Progress In Electromagnetics Research C, Vol. 53, 119–125, 2014

Collocated MIMO Antenna with Reduced Mutual Coupling Using Square Ring DGS

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Abstract—A multimode collocated microstrip patch antenna with reduced mutual coupling is proposed in this paper. The antenna is designed to achieve polarization and pattern diversity for use in multiple-input-multiple-output (MIMO) terminals. The four-port antenna resonates at 2.45 GHz and have total dimension of 1.03λ with reduced mutual coupling (< -20 dB) between its ports. It consists of a simple square patch and a square ring antenna, with a novel square ring slot defected ground structure (DGS). Square ring slot on ground improves isolation by 7 dB by reducing surface waves in both E and H planes. With defected ground structure (DGS), coupling between patch and ring antennas is about -25 dB and correlation factor is less than 0.1. Pattern diversity, mutual coupling and correlation coefficient between signals for a four-port antenna fabricated using FR4 substrate is discussed in this paper.

1. INTRODUCTION

In typical MIMO systems the size of the antenna creates constraints for placing antennas apart in small tablets and mobiles. This restricts the use of MIMO antennas with space diversity in present wireless gadgets. An alternative solution is to make use of polarization and pattern diversity by having multiple ports on the same antenna in collocated form, with improved isolation between ports [1]. Uncorrelated signals are obtained from orthogonal radiation and polarization of antenna elements. The close proximity of feed points will enhance mutual coupling, thereby deteriorating antenna performance.

Many techniques have been proposed for improving isolation between ports in closely spaced antenna elements. Artificial magnetic materials (metamaterials) were developed in order to suppress the electromagnetic coupling between closely spaced antenna elements [2]. Another mechanism proposed previously was to isolate highly coupled antenna elements by using decoupling network [3]. Low mutual coupling can also be achieved using electromagnetic band-gap (EBG) filters [4] by suppressing surface waves. Mutual coupling is reduced by 5.5 dB using a series of metal filled vias in [5], to confine resonant modes within the structure. However vias suffer from circuit complexity and electric loss. These isolation structures provide decoupling effect, but suffer from complicated structures and large structure area. Losses may also be induced in resonant EBG and metamaterial structures. Isolation between ports can also be achieved by using defected ground structures (DGS) [6, 7].

The proposed square ring defected ground structure (DGS) act as a resonant slot which provides isolation by reducing surface waves confined within dielectric that cause coupling between closely spaced antenna elements. It can effectively reduce coupling in both E and H plane because of ring shaped structure. It is easier to fabricate as only a single layer is utilized, when compared to intricate fabrication process required for EBG or vias.

Received 21 July 2014, Accepted 4 September 2014, Scheduled 10 September 2014
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2. ANTENNA DESIGN

The geometry and parameters of 4-port antenna system is shown in Figure 1. The dimension of antenna is given in Table 1. The antenna has a 2 port square patch which is orthogonally polarized to generate 0° and 90° polarized waves. L slots in square radiating patch reduces it dimensions [8] to resonate at 0.4λ, where λ is the wavelength at resonant frequency, making the structure compact than conventional $\lambda/2$ patch. Feed ports P_1 and P_2 on patch excite TM_{01} and TM_{10} modes of antenna.

Feed ports P_3 and P_4 are placed in positions to excite higher order modes of square patch antenna ($W_2 \times W_2$). Ring slot structure etched on top of substrate isolates ports P_3 and P_4 from inner patch feed points, making them resonate based on principle of square ring patch antenna, thus maintaining diverse radiation patterns for square patch and ring patch antennas. Resonant frequency of a ring antenna depends on inner and outer lengths of square ring. The microstrip square ring antenna resonates for a width W of approximately 0.3λ for fundamental mode. The width W is the average of W_2 and W_3, where W_2 and W_3 are outer and inner dimensions of ring as shown in Figure 1. Here higher order modes TM_{12} and TM_{21} of ring antenna is utilized to obtain a frequency of 2.45 GHz which corresponds to width W of 0.8λ. Simulations are done with the aid of Ansoft HFSS finite element solver. Though the slot separating patch and ring antenna on top of substrate isolates feed ports 1 & 3 and 2 & 4, coupling between P_2 & P_3 and between P_1 & P_4 is still high because of identical polarization. Isolation in these high coupling areas is achieved by placing a square ring DGS.

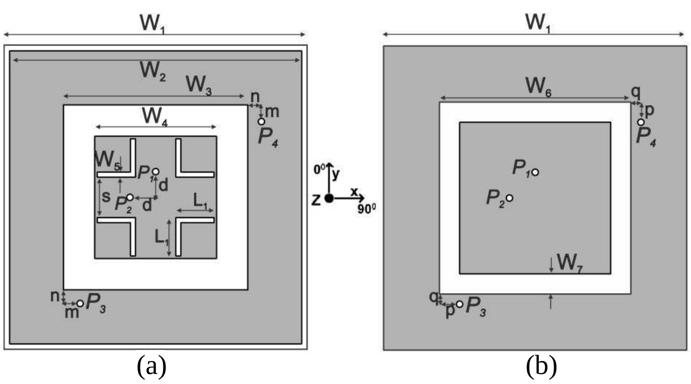


Figure 1. Geometry of compact MIMO antenna system with four ports: (a) top layer, (b) ground layer (with DGS).

Parameter	Value (mm)	Parameter	Value (mm)
W_1	60.2	L_1	7.6
W_2	58	d	5.1
W_3	36.6	s	8
W_4	24.2	m	3.3
W_5	1	n	2.7
W_6	38	p	4
W_7	4	q	2

Table 1. Antenna dimensions.

3. PROPOSED ISOLATION STRUCTURE

Mutual coupling between closely spaced antennas is mainly due to far field coupling and surface wave coupling. DGS structures can efficiently suppress both these coupling currents. Slots etched on ground can block common ground sharing currents to reduce far field coupling. Surface coupling waves propagating within dielectric guided by substrate and finite ground has the lowest mode TM_0 at zero cutoff frequency [9], and is more dominant in this case. Square ring DGS is designed to be a resonant slot antenna at operating frequency, so that it radiates coupling waves between antenna elements to space. This prevents surface waves within dielectric from reaching other ports in their travelling path and cause coupling. In this system patch and ring antennas have feed points in both E and H plane, so it is required to achieve isolation in both planes. By choosing DGS to be a ring shaped structure this can be achieved, with improved isolation for both sets of antenna elements P_1 & P_4 and P_2 & P_3.

To further understand the mechanism of proposed method, E field probing was done using CST Microwave Studio. It was observed that in both high coupling areas, addition of isolation structure has

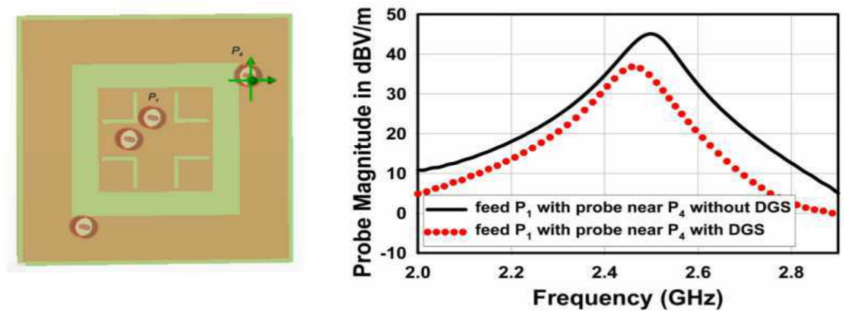
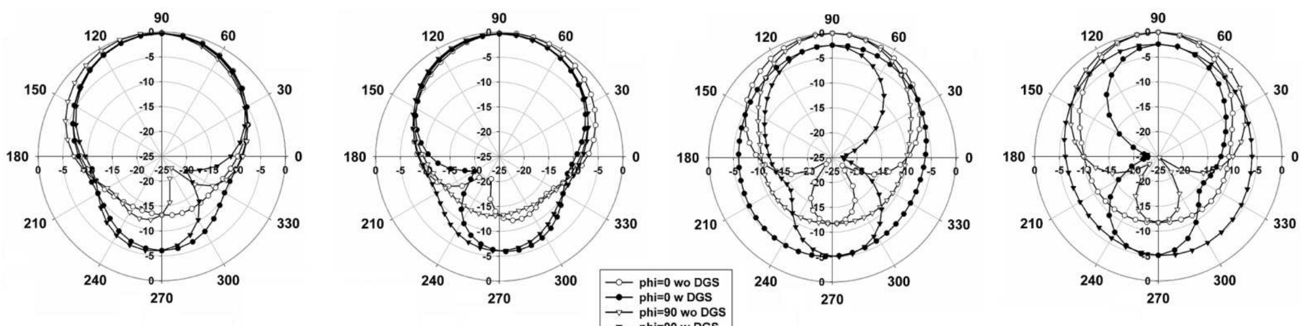


Figure 2. E Field measured within dielectric by simulating using probe.



(a) (b) (c) (d)

Figure 3. Simulated radiation pattern of antennas: (a) P_1, (b) P_2, (c) P_3, and (d) P_4.

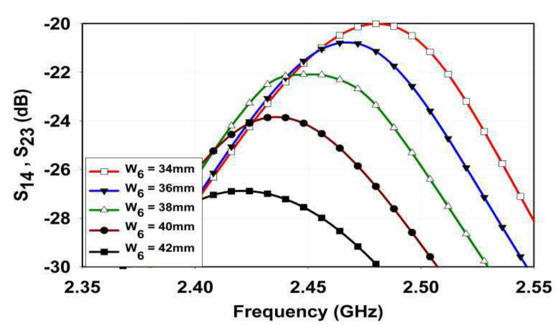


Figure 4. Parametric study of S_{14} and S_{23} with DGS length.

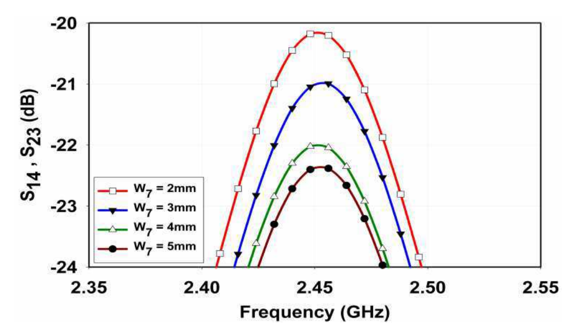


Figure 5. Parametric study of S_{14} and S_{23} with DGS width.

decreased E_Z field within dielectric (E_Z was measured in a direction normal to ground layer) for the operating band. Figure 2 shows E_Z field measured near to feed location P_4 due to feed port P_1. A similar decrease in field with DGS was observed for P_2 and P_3 combination too. A decrease in field ensures that more confined waves are coupled in to space by square ring DGS. It was also observed that field E_Z decreases with decrease in substrate thickness, which holds true for surface waves. Comparison of simulated far field radiation patterns for without DGS (wo DGS) and with DGS case (w DGS) are depicted in Figure 3. An increased back radiation validates that coupling waves are radiated by DGS thus increasing field behind ground in the operating band.

The proposed DGS is nearly $\lambda/2$ square ring slot resonator at the operating frequency of main antenna. For a ring slot, λ depends on both outer and inner dimensions of ring. Parametric study of square ring DGS is done to study impact of length (W_6) and width (W_7) towards mutual coupling. Parametric variation of S_{14} and S_{23} with length and width of ring slot is shown in Figure 4 and 5 respectively. Though increasing the slot length and width improves isolation it decreases matching

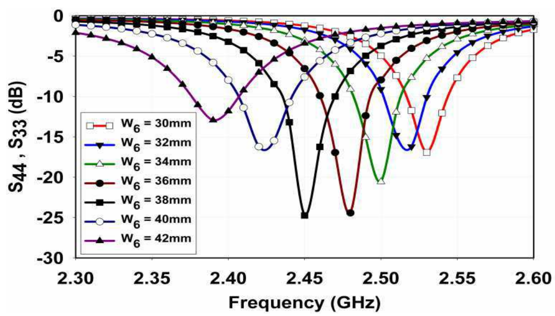


Figure 6. Parametric study of S_{33} and S_{44} with DGS length.

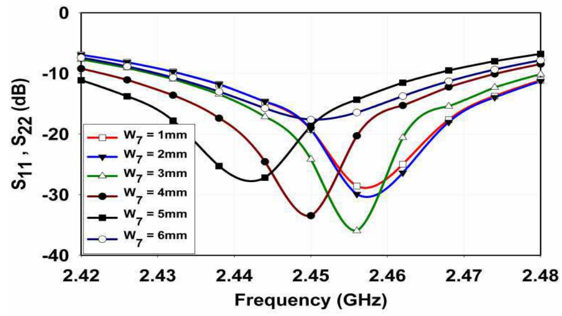


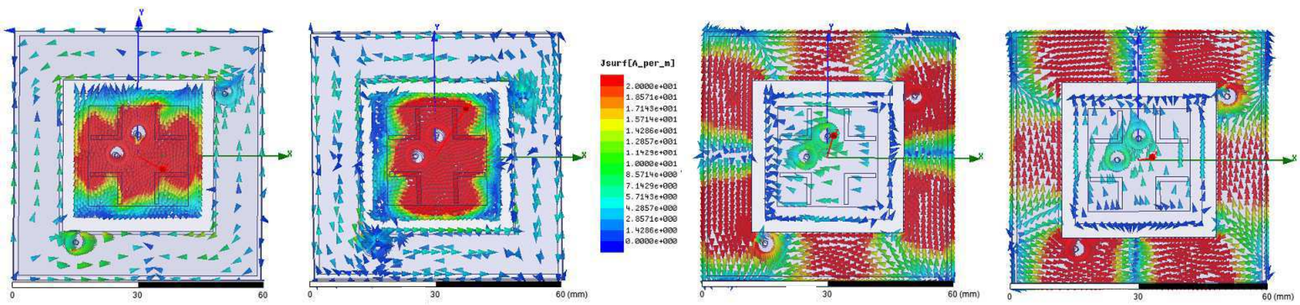
Figure 7. Parametric study of S_{11} and S_{22} with DGS width.

of patch and ring antennas and shifts its resonant frequencies, thus making the antenna system not resonating at a single frequency. Length of ring slot affects resonant frequency of square ring antenna. Variation of S_{33} and S_{44} with length of ring slot as shown in Figure 6, indicates that as DGS length increases resonant frequency of ring antenna decreases, a length of 38 mm is selected for resonance at 2.45 GHz. Parametric study of width of ring slot in Figure 7 with W_6 fixed at 38 mm shows that resonance of inner patch antenna varies with W_7, width of 4 mm provides good isolation and matching at 2.45 GHz for square patch feed ports.

4. RESULTS AND PERFORMANCE ANALYSIS

4.1. Simulated Results

Figure 8 shows simulated current patterns of all feed ports of antenna from which modes of operation can be identified. The patch excites TM_{01} and TM_{10} modes which are orthogonal; one has a null in the direction in which other has maximum. Higher order orthogonal modes produced by square ring patch are TM_{12} and TM_{21} which has a different radiation behavior than lower modes of square patch thus ensuring pattern diversity for antenna system. It can be observed that square ring DGS provides high isolation between patch and ring ports of antenna. Inductive slot etched in the form of a ring in ground plane improves isolation from -15 dB to -22 dB. By reducing coupling currents using a simple square ring DGS, about 7 dB improvement in isolation is achieved when compared to a value of 5.5 dB obtained with series of vias in [5]. Ground slot causes meandering of surface current path of ring antenna, thereby decreasing resonant frequencies of ring antenna without any increase in antenna dimensions. Simulated S parameters of four-port antenna without DGS and with DGS are shown in Figure 9 and Figure 10 respectively. Therefore by introducing isolation structure, apart from improving isolation between ports, ring ports are made to resonate at the same frequency about 2.45 GHz as that of patch antenna. The



(a) (b) (c) (d)

Figure 8. Current distribution of antenna at 2.45 GHz for each port: (a) Port 1, (b) Port 2, (c) Port 3, and (d) Port 4.

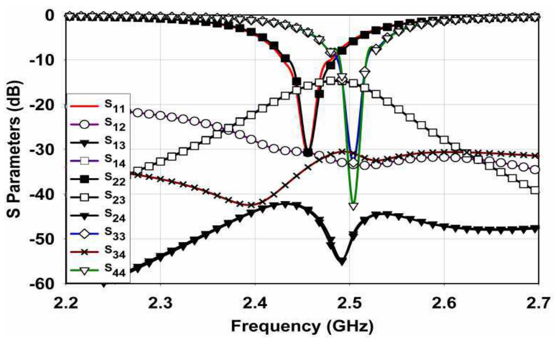


Figure 9. Simulated S parameters without DGS.

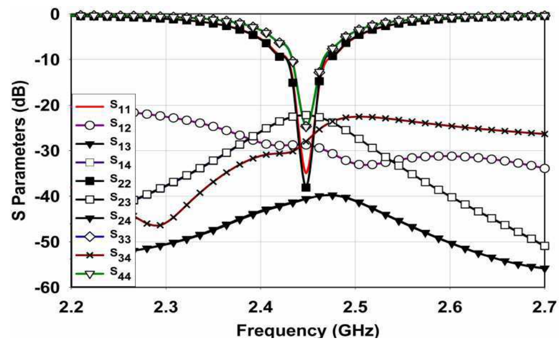


Figure 10. Simulated S parameters with DGS.

-10 dB impedance bandwidth is about 2% for P_1 and P_2, and 1.5% for ring ports P_3 and P_4, which is comparatively higher than in [5]. The total efficiency of the MIMO antenna is about 61.89%.

4.2. Experimental Results

The prototype of four-port coaxially fed multimode microstrip patch antenna is fabricated using FR4 substrate with relative dielectric constant (ε_r) 4.4 and substrate thickness 1.6 mm as shown in Figure 11. Antenna performance is measured using Agilent PNA E8362B Vector Network Analyzer. S parameter measurements were done with 2 ports of antenna connected to analyzer and other two ports terminated with matched load. Measured results in Figure 12 shows that all feed ports resonate at 2.45 GHz, identical to simulation curves, though a slight variation accounts for manufacturing tolerances. The results obtained ensure good MIMO performance as mutual coupling between all ports is well below -20 dB. Isolation between patch and ring modes are below -25 dB, better than simulated results. The antennas have a measured peak gain of 4.4 dBi for patch antenna ports and 1.2 dBi for ring antenna ports. Measured normalized radiation pattern for all four modes in the 0° plane and 90° planes of antenna are as shown in Figure 13. Radiation pattern measurements were done in an anechoic chamber available at laboratory, by exciting individual ports while terminating all other 3 ports with matched load. It can be observed that feed ports P_1 and P_2 have polarization planes perpendicular to each other which ensures least coupling between ports. The same polarization diversity can be observed between ring antenna ports P_3 and P_4. The asymmetric ring ports P_3 and P_4 are second order modes and have slightly high cross polar levels in the measured pattern. The shape of the pattern is different for patch and ring antenna so that they radiate differently which guarantees pattern diversity.

Figure 11. Prototype of antenna (top and bottom view).

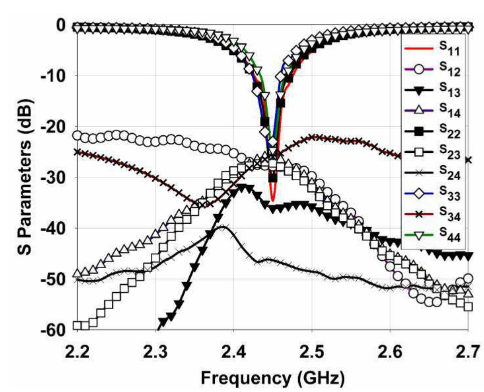


Figure 12. Measured S parameters of four-port antenna.

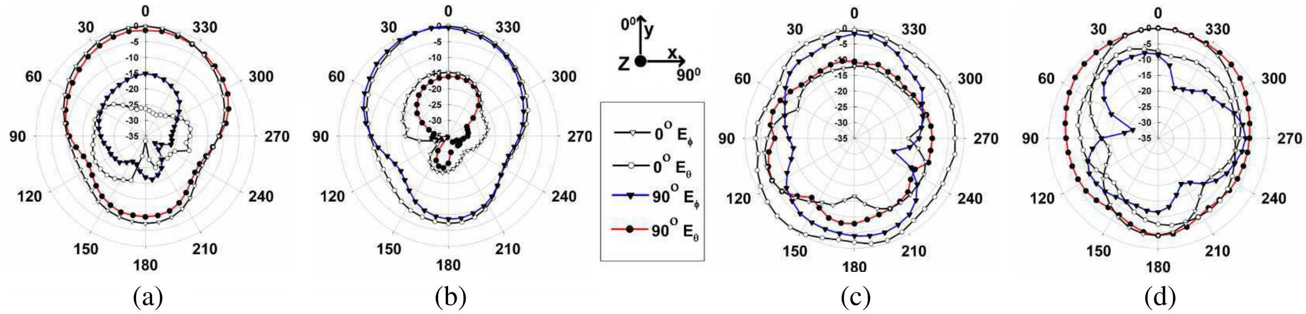


Figure 13. Measured radiation pattern in 0° plane and 90° plane for each ports: (a) P_1, (b) P_2, (c) P_3, and (d) P_4.

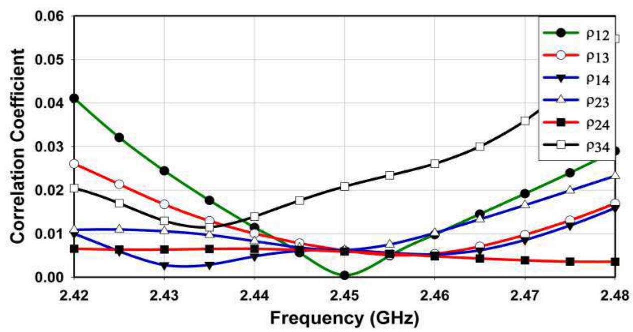


Figure 14. Correlation Coefficients between waveforms.

4.3. MIMO Performance Analysis

A relation between correlation factor ρ_{ij} and scattered parameters for N port antenna is derived in [10] and is given as

$$\rho_{ij} = \frac{\left|\sum_{n=1}^{N} S_{ni}^{*} S_{nj}\right|}{\sqrt{\left(1 - \sum_{n=1}^{N} |S_{ni}|^2\right)\left(1 - \sum_{n=1}^{N} |S_{nj}|^2\right)}}$$

For antennas with more than 2 ports, above equation evaluates correlation coefficients, whose values as low as 0.2 can provide good decoupling with low correlation between radiated signals. But the system being not completely lossless this formula gives an approximate of the diversity performances. Correlation coefficients computed for both simulated and measured data are satisfactory with very low correlation values across impedance bandwidth. The envelope correlation coefficients ρ_{ij} for all ports of fabricated antenna is below 0.1 across the operating band as shown in Figure 14. It shows that the antenna system radiates uncorrelated waveforms which indicate very good performance as MIMO.

5. CONCLUSION

This paper presents a new defected ground structure for reducing mutual coupling between closely packed antenna elements spread across both E and H planes of a collocated microstrip antenna, exhibiting multiple modes of operation in same resonant frequency. A simple square ring slot on ground reduces coupling between patch modes and ring modes of antenna. It is very simple to construct than micro-machined substrates and high isolation can be achieved as demonstrated. This technique of ring DGS around antenna elements may also be utilized in arrays to reduce coupling between elements by reducing surface waves. It can also be employed between circular patch and annular ring antennas or in structures where one antenna element is embedded within another element and having feed points in both E and H planes. The proposed antenna can well meet MIMO wireless communication requirements by employing technique of polarization/pattern diversity.

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