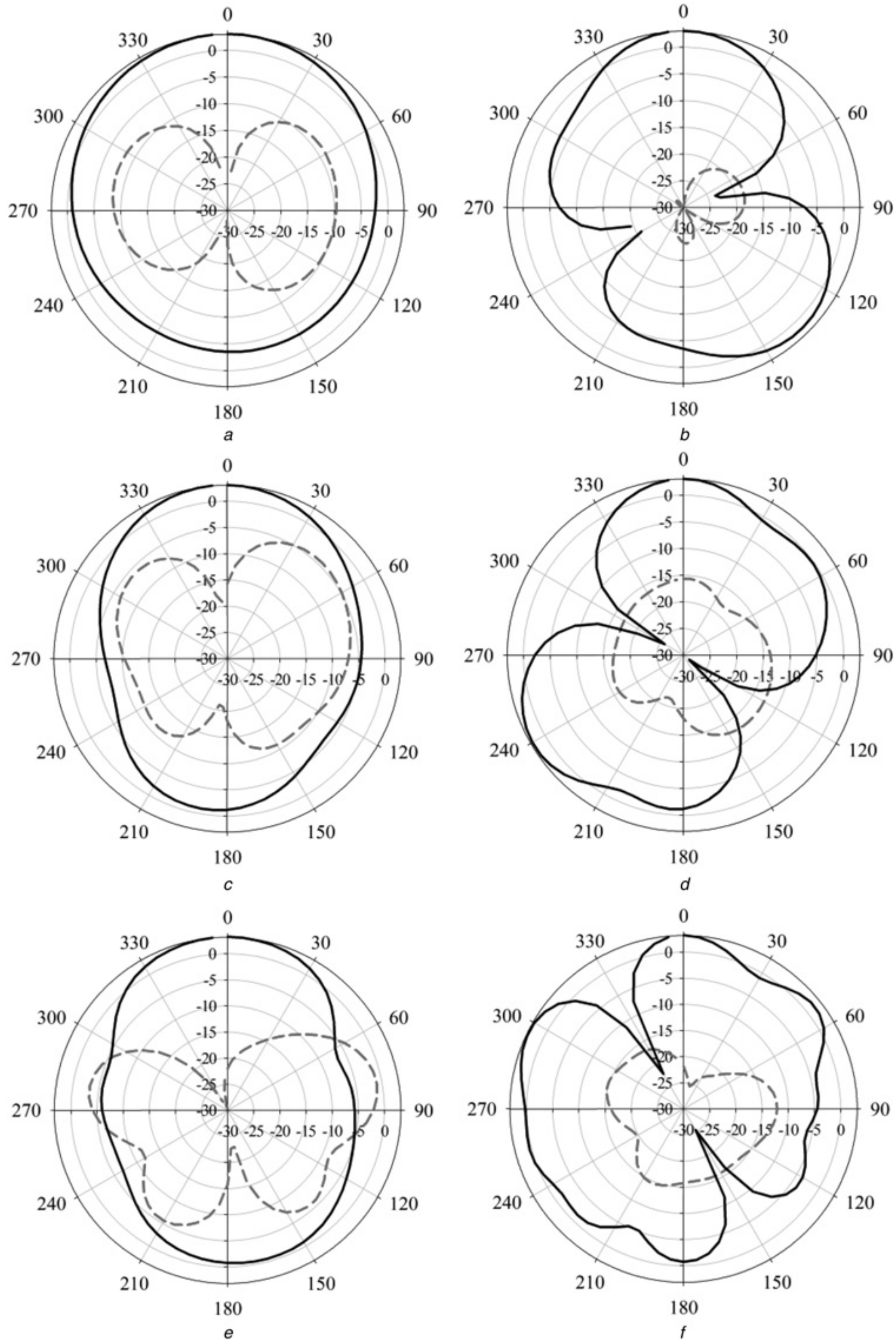

Fig. 9 *Measured radiation gain patterns (dBi) of Antenna 1 in*

a xz plane at 4 GHz
b yz plane at 4 GHz
c xz plane at 6.28
d yz plane at 6.28
e xz plane at 9.08 GHz
f yz plane at 9.08 GHz (solid lines: co-pol, dash lines: cross-pol)

The simulations were performed over the frequency range from 1 to 13 GHz for 601 discrete frequency points.

3.2 Parametric study for the single element

The shapes of both PR and ground plane play a key role to enhance the impedance bandwidth. A parametric study related to both the geometry of the antenna element, and the space width between the edges of the PR and ground plane have been carried out to determine the optimum value of *d*. To investigate the best antenna element to be used in the MIMO antenna configuration, four models are given in Fig. 2 and respective simulated s_{11} parameter plots are given in Fig. 3. It can be seen that the s_{11} parameter of Model I whose both PR and ground plane is rectangular generally remains above -10 dB, hence it cannot satisfy the requirement of

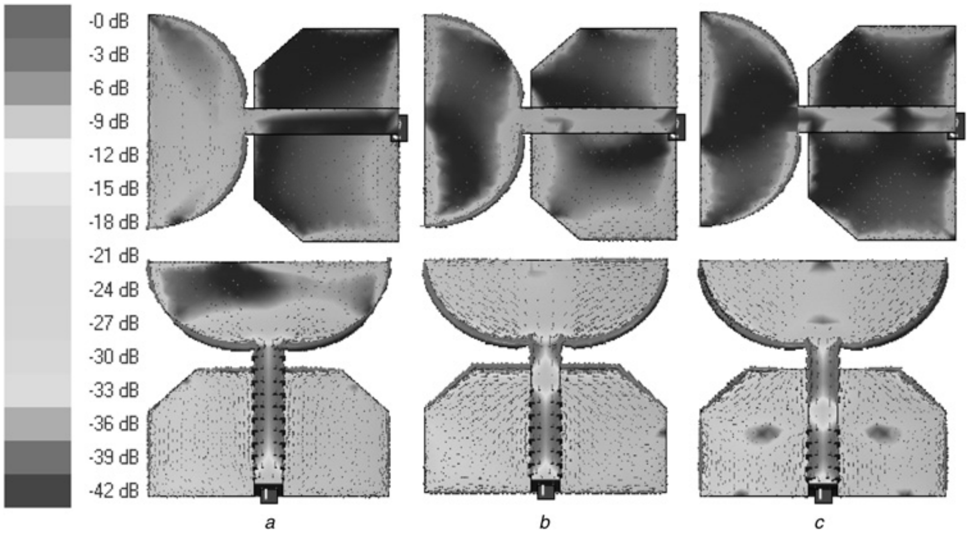

Fig. 10 *Surface current distributions for Port 1 excitation*

a 4 GHz
b 6.28 GHz
c 9.08 GHz

UWB operation. Reducing the ground plane length to the lower edge of PR, as given in Model II, improve the impedance matching. Since the radiation mainly occurs between the edges of PR and ground plane, any modifications on the lower edge of PR have more effects rather than on the upper edge with regard to the bandwidth. Therefore the lower corners of the PR are circularly trimmed as seen in Model III. The impedance bandwidth is increased and the s_{11} parameter shifts below −10 dB over almost entire frequency range of UWB operation. To further increase the impedance bandwidth, the upper corners of ground plane have been triangularly clipped as in Model IV. Thus, the s_{11} parameter less than −15 dB over a frequency range of 3.1–12.3 GHz has been achieved.

The simulated s_{11} parameters for four different space width values of d are given in Fig. 4 so as to determine the optimum value of d. It is clearly seen that the impedance bandwidth highly depends on the value of d. The best s_{11} parameter which less than −15 dB has been achieved over UWB frequency range for $d = 1$ mm.

3.3 Design process of the MIMO structures

Three possible dual-element arrangements along with s–parameters are given in Fig. 5 to investigate the best MIMO design which provides the requirements of UWB operation with low correlations. Two identical elements of Model IV are arranged alongside (Case I), facing each other (Case II) and orthogonal to each other (Case III) by leaving 4 mm gap between antenna elements. As is to be expected, s_{11} parameters vary similar to each other for all arrangements. Since less current induced on Antenna 1 because of orthogonality in Case III, satisfactory results of s_{12} has been achieved less than −25 dB across the impedance bandwidth from 3.1 to 12.3 GHz.

To further inspect the performance of the MIMO antenna with quad-elements, a MIMO arrangement in a size of 55×55 mm^2 is given in Fig. 6*a*. The antenna has good isolation with regard of s_{12}, s_{13} and s_{14} as it is seen from the s–parameter variations given in Fig. 6*b*. These results show that the proposed antenna element can be used as dual or quad element forms for MIMO operations.

4 Fabrication of the UWB MIMO antenna

The prototype of the proposed antenna is illustrated in Fig. 7. The MIMO antenna was fabricated by using the PCB material of FR4 having a thickness of 1.6 mm, dielectric permittivity of 4.4 and tangent loss of 0.017. The microstrip lines were fed through 50 Ω SMAs. The performance of the UWB MIMO antenna has been verified through a measurement performed by means of Agilent Technologies N5230A PNA–L RF network analyser. The simulated and measured s–parameter plots are comparatively presented in Fig. 8. It can be seen that the measured s–parameters satisfy the requirements of UWB operation although there is some discrepancies between simulated and measured plots. Note that the discrepancies between those plots may be attributed variations in geometry, permittivity and thicknesses of substrate and copper cladding, and mismatch of feed probe in the fabrication process. The prototyped MIMO antenna has a frequency range covers from 3 to 13 GHz with the isolation over 20 dB

5 Performance analyses

5.1 Radiation characteristic

Fig. 9 shows the two-dimensional radiation gain patterns on xz and yz planes at three distinct frequencies of 4, 6.28 and 9.08 GHz. The co-pol radiation patterns approach omnidirectional at these frequency points. The peak gain levels of 3.02, 3.14 and 3.21 dBi occur at the frequencies of 4 GHz, 6.28 GHz and 9.08 GHz, respectively.

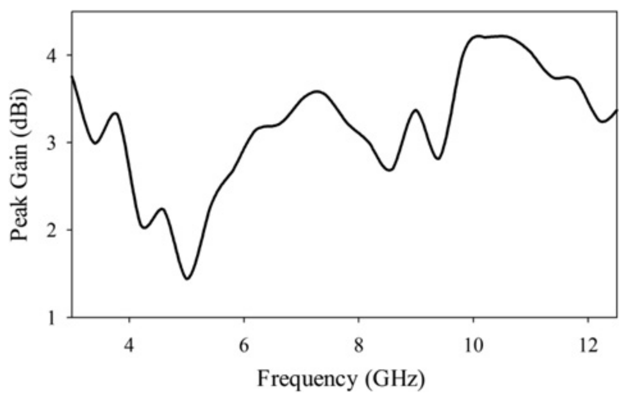

Fig. 11 *Measured peak gain*

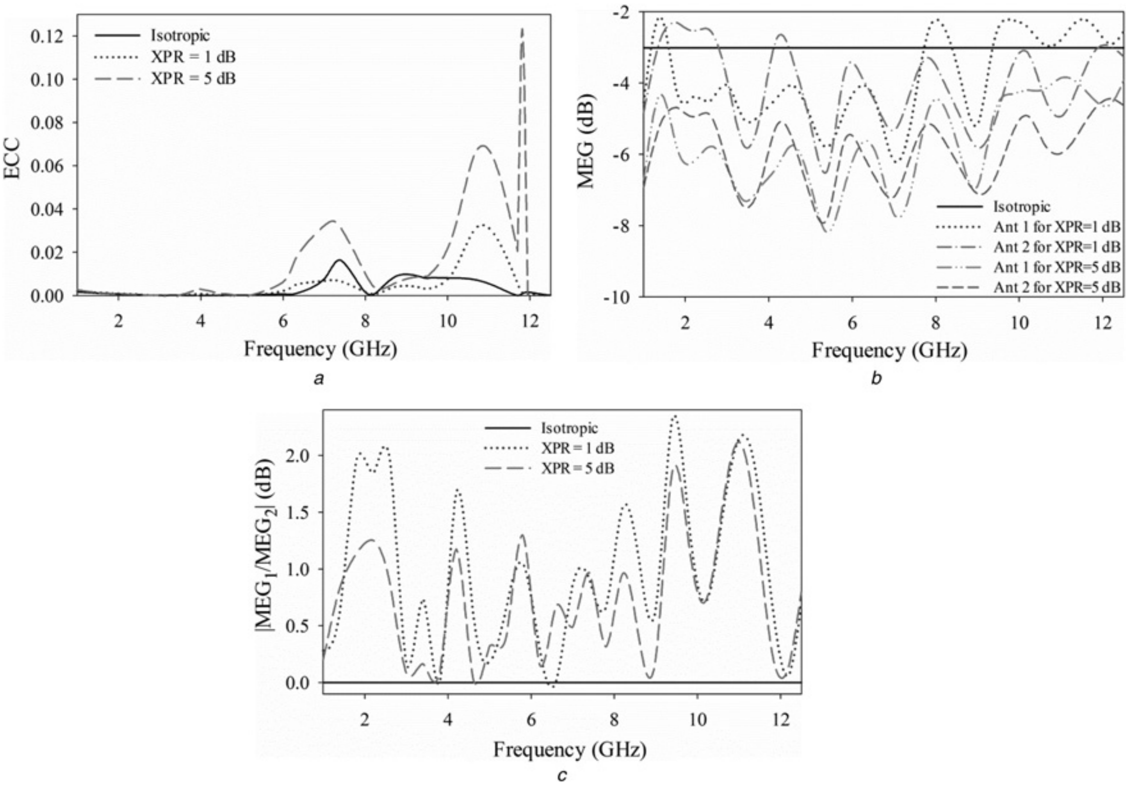

Fig. 12 *Diversity performances of prototyped antenna*

a ECC
b MEG
c $|MEG_1/MEG_2|$

5.2 Surface current distribution

To investigate the underlying current mechanism of the proposed MIMO antenna, simulated surface current distribution at frequency points of 4, 6.28 and 9.08 GHz for Port 1 excitation are given in Fig. 10. It can be observed that the majority of the electric current is concentrated around the lower edge of the PR whose lower corners have been circularly trimmed. On the other hand, the upper edge of ground plane has weaker concentration. Peak currents of 80.1, 77.4 and 74.6 A/m are obtained at the frequencies of 4 GHz, 6.28 GHz and 9.08 GHz, respectively. Besides, less current induces on adjacent antenna element owing to being orthogonal to each other.

5.3 Peak gain

In Fig. 11, the measured peak gain plot of the prototyped antenna is presented. It can be observed that the gain varies over 1.5 dBi across the frequency range of 3–13 GHz while it occurs the highest values of 3.8 and 4.2 dBi at the vicinity of 3 GHz and 10.2 GHz, respectively. The main consideration for getting this gain is the high tangent loss of FR4 used in the prototyped antenna. If a substrate with low tangent loss can used in fabrication of the antenna, better gain would be obtained.

5.4 Diversity

The ECC and MEG are the critical parameters for evaluating the diversity performance of a MIMO system. ECC for a dual-elements system can be computed by using [33]

$$\mathrm{ECC} = \frac{\left|\iint_{4\pi}\left[\boldsymbol{F}_1(\theta,\phi)\bullet\boldsymbol{F}_2(\theta,\phi)\,\mathrm{d}\Omega\right]\right|^2}{\iint_{4\pi}\left|\boldsymbol{F}_1(\theta,\phi)\right|^2\mathrm{d}\Omega\iint_{4\pi}\left|\boldsymbol{F}_2(\theta,\phi)\right|^2\mathrm{d}\Omega} \tag{1}$$

where $F_i(\theta, \phi)$ is the field radiation pattern of the antenna system when port i is excited, and $\bullet$ denotes the Hermitian product. The MEG of the ith antenna element is defined as the ratio of the mean received power (P_{rec}) to the mean incident power (P_{inc}) at that element. To calculate the antenna element's MEG, the following expression can be used [34]

$$\mathrm{MEG}_i = \frac{P_{\mathrm{rec}}}{P_{\mathrm{inc}}} = \oint\left[\frac{\mathrm{XPR}\cdot G_{\theta i}(\Omega)\cdot P_\theta(\Omega) + G_{\varphi i}(\Omega)\cdot P_\varphi(\Omega)}{1+\mathrm{XPR}}\right]\mathrm{d}\Omega \tag{2}$$

where, XPR is the cross polarisation power ratio of the incident waves, P_θ and P_φ are the θ and φ components of the angular density functions of the incoming plane waves, G_θ and G_φ are the θ and φ polarised components of the antennas' power gain patterns, and Ω is the solid angle. The ECC, MEG and $|MEG_1/MEG_2|$ parameters of the MIMO antenna calculated from the radiation patterns by IE3D™ against frequency are plotted in Fig. 12. In the calculation of these parameters, three propagation models are considered for XPR = 0 dB, XPR = 1 dB and XPR = 5 dB, respectively, corresponding to isotropic, outdoor and indoor of Gaussian scenarios with the mean elevation angles of vertical/horizontal polarised distributions $m_V = 10°$, $m_H = 10°$ and standard deviation of vertical/horizontal polarised wave distributions $\sigma_V = 15°$, $\sigma_H = 15°$ [34]. A good diversity has been achieved, because the antenna satisfies the following criteria [34, 35] over entire the frequency range of 3.1–13 GHz. These results are regarded to both good isolation and diversity because of the effectiveness of the design

$$\mathrm{ECC} \ll 0.5 \text{ and } \left|\mathrm{MEG}_i/\mathrm{MEG}_j\right| \le 3\,\mathrm{dB} \tag{3}$$

Table 2 Comparison with previous works of UWB MIMO designs

Ref. No.	Main geometry	Additional structure	Geometric complexity	Size (W × L) mm^2	Frequency range, GHz at −10 dB	Mutual coupling level, −dB
this study	two identical MEs consisting of a down corner rounded radiator with a MF over a GP	–	simple	26 × 55	3.1–12.3	20
[16]	two identical MEs consisting of a stepped patch element with a slot and a MF over a GP	–	medium	30 × 68	3.1–10.6	15
[17]	two identical MEs composed of a circular microstrip patch with a slot and a MF overall on a GP	–	simple	35 × 70	2.3–12.2	15
[18]	two identical MEs consisting of a U-shaped patch and a T-shaped monopole path, overall on pentagonal wide slot in the GP	–	simple	56 × 56	3.1–10.6	20
[19]	two identical MEs consisting of seven circles surrounding a centre circle with a MF and partial GP	–	medium	38 × 91	2.8–8	10
[20]	two identical MEs constructed with a triangular patch with a slot and a MF overall on a GP	tree-like structure with five branches	complex	35 × 40	3.1–10.6	16
[21]	IFA is constituted with two identical printed folded MEs. Each element is composed of an open stub overall connected a GP	successive inverted-L elements	complex	13.5 × 55[a]	1.8–5.15; 5.85–11.9	17
[22]	two identical MEs. Each element is a rectangular patch with MF and both are on a rectangular GP with a circular slot.	a disk with strip on GP	medium	80 × 80	3–12	15
[23]	two identical MEs composed of a rectangular radiator and a MF overall on a GP	a rectangular with sleeves on the GP	medium	38 × 62	3.1–10	17[c]
[24]	two identical MEs consisting of a rectangular patch and a MF on a GP	two strips on the ground	medium	26 × 40	3.1–10.6	15
[25]	two identical MEs composed of a rectangular patch and a MF overall on a GP	T-shaped stub	simple	45 × 62	3.3–10.4	18
[26]	two identical MEs composed of a rectangular patch and a MF overall on a GP	a cross shaped stub	simple	45 × 62	3.3–10.5	18
[27]	two identical MEs both of that on an annulus GP	a cross shaped strip	medium	62 × 62	2.6–11	12
[28]	the antenna consists of a MF rectangular aperture antenna and an exponentially tapered slotline antenna with a MF to slotline transition	–	complex	40 × 50	3.1–10.6[b]	20
[29]	the antenna has two elements, one is a monopole with a crescent shape with two slots over a semi-elliptical shaped GP, the second is a circular monopole	–	medium	25 × 40	3.1–5.15	20

ME: Monopole Elements; MF: Microstrip-Fed; GP: Gound Plane.
a GP: 55 × 100 mm^2.
b Some parts of *s*–parameters are not less than −10 dB.
c For 4.5–10 GHz.

5.5 Comparison with the literature

Table 2 presents a comparison of proposed UWB MIMO antenna against the others previously reported in the literature. The antennas are tabulated in terms of various criteria such as geometric size and complexity, use of additional structure, bandwidth and mutual coupling level. It is worth noting that an additional structure is able to help to minimise the mutual coupling, however it may cause a complicated and large antenna design. It is very difficult to decide on the antenna which is the best for all given criteria since they vary among these parameters. The antenna proposed in [29] has the smallest size, whereas its measured bandwidth is from 3.1 to 5.15 GHz which do not satisfy the demand of UWB operation and its geometric simplicity is regarded as medium. In other study [24], the second smallest MIMO antenna is proposed and its geometry is considered as medium, whereas it has an additional structure and a mutual coupling level of 15 dB. Therefore our MIMO antenna has outstanding characteristics because of geometric simplicity, small size, large bandwidth, low correlation and good diversity performance. All the results demonstrate that the proposed MIMO antenna configuration is a good candidate for the UWB portable devices.

6 Conclusion

A compact UWB MIMO antenna with a small size and low correlation has been proposed for the portable devices. The antenna design consists of two identical PRs placed orthogonally to achieve good isolation between the input ports. The prototype of the antenna has been printed on FR 4 substrate with dielectric permittivity of 4.4 and thickness of 1.6 mm. A parametric study has been carried out to investigate the effects of the geometry on performance and a MIMO arrangement with quad-elements has been analysed, as well. Simulated and measured results show that the antenna can operate over UWB band from 3.1 to 10.6 GHz with mutual coupling of less than −20 dB. The MIMO antenna configuration has less than 0.1 ECC and less than 2 dB MEGs ratio across the UWB frequency. Moreover, the antenna has been compared in detail with other UWB MIMO designs in terms of the geometric size and complexity, bandwidth, mutual coupling level and use of additional structure. All results indicate that our antenna has more advantages than other suggestions in points of these criteria and it can be a potential candidate for the portable UWB applications.

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