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A Compact MIMO Antenna with Improved Isolation for 3G, 4G, Wi-Fi, Bluetooth and UWB Applications

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Abstract—In this paper, a compact MIMO antenna with improved isolation is proposed. Elliptical slots and an SRR like structure are employed to improve the isolation. The proposed MIMO antenna structure consists of two semi-circular radiators attached to a rectangular monopole which are mirror images of each other with edge to edge spacing of $0.125\lambda_0$, where λ_0 is the free space wavelength corresponding to the lowest operating frequency of the structure. Two square steps are added to the above semi-circular monopole to increase the effective path length to cover the lower frequencies. Thereafter, a semi-annular ring slot is introduced, and square steps above the semi-circular monopole are modified to curved steps to further improve the impedance bandwidth of the antenna. The mutual coupling over the wideband is reduced by placing elliptical slots and SRR like structure in the ground plane. The proposed antenna has impedance bandwidth of 2.1–12 GHz with $|S_{21}| < -20$ dB over the entire frequency range. The antenna is designed and fabricated on an FR-4 substrate having overall dimensions of 38 mm × 33.4 mm × 1.6 mm. The measured results show a good correlation with the simulated ones. The envelope correlation coefficient (ECC) of the antenna is less than 0.02 over the entire band. The proposed MIMO antenna is an appropriate candidate for 3G, 4G, Wi-Fi, Bluetooth and UWB applications.

1. INTRODUCTION

MIMO antennas have gained a lot of importance in present communication systems due to their numerous benefits such as low multipath fading, increased capacity, high data rate and low co-channel interference [1]. A MIMO antenna employs more than one antenna element to transmit and receive signals effectively. It deals with diversity schemes such as space diversity, polarization diversity and pattern diversity to overcome the multipath fading [2]. The main hurdle in designing a MIMO antenna is to place the multiple antennas in a limited space to have a compact size and at the same time, to have high isolation between the elements. The multiple antenna elements, when being closely placed, lead to high mutual coupling which degrades the radiation pattern, total efficiency and affects the overall performance of a MIMO system. Hence reducing mutual coupling is a major issue in designing a compact MIMO antenna structure.

A number of techniques for reducing the mutual coupling and improving the isolation between closely spaced MIMO antenna elements have been reported in recent years which employ electromagnetic bandgap structure (EBG), metamaterial or defected ground structure (DGS) [3–10]. EBG structures are periodic structures with band gap characteristics which help to improve the isolation between the antenna elements [3–5]. However, these structures are complex and occupy a large area. Mutual coupling is reduced by using metamaterials which possess negative permittivity and negative permeability and can be realized using SRR or meandered transmission lines [6, 7]. They help to miniaturize the overall

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size of the antenna but its constraint lies in design complexity and isolation over wide band. DGS has been widely used for improving the isolation by introducing defects in the ground plane [8–10]. These defects act as band stop filter as inductance and capacitance of the defect block the surface wave from one antenna to another [8]. The isolation is improved by 7 dB over the band by using a square ring DGS in a collated MIMO antenna [9]. A folded monopole MIMO antenna is designed with a stepped slot DGS and an elliptical-shaped DGS to reduce the mutual coupling less than -20 dB over the operating frequency band [10]. However, all these structures are designed over narrow bands.

Several methods such as polarization diversity, space diversity, slots and stubs in the ground plane, split ground, modified shaped ground plane or combination of these have been proposed to reduce the mutual coupling in wideband MIMO antennas [11–25]. Two stair case shaped antennas are placed orthogonally and fed by asymmetric coplanar strip (ACS). A fence metal stub is used to improve the isolation > 15 dB over 3.1–10.6 GHz [11]. Two inverted L-shaped stubs and a T-shaped slot are introduced in ground plane to lower the mutual coupling < -20 dB over 2.26–6.78 GHz [12]. However, this antenna does not cover the entire UWB. A square-shaped monopole MIMO antenna with a T-shaped stub provides isolation > 18 dB for UWB applications over 3.3–10.4 GHz [13]. A fork-shaped structure is placed at the center of ground plane to mitigate the effect of mutual coupling over 4.4–10.7 GHz in a compact MIMO antenna in [14]. A UWB MIMO antenna consisting of two identical circular discs with center to center separation of 43.5 mm is designed. It uses spatial diversity to improve the isolation of the antenna elements [15]. In a circular monopole MIMO antenna, an inverted Y-shaped stub is inserted in ground plane to improve the isolation > 15 dB over the UWB [16]. A MIMO antenna consisting of two monopoles is designed with a split ground plane over 2.3–12 GHz covering Bluetooth and UWB applications. The mutual coupling < -20 dB is achieved by placing an inverted T-shaped stub connecting the split ground planes [17]. A printed circular monopole antenna with a trapezoidal shape ground plane for wideband application has been reported [18]. To decouple the antennas over 2.71–11.67 GHz frequency band, a T-shaped stub with fork and slot is introduced in the ground, and isolation > 18 dB is achieved over the band. Mutual coupling between wrench MIMO antennas is reduced by introducing a Y-shaped stub followed by a rectangular slot in the middle of the ground plane [19]. A MIMO antennas with a tree-shaped structure has isolation > 16 dB over the UWB band [20]. However, all these structures have large dimensions, and some of the structures with isolation > 20 dB employ split ground.

In [21], a UWB diversity antenna with isolation > 20 dB is designed over 3.1–5 GHz. The antenna has efficiency greater than 70% and stable correlation coefficient. However, the structure operates only over upper UWB. A simple step-shaped impedance resonator is used to reduce the mutual coupling in a printed UWB MIMO antenna in [22]. Two semicircle-shaped monopoles with a stepped structure, placed at 90° to each other, are designed over 2–10.6 GHz in [23]. Mutual coupling < -20 dB is achieved by using a circular reflector in the ground plane for Bluetooth, Wi-Fi, Wi-Max and UWB applications. In [24], two rectangular monopole antennas with a T stub are placed orthogonally to improve the isolation over 2.4–10.6 GHz. A two-element MIMO antenna is designed, in which each element has a central circular monopole connected through strips to seven small circular structures [25]. The antenna provides mutual coupling < -17 dB over the 2.8–12.0 GHz; however, it is designed using split ground. All these antennas have comparatively large dimensions as compared to the antenna proposed here.

In this paper, a compact MIMO antenna with improved isolation is proposed. Elliptical slots and an SRR like structure are employed to improve the isolation. The proposed MIMO antenna consists of two semi-circular radiators attached to a rectangular monopole with edge to edge spacing of $0.125\lambda_0$, where λ_0 is the free space wavelength corresponding to the lowest operating frequency of the structure. They are placed at an angle of 180° with respect to each other to achieve space diversity. Initially, two square steps are placed above the semi-circular monopole to increase the effective current path length and to improve the impedance bandwidth. A semi-annular ring slot is cut in the semi-circular monopole, and square steps are modified to curved steps to further increase the electrical path length and impedance bandwidth of the antenna. The mutual coupling over the wideband is reduced by placing elliptical slots and SRR like structure. The $|S_{11}| < -10$ dB with mutual coupling < -20 dB is achieved over 2.1–12 GHz. The antenna is fabricated on a low cost FR-4 substrate and has compact size of 38 mm × 33.4 mm × 1.6 mm. The ECC of the proposed MIMO antenna is < 0.02 over the entire band. The proposed antenna covers applications such as Wi-Fi, Bluetooth and UWB. Section 2 shows the step by step evolution design of the proposed MIMO antenna and their simulated and measured results. Section 3 deals with the conclusion.

2. ANTENNA GEOMETRY AND DESIGN THEORY

The step by step evolution of the proposed wideband MIMO antenna is shown in Figure 1. Antenna 1 has two elements, and each element comprises a semi-circular radiator attached to a rectangular monopole. The elements are placed at an angle of 180° with respect to each other having edge to edge separation of 18 mm which is $0.125\lambda_0$, where λ_0 is the free space wavelength corresponding to 2.1 GHz, the lowest desirable operating frequency of the proposed structure. The elements are fed by a microstrip line of width 'w'. A semi-circular monopole as a radiator helps in 50% size reduction as compared to the circular monopole as surface current flows over two different paths, one along the semi-circular edge and the other along the rectangular edge [26]. The radius of the semi-circular monopole radiator attached to a rectangular monopole of length '$2a$' and width 'w' is obtained by using Equation (1)

$$f_L = \frac{c}{\lambda} = \frac{300}{4 \times ((\pi \times a) + p + w)} \text{ GHz} \tag{1}$$

where f_L is the lower resonance frequency corresponding to VSWR = 2, a = radius of the circular monopole, and p is the gap between the radiating element and ground plane in mm.

The radius 'a' for $f_L = 3.75$ GHz is calculated using Eq. (1). The calculated radius is 5.3 mm, whereas simulated radius is 5.5 mm for $p = 0.4$, which is close to the calculated radius. Both radiating element and the ground plane dimension play an important role in the impedance matching of a monopole antenna. So, dimensions of the ground plane are also optimized to achieve the desired

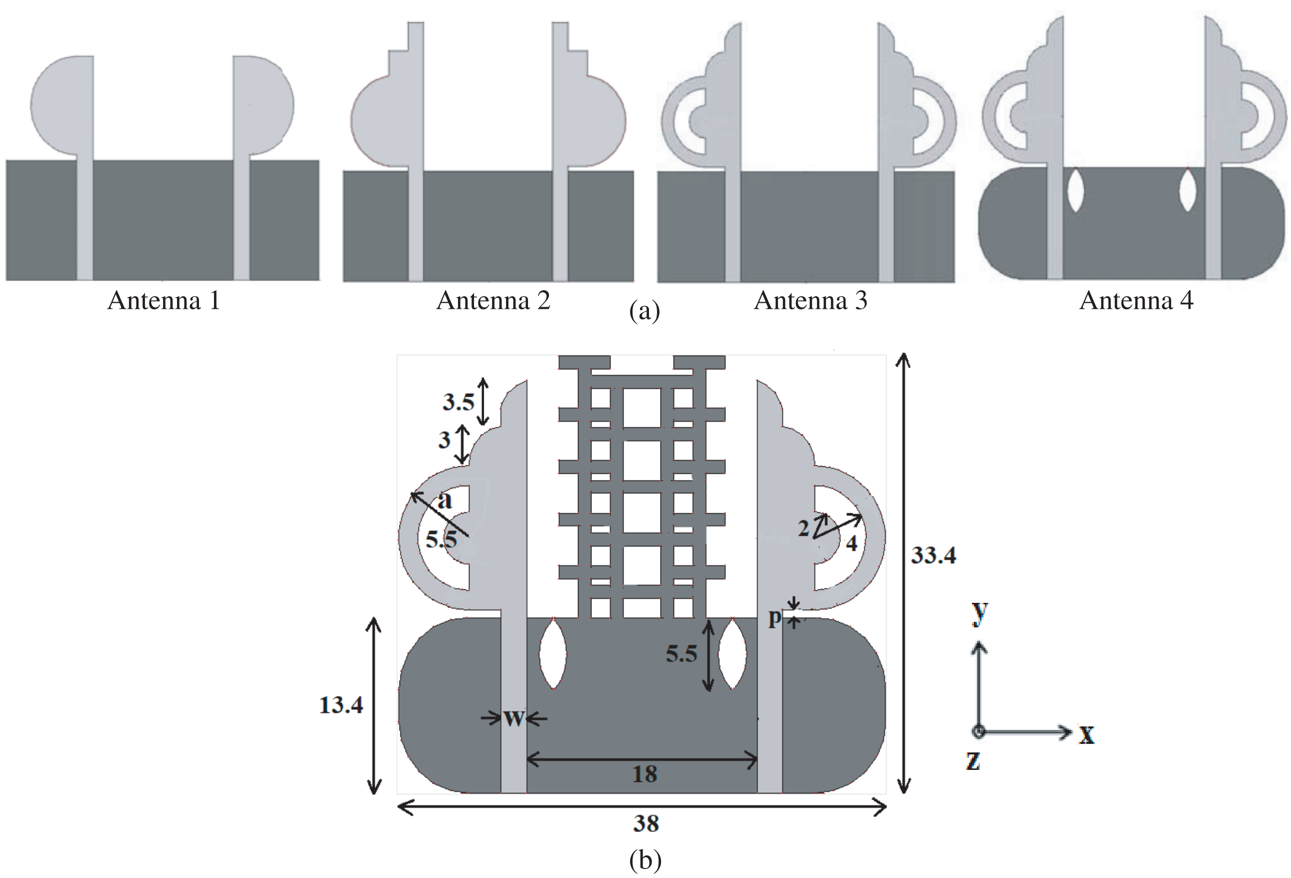


Figure 1. (a) Step by step evolution of proposed MIMO antenna, (b) proposed MIMO structure.

wideband operation. $|S_{11}| < -10$ dB is obtained from 3.75–12 GHz, but it has high mutual coupling due to the strong interaction between closely placed antenna elements. $|S_{21}|$ is less than -12 dB over the frequency 3.75–12 GHz. To improve the impedance matching at lower frequency, the perimeter of the antenna is increased by placing two square steps above the semi-circular monopole leading to Antenna 2 [27]. As a result, $|S_{11}| < -10$ dB is achieved over 3–12 GHz, with a slight improvement in mutual coupling.

In Antenna 3, a semi-annular ring slot is introduced, and square steps are modified by curved steps to further increase the effective surface current path length and to enhance the impedance bandwidth of the antenna from 2.1 to 12 GHz. The semi-annular ring slot increases the surface current density along its periphery and thus increases the effective path length and improves impedance bandwidth. However, increase in surface current density results in increase in mutual coupling.

To lower the mutual coupling between the antenna elements, elliptical slots are introduced in the ground plane as shown in Antenna 4. The elliptical slots act as a wideband notch filter due to excitation of number of higher order modes with each mode having wideband notch, and as a results, it reduces mutual coupling over wide band. The ground plane is also modified by curving both the ends of the ground plane to reduce mutual coupling due to reflection of surface wave at the ground edges. By placing elliptical slots, mutual coupling (S_{21}) is significantly reduced over 4.5–12 GHz frequency i.e., $|S_{21}| < -20$ dB over 4.5–12 GHz, whereas mutual coupling over lower band frequency 2.1–4.5 GHz is not reduced which is indicated by $|S_{21}| < -10$ dB.

An SRR like structure is added to the ground plane which acts as a reflector to space waves and also provides a decoupling path to the surface current due to surface waves [28]. Isolation at lower frequencies improves significantly. The SRR like structure also affects the impedance bandwidth. The gap between the antenna and the ground plane is, therefore, optimized again. $|S_{11}| < -10$ dB and $|S_{21}| < -20$ dB are obtained over the frequency range 2.1–12 GHz. The proposed MIMO antenna structure is shown in the Figure 1(b). The comparison of S-parameters (S_{11} and S_{21}) for various MIMO antenna structures developed in the evolution of proposed antenna are shown in the Figure 2. Impedance variations of these structures at port 1 with port 2 terminated with match load are shown in Figure 3. The structures are designed on an easily available FR-4 substrate having 1.6 mm thickness, dielectric permittivity of 4.4 and loss tangent of 0.02, and simulated using IE3D software [29].

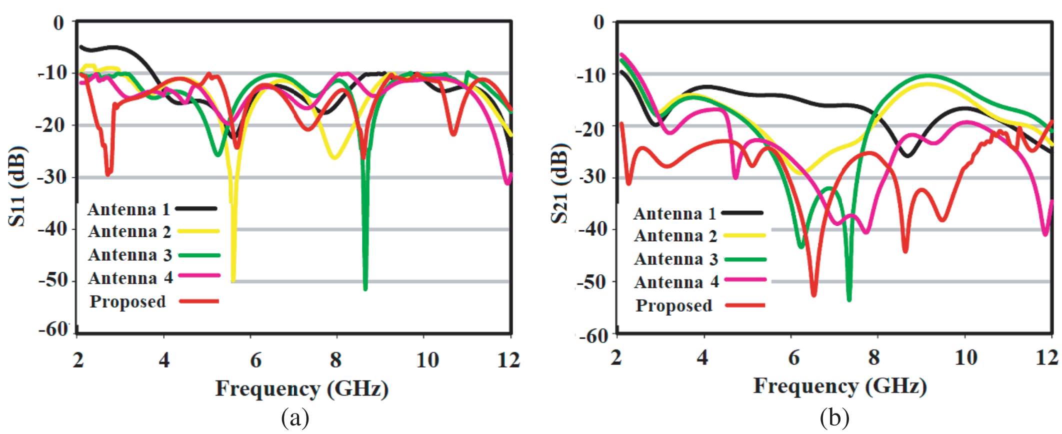


Figure 2. (a) Simulated S_{11} and (b) simulated S_{21} of all structure.

Mutual coupling reduction can be explained using surface current distribution. The surface current distributions of various structures with port 1 excited and the other port match terminated by a load of 50 ohm are shown in Figure 4. When two antennas are placed closely on the same ground plane, the current is induced in the other antenna elements due to surface wave and near-field coupling. Mutual coupling among the antenna elements degrades the performance of the MIMO antenna. In the proposed structure, the mutual coupling is improved by employing elliptical slots and an SRR like structure. An elliptical slot acts as a wide band stop filter which blocks the surface current to propagate from one antenna element to the other. As a result, the surface current coupled to other element in Antenna 4 is

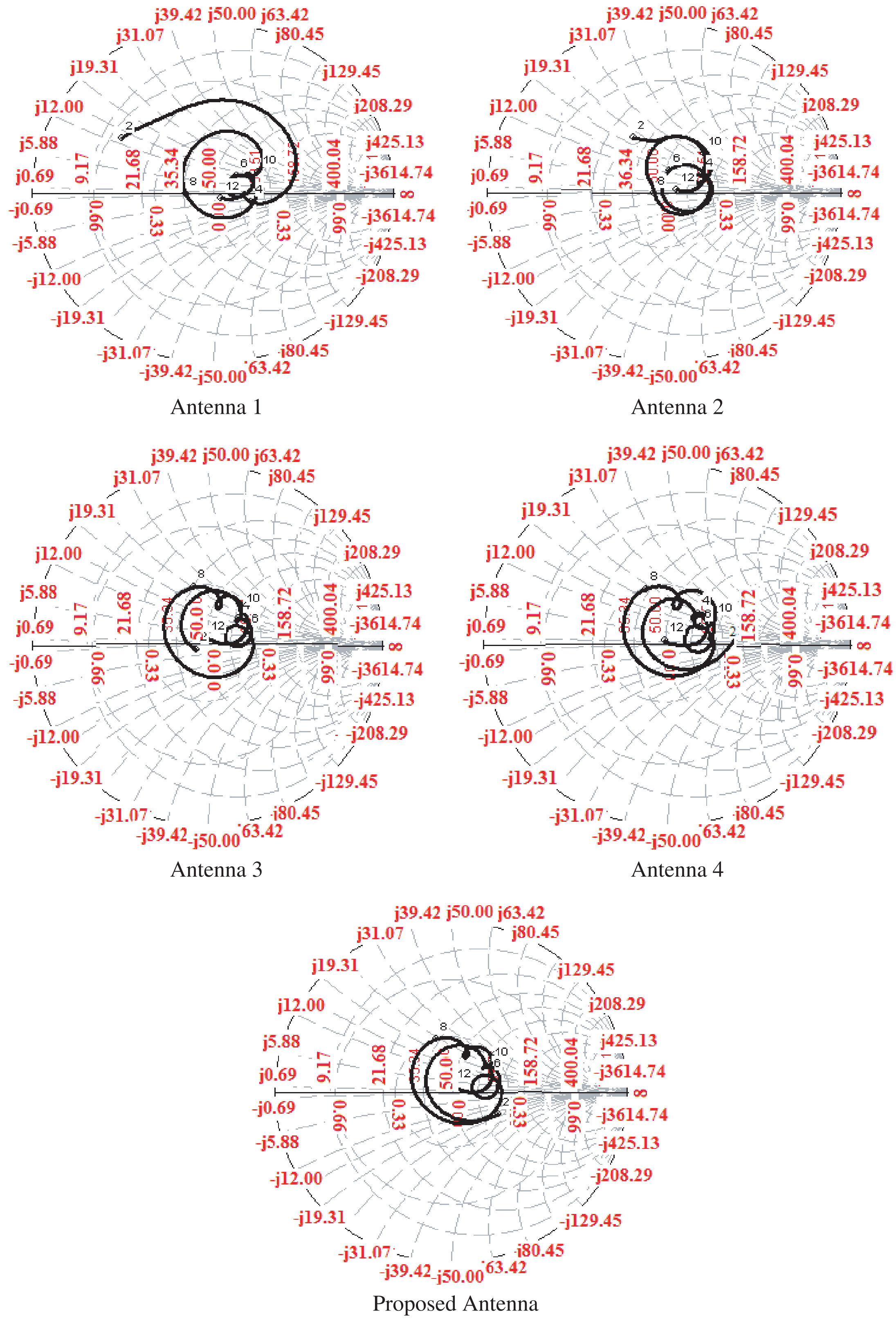


Figure 3. Impedance variation of various MIMO structure.

comparatively less than Antenna 3. The SRR like structure acts as a reflector to space waves and also provides a decoupling path to the surface current due to surface waves. Hence the current induced in the second antenna element in the proposed MIMO structure is further reduced. The surface current distributions for Antenna 3, Antenna 4 and the proposed structure at frequency 2.5 GHz, 5.5 GHz, 8.5 GHz and 10.5 are shown in Figures 4 (a), 4(b), 4(c) and 4(d), respectively.

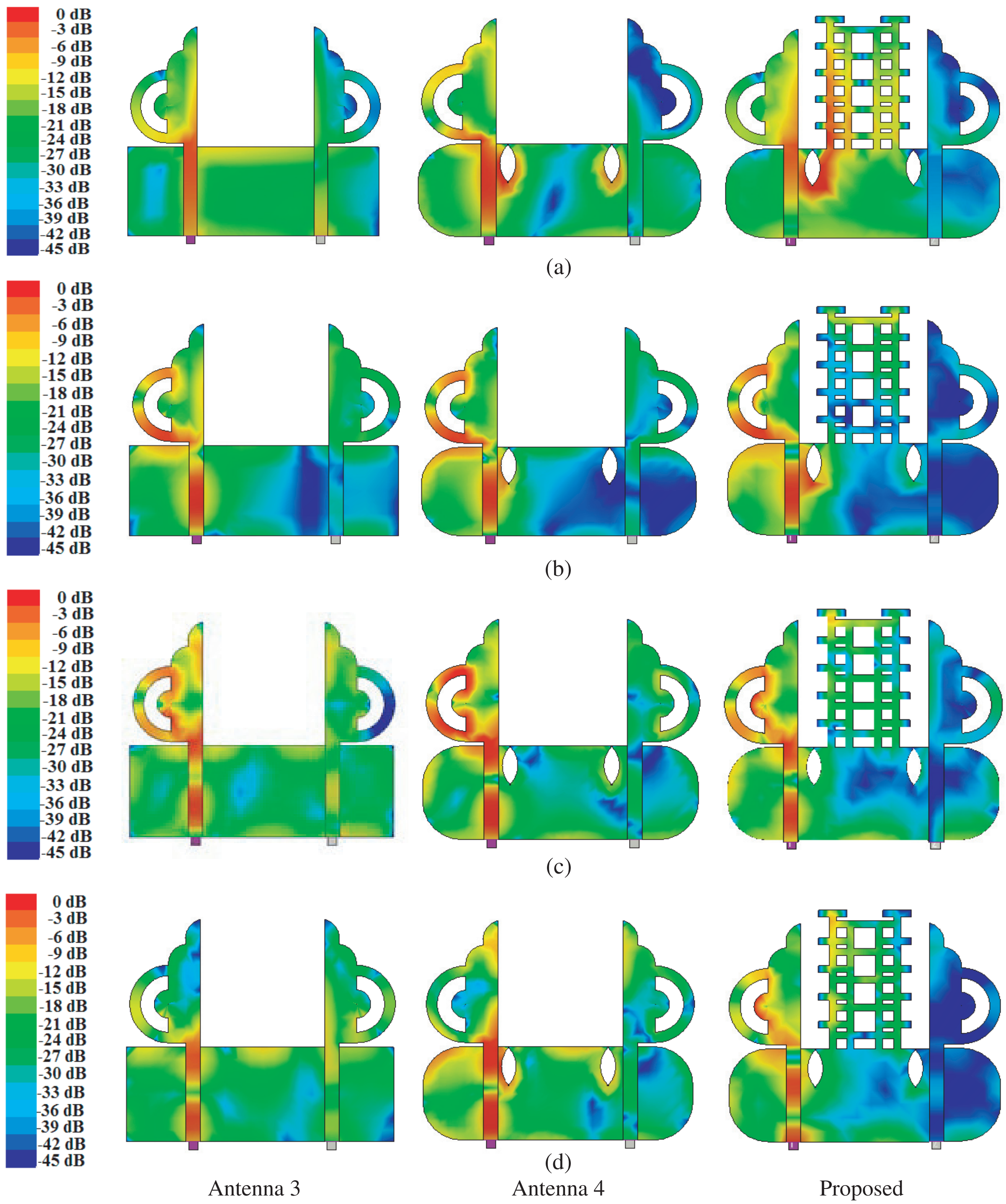


Figure 4. Surface current distribution at frequency (a) 2.5 GHz, (b) 5.5 GHz, (c) 8.5 GHz and (d) 10.5 GHz.

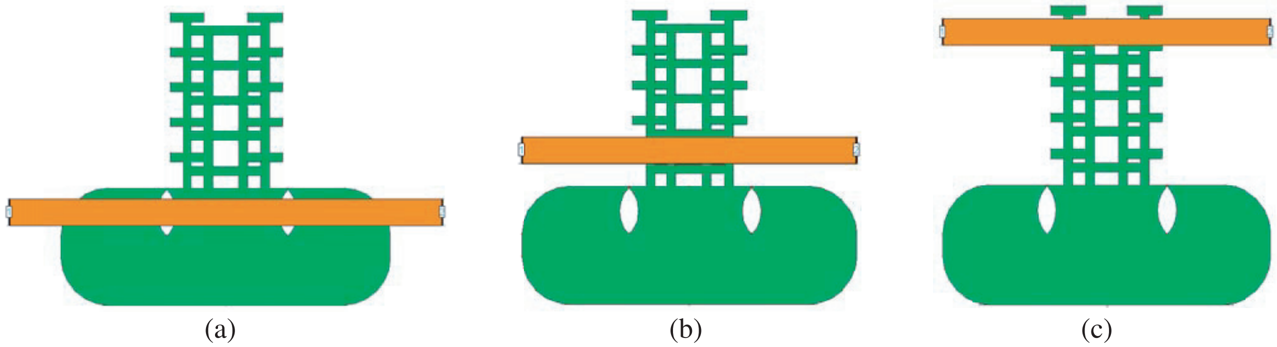


Figure 5. Proposed ground plane with elliptical slots and SRR like structure with 50 Ω microstrip line.

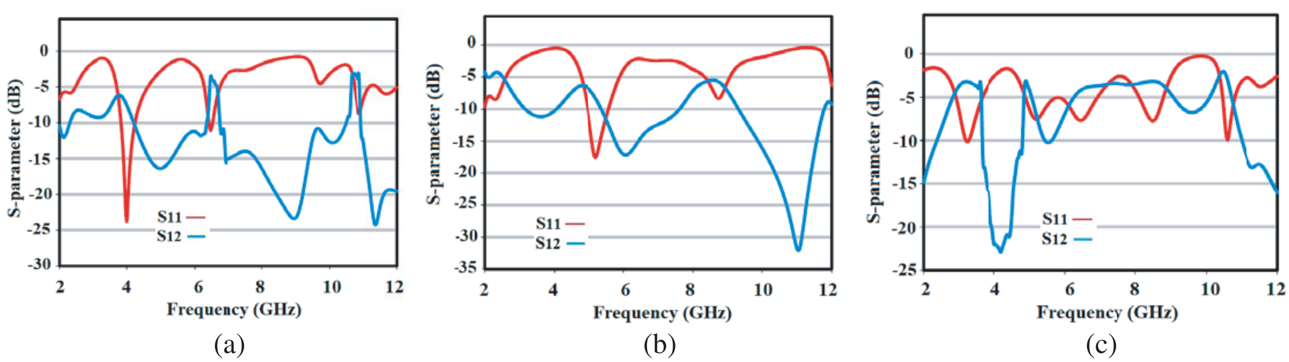


Figure 6. Simulated S-parameter of proposed ground plane with elliptical slots and SRR like structure.

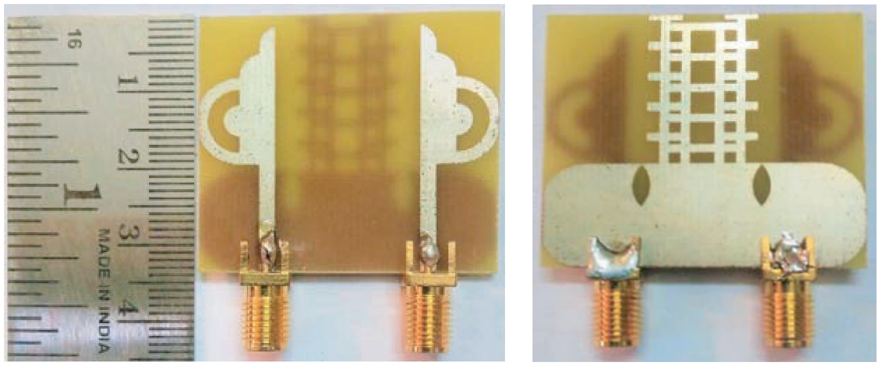
Mutual coupling reduction due to elliptical slots and the SRR like structure can also be analyzed using reflection and transmission coefficients. Transmission and reflection coefficients and band-stop characteristic of the SRR like structure and elliptical slots are analyzed by placing a 50 Ω microstrip line at different positions over the SRR like structure and elliptical slots as shown in Figures 5(a), 5(b) and 5(c). The S parameters of the corresponding structures are shown in Figures 6(a), 6(b) and 6(c). These isolation structures act as a multireasonant structure with band rejection characteristic. The elliptical slots act as a wide band stop filter except at narrow bands centered at 4.0, 6.5 and 10.5 GHz. The SRR like structure also shows band-stop filter characteristics and rejects the bands which are not rejected properly by elliptical slots. As a result, the SRR like structure and elliptical slots suppress the surface waves and space wave which can induce current in the second element, thus reduce the mutual coupling and improve the overall isolation more than 20 dB from 2.1 to 12 GHz.

2.1. Fabricated Antenna and Measured Results

The proposed MIMO antenna structure is fabricated on a low cost FR-4 substrate and tested using Agilent 9916 A network analyzer. The prototype of the fabricated MIMO antenna is shown in Figure 7. The overall substrate dimensions are 38 mm × 33.4 mm × 1.6 mm. The measured results agree with the simulated ones as shown in Figure 8. $|S_{11}| < -10$ dB and $|S_{12}| < -20$ dB is obtained from 2.1 to 12 GHz. The slight discrepancy in the results may be accounted due to fabrication errors and loading effect of connectors.

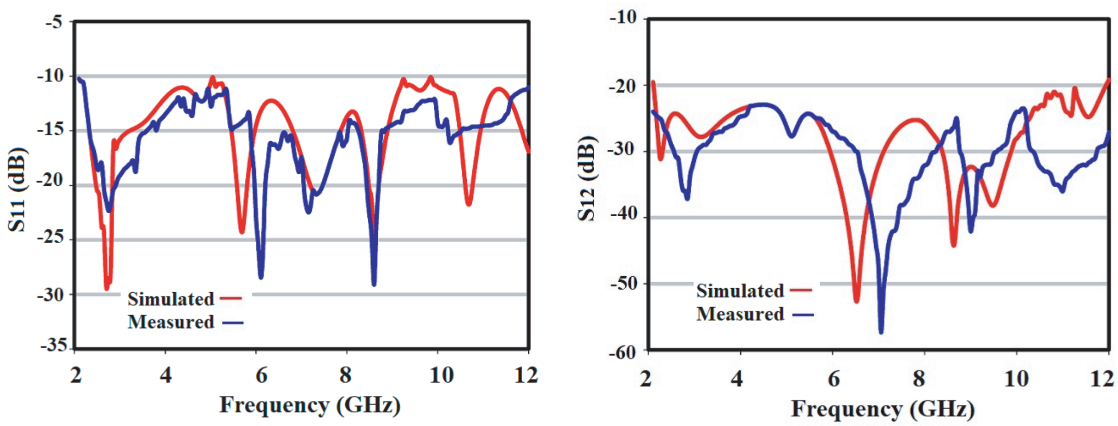
2.2. Radiation Characteristics and Diversity Performance

The measured gain of the proposed antenna is shown in Figure 9. The variation in gain is less than 4.5 dB over the frequency 2.1–12 GHz. The measurement is done by exciting one port and terminating the other port with 50 Ω load. The radiation patterns are measured in two principal planes at $\varphi = 0°$ and



(a) (b)

Figure 7. (a) Top and (b) bottom view of the proposed fabricated antenna.



(a) (b)

Figure 8. Measured and simulated S-parameters (a) S_{11} and (b) S_{12}.

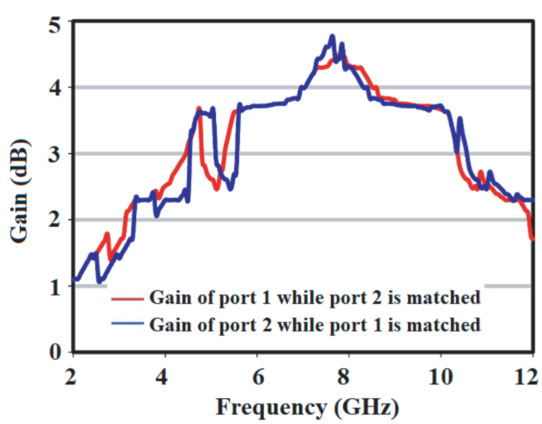
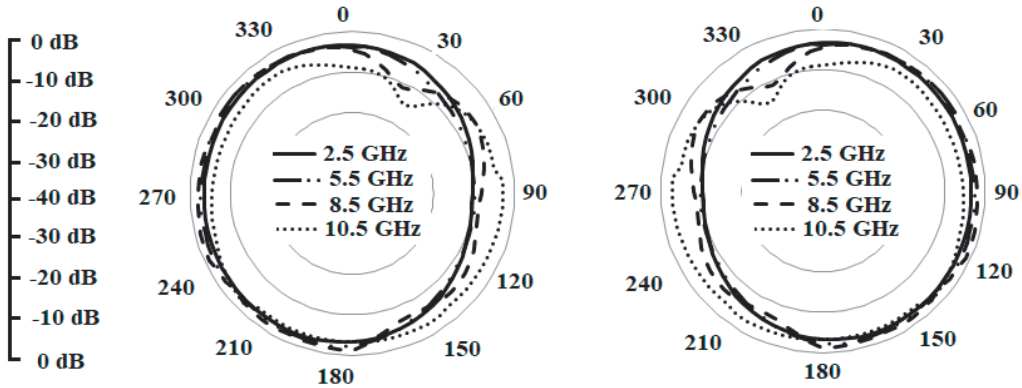


Figure 9. Measured gain of proposed structure.

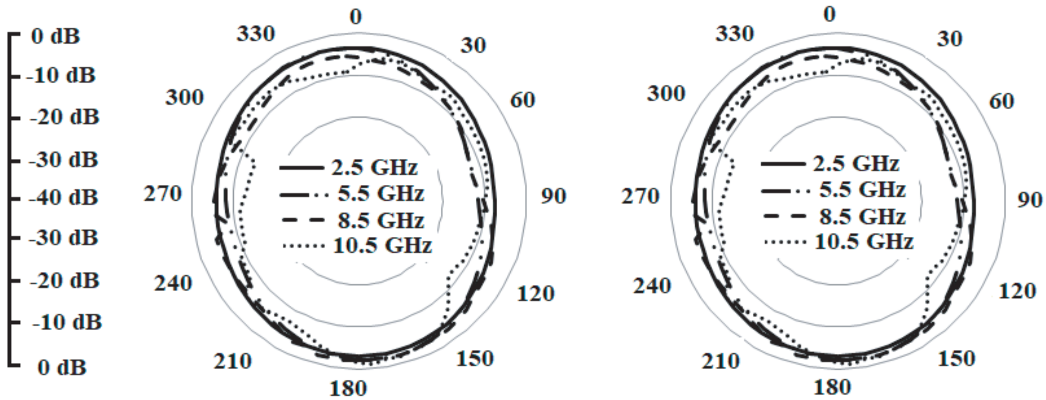
$\varphi = 90°$ which correspond to X-Z plane and Y-Z plane, respectively. Radiation patterns at 2.5 GHz, 5.5 GHz, 8.5 GHz and 10.5 GHz in X-Z plane and Y-Z plane are shown in Figure 10 and Figure 11, respectively. It is observed that the radiation patterns are stable over the impedance bandwidth.

The correlation coefficient is an important parameter in analyzing the diversity performance of



(a) (b)

Figure 10. Measured radiation pattern in X-Z plane of antenna (a) at port 1, (b) at port 2.



(a) (b)

Figure 11. Measured radiation pattern in Y-Z plane of antenna (a) at port 1, (b) at port 2.

MIMO antennas. To achieve high diversity in MIMO antennas, the value of correlation coefficient should be less than 0.5 dB. The correlation coefficient is calculated from the field radiation patterns for uniform multipath indoor environment using Eq. (2) [30]

$$\rho = \frac{\left|\iint_{4\pi}^{0}[\vec{F}1(\theta,\Phi)\cdot\vec{F}2(\theta,\Phi)\,d\Omega]\right|^2}{\left|\iint_{4\pi}^{0}[\vec{F}1(\theta,\Phi)\,d\Omega]\right|^2\left|\iint_{4\pi}^{0}[\vec{F}2(\theta,\Phi)\,d\Omega]\right|^2} \tag{2}$$

where the symbol $(\cdot)$ denotes the Hermitian product, Ω the solid angle, and $F(\ )$ the antennas field radiation pattern obtained by exciting one port and terminating the other port with matched load of 50 ohm.

The correlation coefficient plot of the proposed antenna structure is shown in Figure 12. ECC is less than 0.02 over the entire band from 2.1 GHz to 12 GHz. The diversity gain of the MIMO antennas is also calculated by using Eq. (3)

$$G_{app} = 10 \times \sqrt{1-|\rho|} \tag{3}$$

where ρ is the correlation coefficient between the antenna elements. The diversity gain is greater than 9 dB over the desired operating frequency band from 2.1 GHz to 12 GHz.

The group delay is an important performance parameter in time domain analysis of UWB antennas. The group delay should be constant over the operating frequency range to ensure good time domain

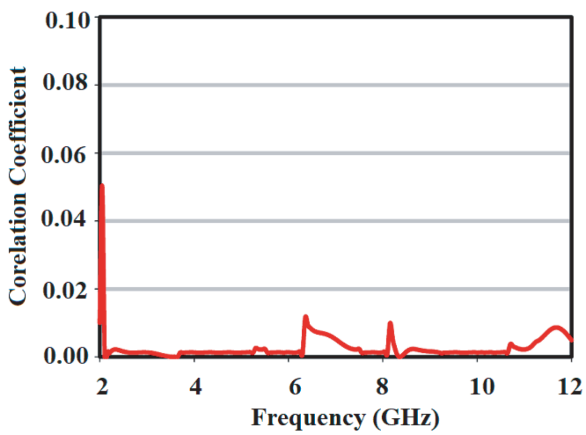


Figure 12. ECC v/s frequency.

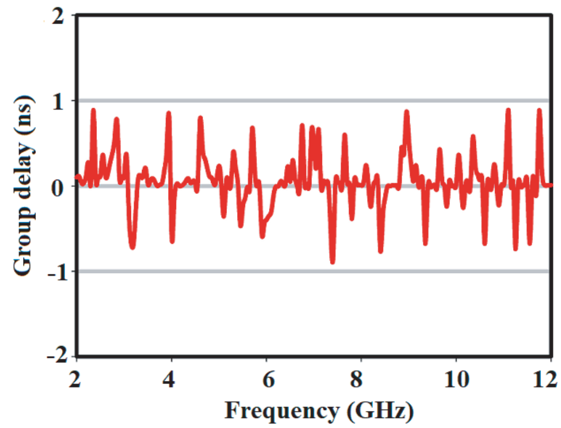


Figure 13. Group delay.

Table 1. Comparison of the proposed MIMO antenna with other wideband antenna.

Reference	Frequency range	S_{21} (dB)	Substrate	Gain (dB) Min-Max	Size (mm^3)	Area (mm^2)
11	3.1–10.6 GHz	−15	FR-4	2.25–3.4	43.5 × 43.5 × 1.6	3027.6
12	2.26–6.78 GHz	−22.5	FR-4	2.35–3.51	55 × 50 × 0.8	2750
13	3.3–10.4 GHz	−18	Benzocyclobutene	3–5.8	62 × 45 × 1	2790
14	4.4–10.7 GHz	−20	FR-4	4–5.5	35 × 40 × 1.6	1400
15	3.1–10.6 GHz	−15	FR-4	Not Reported	43 × 80 × 0.8	3440
16	3.1–10.6 GHz	−15	FR-4	2.2–4.8	40 × 68 × 0.8	2720
17	2.3–12 GHz	−20	RT/ duroid	Not Reported	72 × 48 × 0.76	3456
18	2.71–11.67 GHz	−18	Benzocyclobutene	Not Reported	40 × 50 × 0.4	2000
19	4.2–9 GHz	−16 (4.2–5.2 GHz) −21 (5.2–9 GHz)	FR-4	Not Reported	35 × 38 × 1.6	1330
20	3.1–10.6 GHz	−16	Taconic ORCER RF-35	3–6.5	35 × 40 × 0.8	1400
21	3.1–5 GHz	−20 dB	Rogers4003	Not Reported	37 × 45 × 0.8	1665
22	3.1–10 GHz	−23 dB	Benzocyclobutene	Not Reported	62 × 38 × 1	2356
23	2–10.6 GHz	−14 (2.0–3.1 GHz) −20 (3.1–10.6 GHz)	RT duroid	2–5.8	46 × 37 × 0.787	1702
24	2.4–10.6 GHz	−20 (2.4–3.1 GHz) −18 (3.1–10.6 GHz)	FR-4	2.5–5	40 × 40 × 0.8	1600
25	2.8–12 GHz	−17	Taconic TLY-5	3–5.5	38 × 91 × 1.5748	3458
Proposed work	2.1–12 GHz	−20	FR-4	1.5–4.8	38 × 33.4 × 1.6	1269.2

characteristics. The simulated group delay is as shown in the Figure 13. It indicates that the variation in group delay is less than 2 ns over the operating frequency band which shows good linear phase response.

Table 1 indicates that the proposed MIMO antenna is small in size and has large bandwidth as compared to other wideband MIMO antennas reported in the literature. The proposed antenna has isolation > 20 dB, ECC < 0.02, diversity gain > 9 dB over the entire operating band and therefore possesses good diversity performance. Hence these results indicate that the proposed antenna is a suitable candidate for MIMO applications.

3. CONCLUSION

A compact MIMO antenna for 3G, 4G, Wi-Fi, Bluetooth and UWB applications is proposed. The proposed antenna is simple to design, small in size and fabricated on a low cost FR4 substrate with overall dimensions of 38 mm × 33.4 mm × 1.6 mm. $|S_{11}| < -10$ dB is achieved by using semi-annular ring with curved steps, and $|S_{21}| < -20$ dB is achieved by elliptical slots and SRR like structure over 2.1 GHz to 12 GHz. The structure has envelope correlation coefficient less than 0.02, diversity gain more than 9 dB and less than 2 ns group delay variation over the entire band. All these characteristics make the proposed antenna an appropriate candidate for MIMO applications.

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