

Review on Isolation Techniques in MIMO Antenna Systems

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Abstract

Objectives: Presently, wireless applications are quickly moving towards multiple input multiple output configuration, thereby the quest for integration of many antennas in the user's equipment enhanced. A MIMO Antenna is used as a reason of enhancing the capacity of the channel without the need of additional power or frequency band. It requires many antennas set up in the transmitter with less coupling between them. **Methods/Statistical Analysis:** Hence, for an effective MIMO antenna system mutual coupling between the antennas should be low. Various MIMO antenna designs have been reported by antenna researchers for wireless application. The main design challenge in MIMO antennas is to attain high isolation amid the antenna elements. This paper reviews various isolation techniques proposed in the recent years. A detailed analysis on the design issues such as antenna miniaturization, integration issues, antenna coupling and isolation enhancement techniques are presented. **Findings:** among the isolation methods discussed better isolation is achieved using meta materials, decoupling networks and defected ground structures. **Application:** MIMO antenna systems find application in portable devices, automotive applications, handheld devices, personal digital assistant etc.

Keywords: Decoupling Network, Defected Ground Structures, Isolation, MIMO Antenna, Metamaterials, Neutralization Line, Parasitic Elements, Return Loss

1. Introduction

The growing mandate for high channel bandwidth and data rate is essentially needed in modern wireless communication systems. Due to the increasing demand for the incorporation of multiple antennas in the user equipment, wireless applications are rapidly shifting towards MIMO from Single Input and Single Output (SISO) and Single Input Multiple Output (SIMO) systems¹. Researchers have focused on the MIMO antenna because of its high capacity and high-speed wireless communication². The origin for MIMO was at Bell Labs in the 1997 to 2002 period called BLAST for Bell Labs Layered Space-Time. With MIMO, it exploits multipath to gain very high spectral efficiencies (10s of bits/sec/Hz were measured)³.

The various design challenges for 4G MIMO antenna considered are mutual coupling, antenna size⁴, in-situ performance, channel capacity and compliance with SAR

regulation⁵. An increased mutual coupling between the elements and high correlation in the channel degrades the performance of a MIMO antenna system⁶. Various methods of decreasing mutual coupling have been recommended by the researchers for the past decade. This paper presents a review of various MIMO antenna isolation techniques.

2. Techniques to Improve Isolation in MIMO Antenna Systems

Adjacently placed antennas of distance less than $\lambda/4$ cause high coupling. Mutual coupling can be minimized by employing the antennas with some separation distance within the mobile terminal. It can be placed either on top two edges or one at the upper part and other at the lower part. The positioning of the antennas also

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disturbs the phase of the coupling currents along with bothering the polarization of the radiated fields. The ground coupling and field coupling can be decreased if the adjacent antennas are oriented perpendicularly to each other (i.e., 90°). Linearly polarized antennas located orthogonally to each other, increase the isolation and provide polarization diversity^{7,8}. However, they require a large antenna space and ground. Various isolation methods for MIMO antenna systems have been reported in the literature. They have been convened into five classifications in this paper and are explained in detail in the subsequent section.

2.1 Decoupling Networks

Mutual coupling is defined as the interaction of electromagnetic field between the antenna elements. It changes the radiation pattern, received element voltages and the matching characteristic of the antenna element. The mutual coupling can be minimized by using decoupling networks. They decouple the input ports of adjacent elements by providing negative coupling such that it cancels the coupling caused between the adjacent antennas. Lumped elements along with the distributed elements have been successfully applied to reduce the coupling thereby enhancing the isolation between adjacent antennas. In⁹, Decoupling networks constructed using lumped elements will not work for frequencies less than 700 MHz, since the transmission line gets longer for a decoupling network and hence lumped elements are realized using hybrid couplers solves the space issue¹⁰. Decoupling Networks (DN) have been frequently used due to their advantage of spatial efficiency. Though conventional DNs also have a disadvantage of narrow bandwidth, in¹¹ broad bandwidth is achieved in DN using parallel resonant circuit, which is suitable for small spaces such as mobile devices.

A floating parasitic digitated decoupling structure for ultra wide band antenna provides wideband isolation characteristics of about 20 dB¹². Stubs placed on the ground plane of radiator are responsible for achieving wideband. Parasitic elements on the rear end of antenna act as independent parasitic resonators. The strips are assembled in the form of digits. The strips and slots made in between them act as resonant elements for different frequencies and also help in increasing isolation by introducing several resonances.

In¹³, indirect coupling is achieved by decoupling network composed of two directional couplers. These

couplers are joined by two segments of transmission line of length 25.4 mm. A part of input signal from port 1 can be coupled to port 2, introducing an indirect coupling with controlled magnitude and phase, which is used to cancel out the direct coupling caused by space waves and surface waves between array elements. The observed mutual coupling was below -58 dB at the center frequency of 7.5 GHz as shown in Figure 1. (b).

In¹⁴, decoupling is achieved using dual-mode 180° hybrid coupler which is constructed using microstrip lines, comprising of line inductors, series LC tanks and parallel-plate capacitors. This works as a coupler in 2.45 GHz band and acts as a pair of isolated transmission line in 5.25 GHz band. The mutual coupling with an array spacing of 0.08λ is below -20 dB in both the bands.

Two simple couple-fed PIFAs were proposed for LTE 700/WWAN operating band¹⁵. Isolation of -10 dB and -15 dB are achieved for lower band (704 to 960 MHz) and (1710 to 2170 MHz) higher band respectively by using the decoupling structure. This structure consists of adjoined transmission line with two terminals short circuited to the ground plane and a capacitor implanted at the middle of the line. The isolation frequency can also be varied by

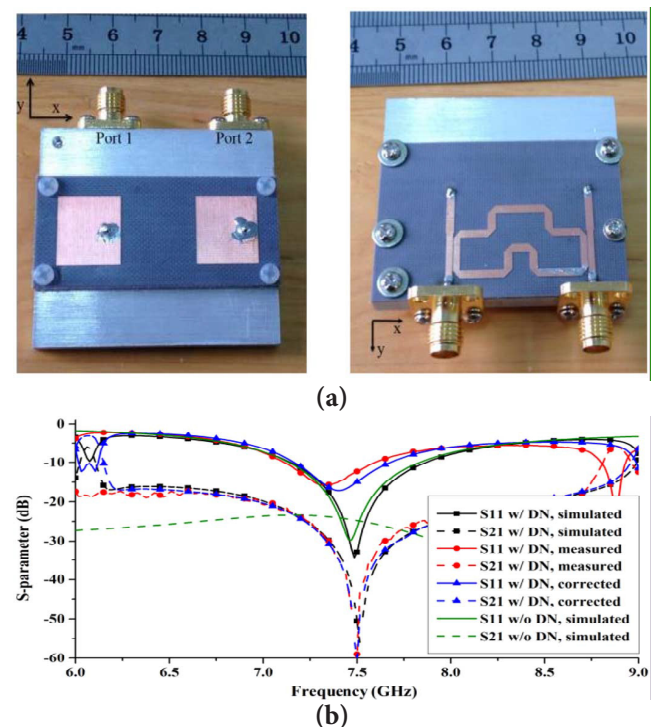


Figure 1. (a) Fabricated antenna (top and bottom view). (b) Mutual coupling and return loss of Element 1.

tuning the capacitance. Tunable isolation bandwidth of 260 MHz is obtained.

2.2 Parasitic Elements

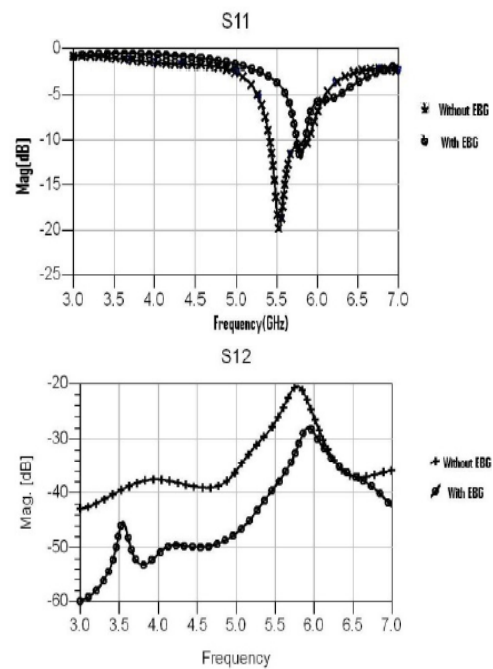
Parasitic elements are not actually connected to the antennas. These elements are used amid the antennas to terminate part of the coupled fields between them by creating an opposite coupling field thus minimizing the total coupling on the target antenna. They can be of a resonator type, floating or shorted stubs¹⁶. Also parasitic elements are designed to control the bandwidth, range of isolation and the amount of coupling⁶. A T-shaped ground stub with a slot is used amid the two square monopole elements to minimize mutual coupling in¹⁷. The stub improves the matching of antenna and the slot within it reflects the radiation from the elements and improves the isolation.

Strips in the ground plane are used to create a stop band to suppress interference in the WLAN band. In¹⁸, Rectangle Stepped Impedance Resonator (R-SIR) and Roundness Stepped Impedance Resonator (RD-SIR) on the ground plane provides isolation of over 23 dB for a wide range from 3.1GHz to 10 GHz. A -37.2 dB mutual coupling reduction was obtained by placing the parasitic tape over the microstrip patch antenna¹⁹. The spacing between the tape and antenna is 4 mm. The tapes are placed over a dielectric board of $\epsilon_r = 3$ for support. The size and position of the tape is significant for the decrease of the mutual coupling.

The Electromagnetic Band Gap (EBG) structures are metallic or dielectric elements arranged periodically which exhibits one or more forbidden frequency bands. EBG structures are used for reducing the mutual coupling^{11,20}, although, they are complicated and require a large structure. In²¹, Mushroom EBG structure acts as parasitic element and it is introduced between two antenna elements which supports either Transverse Electric (TE) or Transverse Magnetic (TM) waves acting like a band-notch filter. A mushroom EBG structure is equal to parallel LC resonant circuit. The capacitance is introduced from the gap and inductance from the current along the neighbouring cells. Thereby surface waves are prohibited to propagate thus decreasing coupling between elements. In²², mushroom EBG structures with slots loaded as in Figure 2 (a) between the monopole antennas reduce the mutual coupling between the rectangular patch elements. Isolation of -36 dB is attained and is shown in Figure 2 (b).



(a)



(b)

Figure 2. (a) Geometry of antenna. (b) Measured S_{11} and S_{12} parameters.

2.3 Defected Ground Structures

The current created on the ground plane can be coupled to neighbouring elements causing high coupling which worsen the MIMO antenna system isolation and correlation⁶. The coupling between neighbouring antenna elements can be minimized by modifying the ground plane²⁰. Modification can be introduced as slits^{24,25} or it can be of dumbbell-shaped defects etc^{26,27}. It acts as band stop filter and suppresses the coupled fields between the neighbouring antenna elements by decreasing the current on the ground plane. A DGS is categorized by its band stop characteristics with which it prevents the

propagation of electromagnetic waves. A DGS is placed below a transmission line which cancels the EMF fields around the defect. Electric fields near the DGS gives rise to the capacitance effect and the superficial currents around a defect cause an inductance effect. DGS acts as band stop filter and suppresses the higher harmonics²⁸. In^{29,30} mutual coupling was reduced using etching slits and slots on the ground plane called a defected ground structure, but a large ground plane is required in order to achieve this reduction. Furthermore, DGS systems have disadvantages in practical implementation due to their complicated ground structures.

In³¹, a H shaped DGS $W_d \times L_d$ of dimension $2 \times 20 \text{ mm}^2$ with centre gap of 0.2 mm is etched under the square patch of dimension $52 \times 52 \text{ mm}^2$ functions as a band stop filter by suppressing the higher order harmonics greater than 20 dB. The coupling between the ports of two rectangular patches is reduced by introducing defected ground structure under the patches in³². It consists of two cocentered circular split ring slots etched on the ground plane, each corresponding to the resonant frequency of the patches. The two split ring resonant slots create two stop bands. By properly choosing the radii dimensions of the circular split ring the required band stop filter the stop band characteristics is obtained at 3.35 GHz and 4.5 GHz. The coupling co-efficient obtained is -33 dB at 3.35 GHz and -27 dB at 4.5GHz.

In³³, the antenna provides two frequency bands centred at 2.70 and 3.95 GHz, providing WiMAX and WLAN band respectively. It has two symmetric T-shaped and C-shaped slots and six pairs of slits. The T-shaped slots are employed inside the C shaped slots and are fed by two 50Ω microstrip lines as shown in Figure 3(a), Figure 3(b). The C-shaped slots are responsible for low frequency response and the C-shaped slots are coupled to T-shaped slots which provide the higher order response. The six pairs of slits are responsible for reducing the surface current of the antenna providing high isolation. The isolation is better than 18 dB across 2.5 to 3.25 GHz and 21 dB across 3.75 to 4.20 GHz and is shown in Figure 3 (c). The bandwidth of interest can be covered by tuning the widths, lengths and interelement spacing of the slits. The conducting region between the slits acts as capacitor and inductance is introduced by the centre connecting strip. Hence slits acts as band stop filter based on parallel LC resonator. The mutual coupling is suppressed between the antennas with the help of slits which acts as band stop filter and perturbs the surface waves between them³⁴.

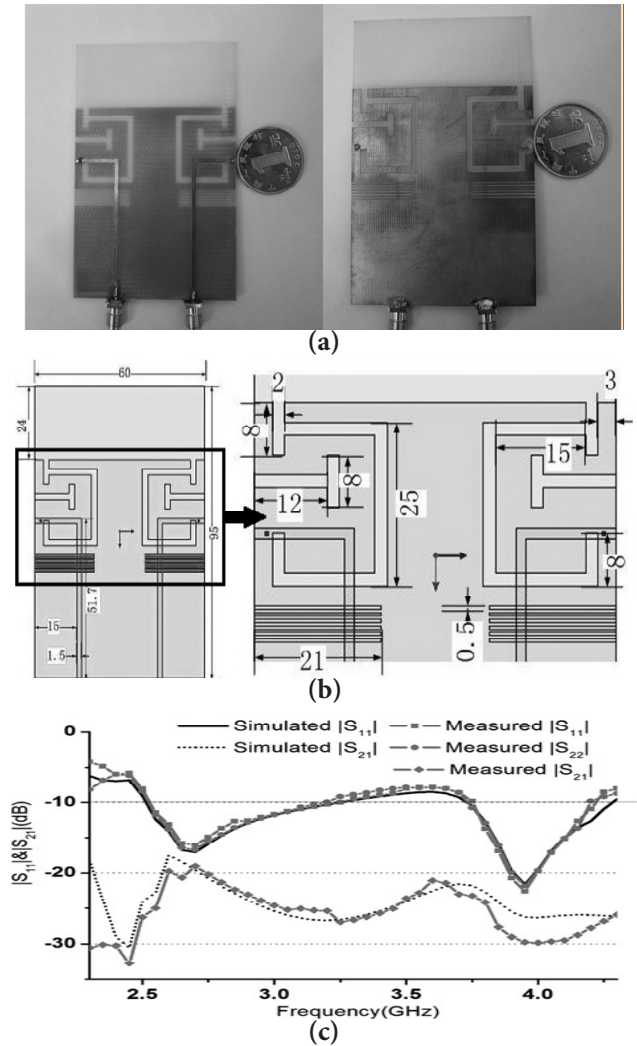


Figure 3. (a) Geometry of antenna. (b) Dimensions of the antenna. (c) Simulated and measured S parameters.

2.4 Neutralization Lines

Isolation can be enhanced by using a Neutralization Line (NL). The current at the input element is taken at a particular location where the impedance is minimum and current is maximum and then its phase is reversed by choosing a suitable length for the NL. This reversed current is fed to the nearby antenna to lessen the amount of the coupled current⁶. In³⁵, NL inserted between two antennas introduces certain current on the neutralization lines and creates an extra electromagnetic field to terminate the mutual coupling. Port decoupling can also be achieved using adjoined metal strip lines that cancel the reactive coupling between antennas and this is referred to as a neutralization technique³⁶. It has the disadvantage of narrow bandwidth and the selection

of location where current is taken for being inverted is complicated since detailed analysis of the current distribution on the radiating antenna is required. In³⁷, to achieve high isolation two symmetric slot antenna elements are placed back-to-back, with a cross-shaped decoupling slot and connecting metal line which is imprinted on the ground plane which acts as decoupling network and neutralization line.

In³⁸, the designed wideband dual antenna consists of two antenna elements (F like monopole) arranged symmetrically and a NL on the top part of the PCB. Each antenna element has a branch attached to the ground plane called grounded branch. This branch can be observed as a parasitic monopole. An NL, connected to the main ground plane with a gap to the two grounded branches of the dual-antenna, is entrenched between the two antenna elements. It provided an isolation of less than -15 dB 1.7–2.76 GHz bands.

Two printed short circuited monopole-antennas of dimension 8 mm×14.5 mm is placed on the opposite crooks of the substrate with a spacing of 14 mm with a dimension of 13 mm×14 mm for ground portion in between them is reported in³⁹. That space can be utilized for placing the feeding network. The small ground portion of the system ground plane was removed only 1.5 mm long inwardly from the top corner to accommodate a thin, printed neutralization line that associates to the monopoles relatively close to the antenna feed ports. With the inclusion of neutralization line antenna port isolation is increased. The antenna port isolation of less than -19 dB was obtained.

In⁴⁰, circular monopoles with a distance of 2.2 mm are printed on the substrate. A neutralization line is connected and interleaved between the two monopoles on the substrate as in Figure 4 (a), Figure 4 (b). The neutralization line consists of two metal strips and a metal circular disc. The circular disc provides decoupling current paths with different lengths to terminate the coupling current on the ground plane, providing a wideband coupling. A circular slot imprinted on the antenna lowers the highest decoupling frequencies to 5 GHz. By adding wideband neutralization line overhead the ground plane a large capacitance is introduced. Since the NL is connected to the two antennas its quality factor is increased which in turn reduces the bandwidth still covering the UWB-MIMO bandwidth of 3.1 GHz–5 GHz providing an isolation of above 22 dB and is shown in Figure 4 (c).

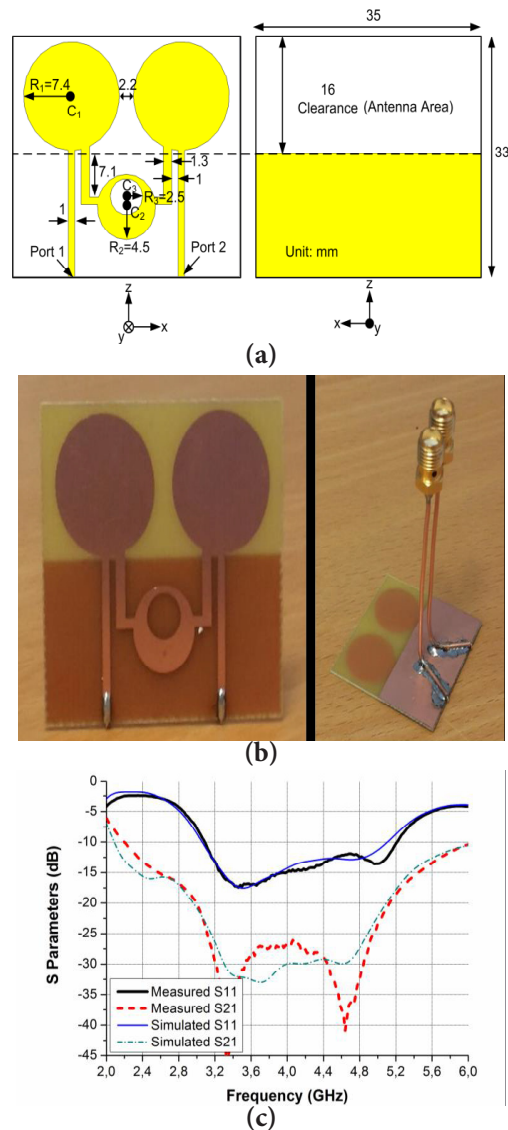


Figure 4. (a) Geometry of antenna. (b) Fabricated prototype. (c) Simulated and measured S parameters.

2.5 Metamaterials

Metamaterials (MTM) are materials that have negative permittivity or permeability or both. Based on the literature, metamaterial based antennas are classified into two types. One that make use of ENG (Epsilon Negative), MNG (μ -negative) or DNG (Double Negative) substrate are called MTM-based antennas and the other that only utilise the MTM unit cell such as the SRR (Split Ring Resonator), CSRR (Complementary Split Ring Resonator) are referred to as MTM-inspired antennas⁴¹.

Metamaterials (MTM) are used for isolation enhancement between adjacent elements due to the existence of a band gap in their frequency response⁶.

The band gaps can act as band notch filters and destroy mutual coupling between neighbouring antenna elements. The most widely used MTM basic structures for isolation enhancement between adjacent elements are the use of Split-Ring Resonators (SRR) and Complementary Split Ring Resonator (CSRR)⁴² or the use of Capacitively-Loaded-Loops (CLL). EM fields from the neighbouring antenna can be obstructed using SRR if the external magnetic field is at right angles to the rings of the resonator⁴³. The Split-Ring Resonators (SRRs) can function as insulators to block EM waves, thus reducing mutual coupling between the elements⁴⁴.

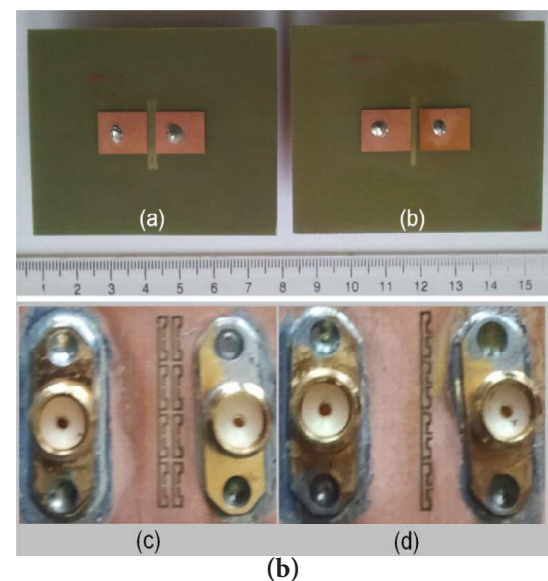
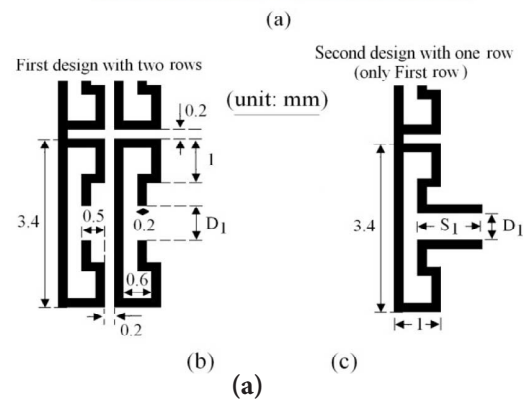
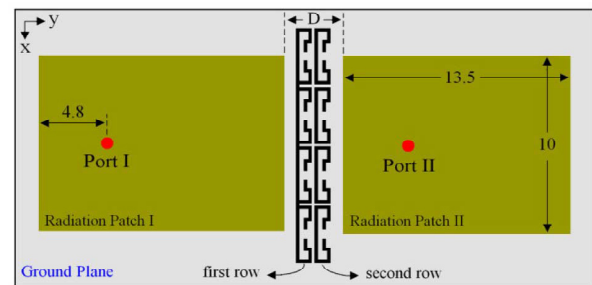
CSRRs are the negative image of SRRs (Babinet's principle), and an axial time varying electric field is essential to excite the rings that create an effective negative ϵ medium and prevent signal propagation at resonance⁴⁵. In⁴⁶, the array built on the metamaterial substrate shows major size reduction, less mutual coupling and significant channel capacity improvement. Still efficiency is lower in the metamaterial substrate due to the copper losses in the unit cells and there is bandwidth deterioration in the metamaterial substrate due to increased permittivity in the substrate. SRR and 1-D EBG structures were acting as reflector and wave trap in⁴⁷. The two antennas with $0.19\lambda_0$ spacing exhibits mutual coupling of less than -30 dB from 2.43 to 2.54 GHz.

In⁴⁵, two cross printed dipole antennas are placed perpendicularly on a ground plane and are excited by two alike microstrip baluns. In order to broaden the impedance bandwidth, the CSRRs are etched on the patch at symmetrical position. CSRRs act as a negative permittivity bandstop filter, hence they can destroy higher-order modes. Microstrip balun and CSRR resonators imprinted in the patch constitute a CSRR based transmission line. The measured port isolation is better than 25 dB over the frequency band from 1 to 2 GHz.

A two element patch array operating at 2.4 GHz with Open Slot Split Ring Resonators (OSSRR) imprinted on the ground plane is presented in⁴³. At the magnetic resonance, the OSSRR has vertical electric fields above the ground plane which behaves as a left-handed material showing negative permeability ($\mu < 0$) and destroys the dominant superficial wave from reaching the nearby elements. With the inclusion of two OSSRR isolation of -37 dB is achieved.

In⁴⁸, two probe fed patch operating at 5.2 GHz with two designs containing one row and two rows of Folded Split Ring Resonators (FSRR) on the ground plane are studied

and is shown in Figure 5(a), Figure 5(b). The resonance performance of the FSRR is due to the induced electromotive force that produces a current that flow within the metallic rings and gaps, creating a balanced inductive-capacitive effect. Such structures have confirmed to be particularly useful in an electromagnetic environment where the electric field is dominantly vertically polarized. Isolation obtained if implemented with single row of FSRR and two rows of FSRR are about -45 dB and -56 dB and is shown in Figure 5(c).



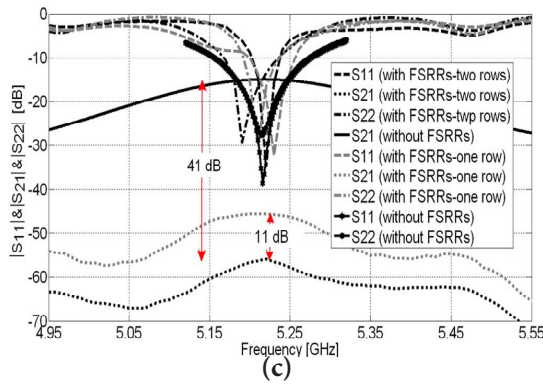


Figure 5. (a) Geometry of antenna. (b) Fabricated prototype. (c) Measured S parameters.

3. Summary of Various Isolation Techniques

Various isolation techniques that have been discussed in the previous section are summarized in Table 1.

From the review of isolation techniques for printed MIMO antenna, it is observed that better isolation is achieved using decoupling networks, defected ground structures and metamaterials compared to the neutralization and parasitic methods. In addition to high isolation, antenna size reduction is also achieved using metamaterials.

Table 1. Comparison of various isolation techniques

Sl. No	Isolation Technique	Frequency	Isolation Achieved in dB	Shape of Isolation Network	Advantages	Disadvantages
1	Decoupling Network ¹³	7.5 GHz	< -58 dB	Two directional coupler	- Simple - Coupler provides large coupling coefficient which helps in cancelling the direct coupling caused by the antenna elements.	Extra space required for the transmission lines
2	Decoupling Networks ¹⁴	2.45 GHz and 5.25 GHz	< -20 dB	Strip Monopole	- ECC with dual band decoupling network was reduced to 0.01 and 0.19	- ECC without dual band decoupling network was 0.12 and 0.29
3	Decoupling Networks ¹⁵	lower band (704 to 960 MHz), higher band (1710 to 2170 MHz)	-10 dB and -15 dB	suspended transmission line shorted to the ground plane with capacitor embedded (40 mm x 1.5mm)	- Decoupling network does not affect the antenna performance and hence no need for matching circuit for improving the input impedance.	Radiation efficiency is reduced due to decoupling network.
4	Parasitic elements ¹⁸	3.1GHz to 10 GHz	> 23 dB	Sleeve coupled rectangle stepped impedance resonator and Sleeve coupled roundness stepped impedance resonator	Better isolations are achieved by using sleeve coupled rectangle stepped impedance resonator (R-SIR) and sleeve coupled roundness stepped impedance resonator (RD-SIR).	Modification done in the ground plane
5	Parasitic elements ¹⁹	4.5 GHz	-37.2 dB	Rectangular parasitic tape	- avoids etching the slot on the ground or in the dielectric without significant increase in antenna height	- Optimization for the dimensions and location of the conducting tape has to be done carefully
6	Parasitic elements ²²	6 GHz	-36 dB	slots loaded in the conventional mushroom EBG structure	- provides very good isolation - correlation co-efficient is nearly zero, good diversity gain	With the inclusion of EBG structures, the resonant frequency of the antenna is shifted from 5.8 GHz to 5.5 GHz.
7	Defected Ground Plane Structures ³¹	1.8 GHz	<-10 dB	H shaped DGS (20 mm x 5.4mm)	- Compact, low-cost	- little distortion in the radiation profile due to H shaped DGS.
8	Defected Ground Plane Structures ³²	3.35 GHz and 4.5 GHz	-33 dB and -27 dB	cocentered circular split ring slots	- ECC is very low - good spatial diversity	- Proper selection of radii of the slots to control the stop - band frequencies

9	Defected Ground Plane Structures ³³	2.70 and 3.95 GHz	-18 dB and -21 dB	six pairs of slits etched in the middle of ground plane.(0.5 mm in width and 21 mm in length)	<ul style="list-style-type: none"> - compact antenna size - correlation co-efficient less than 0.15 - MEG ratio is close to unity 	<ul style="list-style-type: none"> - optimised length has to be chosen as increase in slit length changes the upper and lower band - Space between the slits affects the performance of antenna in lower band (2.70 GHz) than in the upper band (3.95 GHz).
10	Neutralization lines ³⁸	1.7 – 2.76 GHz	< -15 dB	Neutralization Line	<ul style="list-style-type: none"> - Good impedance Matching - Good Antenna Diversity with diversity gain of nearly 10 dB - low correlation less than 0.5 	<ul style="list-style-type: none"> - Lower frequency band has wider bandwidth when compared to upper frequency band.
11	Neutralization lines ³⁹	2.4 GHz	< -19 db	Neutralization Line	<ul style="list-style-type: none"> - ECC less than 0.006 	<ul style="list-style-type: none"> - occupies very little board space for neutralization line
12	Neutralization lines ⁴⁰	3.1 to 5 GHz	<-22 dB	two metal strips and a metal circular disc with circular slot etched on it.	<ul style="list-style-type: none"> - neutralization line is placed above the ground plane without any modification in ground plane - ECC is less than 0.1 - smaller antenna size - High Isolation 	<ul style="list-style-type: none"> - Bandwidth reduced, still covers lower UWB band of 3.1 – 5 GHz - Total efficiency slightly reduced
13	Metamaterials ⁴⁵	1 to 2 GHz	>-25 dB	Square Complementary split ring resonator	<ul style="list-style-type: none"> - significant size reduction of 18% - less mutual coupling - significant channel capacity Improvement 	<ul style="list-style-type: none"> - reduced efficiency of 30% for metamaterial substrate antenna. - reduced bandwidth - No standard design procedure
14	Metamaterials ⁴³	2.4 GHz	> -37 dB	open slot split ring resonator (OSSRR)	<ul style="list-style-type: none"> - ossrr is less complex and has reduced electric length than CSRR - sharp filtering characteristics - high isolation 	<ul style="list-style-type: none"> - when resonators are displaced horizontally from the centre of the ground plane, the resonator moves away from either of the antenna and reduction in mutual coupling cannot be observed. - No standard design procedure
15	Metamaterials ⁴²	5.2 GHz	-56 dB	folded SRR	<ul style="list-style-type: none"> - Less Space - High Performance - Non-Complex structure - low design complexity 	<ul style="list-style-type: none"> - reduction in bandwidth due to substrate losses. - backward radiation - increasing the distance between the antennas, the performance of FSRR is degraded. - No standard design procedure

4. Conclusion

Many investigators have contributed towards the improvement of channel capacity, Bit Error Rate (BER), diversity and gain of the multi element antennas for MIMO systems. However there are still plenty opportunities for the researchers to work on various reduction techniques in mutual coupling. In this review paper, some background history of wireless technology and various

isolation design techniques are discussed. Along with the discussed methods above, there are other methods for reducing the coupling. Feed points connected together by line are used to cancel the coupling in ports⁴⁹. Polarization diversity (need not be 90°) can be achieved by tilting the antenna beams at various angles with respect to each other⁵⁰. In⁵¹, slots introduced in the ground plane also improve the isolation. Mutual coupling degrades the system performance in terms of pattern diversity⁵² and hence

mutual coupling reduction is a vast and an interesting area of research which has direct application for next generation wireless, i.e., 5G and beyond. MIMO antenna systems finds application in portable devices, automotive applications, handheld devices, personal digital assistant etc.

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