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Analysis of Reduction in Mutual Coupling of 4 Port Microstrip Array Using Innovative Resonating Structures

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Abstract

A shared ground plane between multiple ports always leads to disruption caused by mutual coupling of elements. This paper discusses an advanced solution by insertion of periodic structures between ports of 4 element Coplanar Microstrip Patch Array Antenna. Considering Split Ring Resonator(SRR) as starting elements, multiple designs are studied for reduction in mutual coupling. A Double Slit Complementary Split Ring Resonator(DSCSRR) proves to give better results. This structure is inserted between array units to suppress surface waves. Isolation improvement of 16 dB is possible over normal array antenna by implementing proposed DSCSRR.

Keywords: *Coplanar microstrip patch array antenna, MSA, Resonating Structure, Double Slit Complementary split ring resonators (DSCSRRs), High Frequency Structure Simulation (HFSS) software, mutual coupling.*

1. Introduction

Recent boom in Multiple in Multiple Out (MIMO)systems for wireless communication demands research in efficient use of array antenna. Microstrip antenna array is also used in many applications due to compatibility with RF circuits, smaller size, less weight and easy fabrication. All array elements share substrate and ground. This leads to problems involving mutual coupling caused by surface waves and free space radiation by ground. Available literature categorize 3 different approaches for reducing mutual coupling. First approach is based on innovative and efficient arrangement of radiating elements. It has been observed that deliberately designed truncation and corrugations in edges of elements of Vivaldi antenna drastically reduces mutual coupling [1]. Placing radiating patches near to ground[2] or arranging patches at angular offset with respect to each other[3] also improves performance of array antenna. These nuance changes in positioning and orientation of radiating elements reduces mutual coupling in very small amount. Some of the researchers describe second approach to solve this problem with use of decoupling networks like meander line in ground behind radiators [4]. Such decoupling networks may be lumped or distributed in nature.[5]. This approach did not become very popular among researches due to complex nature of decoupling network design.

Third and most popular approach describes isolation provided by small passive elements like EBG &SRR[6].They include different EBG techniques like multilayer EBG using via holes and without using via holes, mushroom like EBG structure and so on which increases the complexity and cost of fabrication as multilayer substrate material is used in metamaterials.[7][8]

Some techniques described in literature are mushroom like electromagnetic band gap (EBG) structure [9] where via hole structure is used which is not that much attractive from manufacturing perspective. When planar EBG structure is used which eliminate the need of via

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but increases cost and complexity as it requires two dielectric layers [10][20]. Many researchers have proposed innovative methods to reduce calculation complexity involved in analysis of EBG structures, like unit cell analysis [21]. Defected ground structures [DGS] are also used to diminish mutual coupling [11]. DGS are implemented by etching various geometries in ground plane. Metamaterial antenna was implemented in [12], with addition of helix resonators inserted on the substrate causing loss. Use of polarization conversion isolators [13]and polarization rotation wall reduces mutual coupling at the expense of size and cost[14]. 4 layered structure using capacitive loaded loops in ground along with Pi-Shaped array have been also proved useful in improving performance of array[15]. Complementary split ring resonator (CSRR) structures on a plane above radiating patch can be used to reduce mutual coupling[16]. According to logic of Babinet's Principle[17][18]; (CSRR) which is implemented to create band notched filter characteristics in Ultra Wide Band (UWB) Antenna can be used to reduce mutual coupling.[19]

This paper discusses evolution of DSCSRRs structure for mutual coupling reduction from simple Split Ring Resonator. This configuration is etched out from ground plane which is used for harmonic elimination and filtering. Fig. 1 shows the unit cell of DSCSRR which we are using here as a surface wave suppressor.

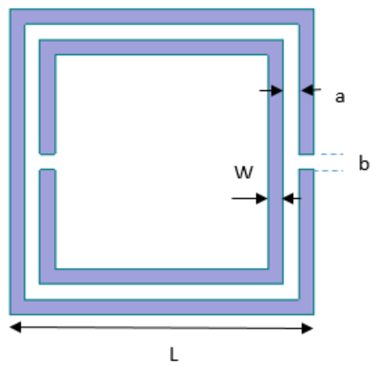

Figure 1: Unit Cell of DSCSRR

Section 2 of Paper discusses design of Microstrip array with simple , unaltered ground plane. Section 3 discusses simulation results for single SRR and Double Slit CSRR structures etched out from ground. Part 4 of this paper describes simulation and fabrication results followed by conclusion. High frequency structure simulator (HFSS) by ANSYS is used for simulation purpose. Even though antenna is four port, it maintains low profile and light weight, and the radiation properties remains unaltered.

2 . 2 X 2 Simple Coplanar Array Antenna Design

Understanding of extent of mutual coupling between multiple ports is important to consider as a standard reference to which modified structures can be compared. A single element Coaxially fed-Rectangular MSA is designed to work on frequency of 4.9 GHz. An array of matrix of 2 X 2 elements is designed on same plane separated by quarter wavelength apart from each other is designed and its mutual coupling effects are studied.

2.1 Antenna Structure

Design of array antenna started with simple rectangular microstrip patch antenna element of size 13 mm X 18 mm. Four such elements symmetrically arranged in 2 rows and 2 columns such that their edges are 15 mm i.e. $0.25\lambda_0$ apart from each other as shown in Figure 2 . Entire structure is designed over FR4 material as substrate which have relative Dielectric Constant of 4.4 and tangent loss factor of 0.002. Substrate used is 1.6mm thick with opposite side covered with copper plane acting as ground having dimensions as 64mm X 71 mm.

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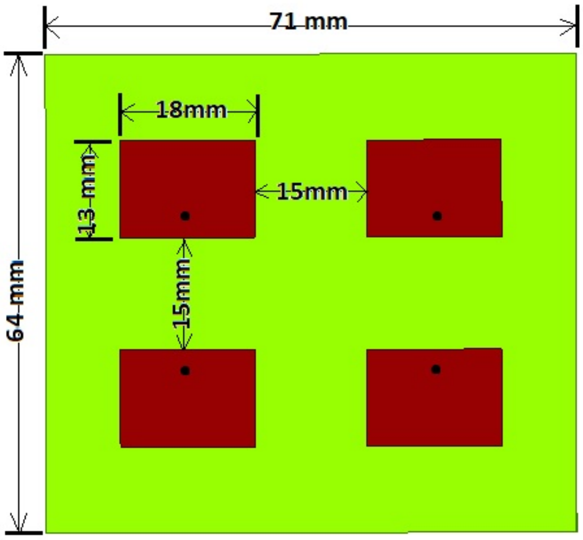

Figure 2: Simple Coplanar 2 X 2 Microstrip Array Antenna

2.2 Simulation Results

2.2.1 **Reflection Coefficient S_{11}:** Return Loss less than -10 dB indicates operating band. Designed antenna operates at resonating frequency of 4.96 GHz with S_{11} as low as -23.1694 dB having narrow bandwidth of 170 MHz starting from 4.87 GHz to 5.04GHz as seen in figure 3.

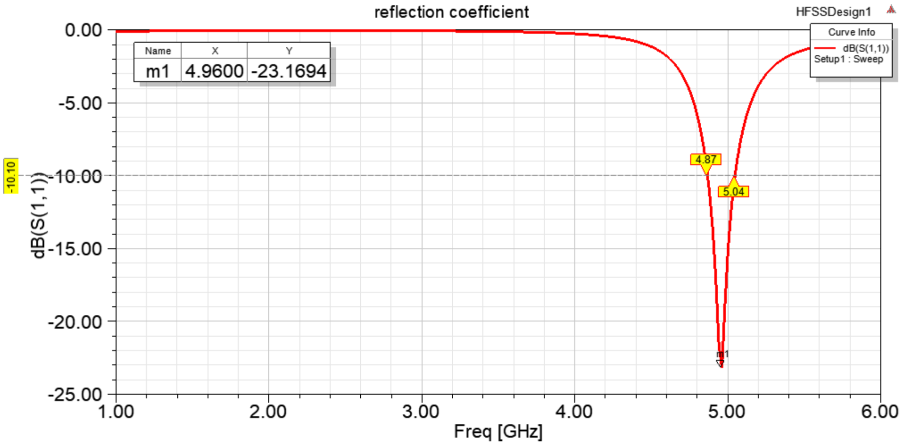

Figure 3: S_{11} of Simple Coplanar 2 X 2 Microstrip Array Antenna

2.2.2 Radiation Pattern: Radiation Pattern of array antenna shows unidirectional radiation in E-Plane and omnidirectional radiation in H-Plane of antenna with maximum gain of 3.6315 dB along 0 degree (boresight) direction as seen from figure 4.

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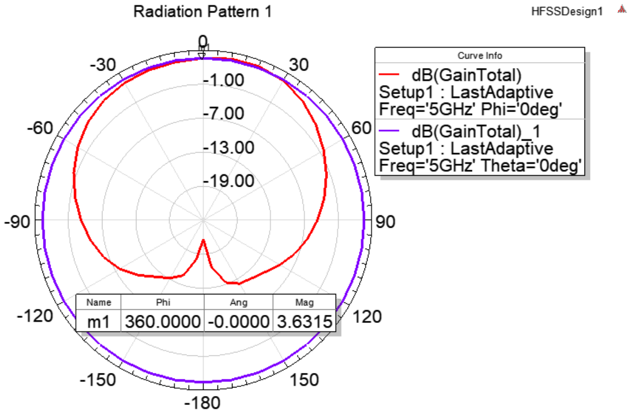

Figure 4:Radiation Pattern of Simple Coplanar 2 X 2 Microstrip Array Antenna

2.2.3. Mutual Coupling S_{12}: Mutual coupling is unwarranted electromagnetic crosstalk between antenna units in an array. That is energy absorbed by one antenna's receiver when another antenna is operating. Total power supplied to each element in array depends on their own excitation and additional contributions from adjacent antenna units. This reduces the antenna efficiency and performance.

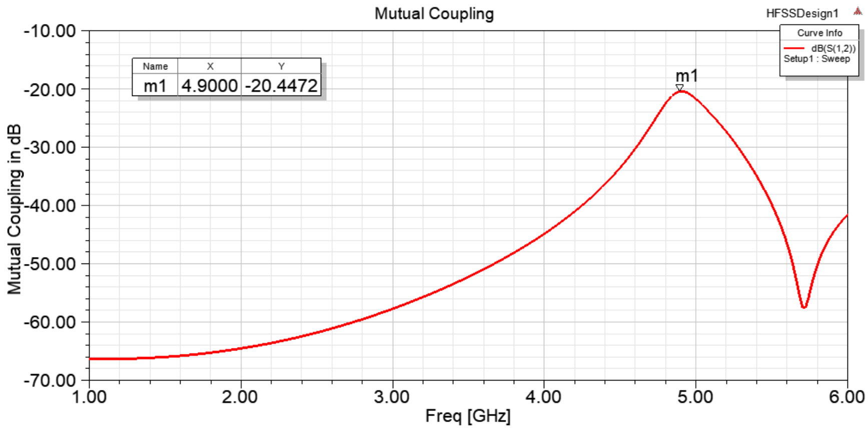

Figure 5: Mutual Coupling of Simple Coplanar 2 X 2 Microstrip Array Antenna

From figure 5, observed mutual coupling of -20.4472 dB between elements of array is under acceptable limits but can further be reduced to improve antenna performance. Subsequent section discusses improvements in mutual coupling by using resonator structures in ground plane of antenna.

3. Complementary Split Ring Resonator

Figure 6 shows a transparent view of array antenna with modified ground plane. All resonating structures in ground plane are symmetrically arranged in respect to excitation ports and radiating antenna. Three cells of CSRR are placed between adjacent patch antennas to improve performance by reducing mutual coupling between radiating elements.

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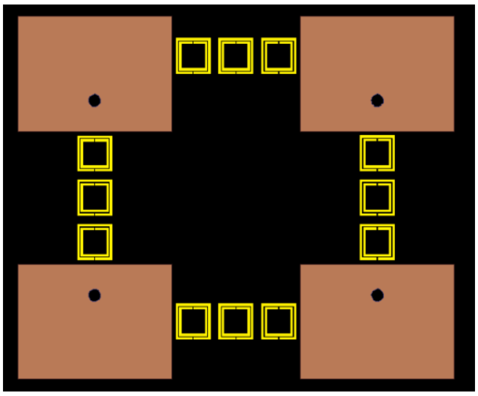

Fig 6: Top view of the four patch antennas with CSRR etched on ground plane.

3.1. CSRR Characterization

The measurements of CSRR unit cell after optimization for antenna operating at 5 GHz are L = 4 mm, a = b = w = 0.2 mm. The structure is etched on a dielectric substrate having Constant ε_r of 4.4 and loss tangent 0.002 and dielectric substrate is 1.6 mm thick. Unit cells are separated by 1 mm, patch and cell are 0.5 mm apart. All other dimensions and positions of 4 microstrip patch array elements are maintained as discussed in part 2 of this paper.

Design of CSRR structure to have resonance with antenna is crucial for reduction in mutual coupling. The resonant frequency of CSRR is mostly dependent on the slot length (L), gap width (a), and split width (b) as given by,

$$f = \frac{v}{(4*(L-b)-a)\sqrt{\frac{\varepsilon_r+1}{2}}} \quad (1)$$

where 'v' is velocity of electromagnetic wave in vacuum and ε_r is the relative permittivity of dielectric substrate. The equivalent structure for the resonating structure is the combination of capacitor and inductor. Following formula gives approximate estimation of L and C :

$$L = \mu_0 h \quad (2)$$

$$C = \frac{W\varepsilon_0(1+\varepsilon_r)}{\pi}\cosh^{-1}\left(\frac{2W+b}{b}\right) \quad (3)$$

where h is the substrate thickness, W is width of patch, b is gap , and μ_0 is the permeability of free space.

3.2. Mutual Coupling

Electromagnetic surface wave interaction between antenna units in an array is mutual coupling. Power supplied to each antenna element depends on their own excitation and also on the contributions from adjacent antenna units. Thus mutual coupling results in reduction of the antenna efficiency and performance. Coupling of microstrip antennas is studied using FDTD [2]. The Scattering matrix is defined as,

$$\begin{bmatrix} b1 \\ b2 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \end{bmatrix} \quad (4)$$

where a_1, a_2, b_1, b_2 are the normalized voltages. Voltages, impedances, currents and waves are related with each other as follows:

$$V_1 = \sqrt{Z_{C1}}(a_1 + b_1) \quad (5)$$

$$I_1 = \frac{1}{\sqrt{Z_{C1}}}(a_1 - b_1) \quad (6)$$

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$$V_2 = \sqrt{Z_{C2}}(a_2 + b_2) \quad (7)$$
$$I_2 = \frac{1}{\sqrt{Z_{C2}}}(a_2 - b_2) \quad (8)$$

where Z_{C1}, Z_{C2} are probe impedances used for feeding. If we put $a_2=0$ i.e. no incident wave at second port since only first port is active and others are terminated in matched load. Thus, equation (4) will be modified as

$$b_1 = S_{11}a_1 \quad (9)$$
$$b_2 = S_{21}a_1 \quad (10)$$

Input impedance and transfer impedances can be calculated by substituting above equations:

$$\frac{V_1}{I_1} = Z_{C1}\frac{1+S_{11}}{1-S_{11}} \quad (11)$$
$$\frac{V_2}{I_1} = \sqrt{Z_{C1}Z_{C2}}\frac{S_{21}}{1-S_{11}} \quad (12)$$

Mutual coupling S_{21} and return loss S_{11} can be easily calculated by rearranging terms in equation (11) and (12) [9].

3.3. Simulated and Fabricated Results

3.3.1. Simulation Results for Split Ring Resonator: As first step to design CSRR we implemented Single Split Ring Resonator structure periodically. Reflection Coefficient and mutual couplings observed are shown in figure 7 and figure 8 respectively.

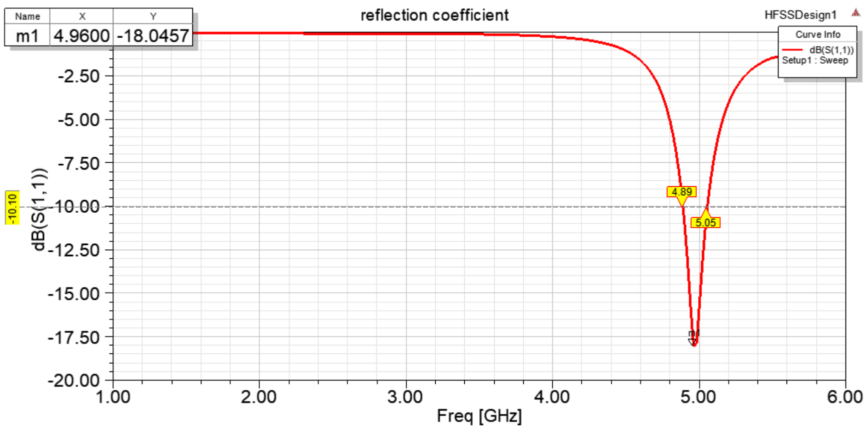

Figure 7: S11 of Coplanar 2 X 2 Microstrip Patch Array Antenna with SRR

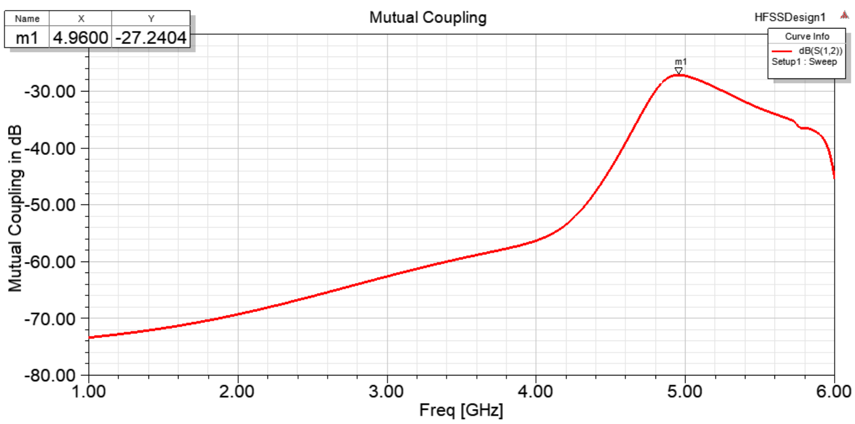

Figure 8. Mutual Coupling of Coplanar 2 X 2 Microstrip Patch Array Antenna with SRR

Addition of periodic SRR structures in ground does not affect resonating frequency of antenna much

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but mutual coupling is drastically reduced to -27.24 dB as compared to -20.4472 dB of Simple array antenna without SRR.

3.3.2. Simulation Results for Double Slit Complementary Split Ring Resonator

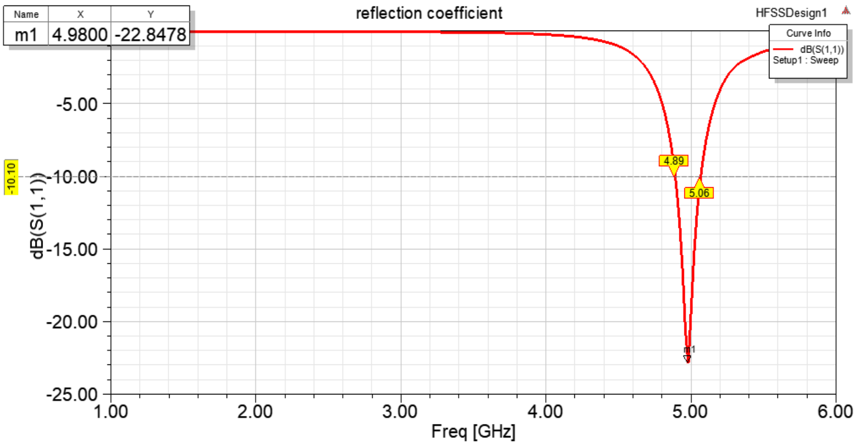

Figure 9. S11 of Coplanar 2 X 2 Microstrip Patch Array Antenna with DSCSRR

Reflection Coefficient graph in figure 9 shows better impedance matching at resonating frequency of 4.98 GHz as evident from S_{11} of -22.8478 dB. Antenna have bandwidth of 170 MHz operating in band of 4.89GHz to 5.06GHz.

Mutual Coupling graph shown in figure 10 gives far superior results as mutual coupling reduces to mere -36.20dB. This is 16 dB less than what we observed for simple array antenna without any periodic structures in ground.

Surface waves generated in abundance on E-plane coupled array elements over high permittivity and thick substrate causes mutual coupling [5]. This configuration ensures the suppression of surface waves between the adjacent patches. The cross coupling also affects the radiation of antenna. But the effect of cross coupling is almost negligible. Amount of mutual coupling is calculated by transmission coefficient.

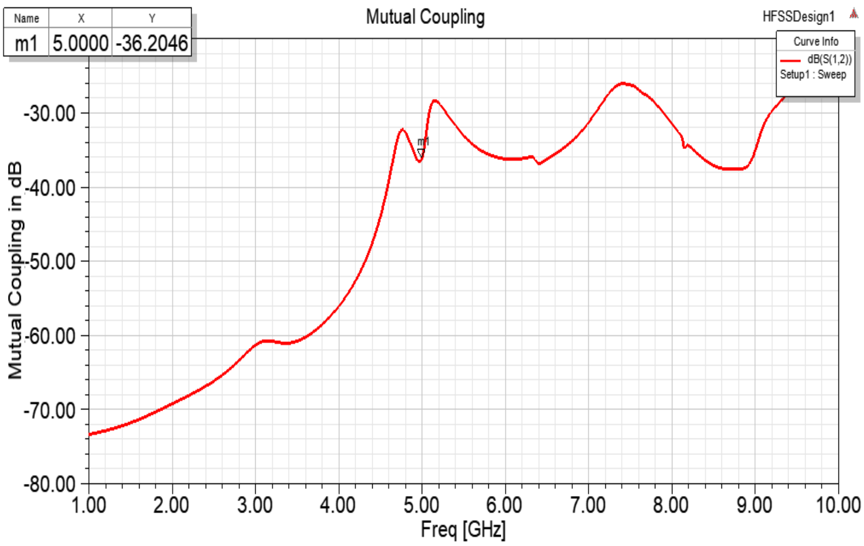

Figure 10. Mutual Coupling of Coplanar 2 X 2 Microstrip Patch Array Antenna with DSCSRR

Figure 11 and figure 12 shows the results for reflection coefficient and mutual coupling respectively between four patch antennas with and without DSCSRR structure. Better impedance matching as signified by lower reflection coefficient; with larger band of operation can be seen from figure 11 for

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array antenna with DSCSRR. A reduction of about 16 dB is observed between the adjacent patch. The antenna gain pattern is computed when one antenna is excited while adjacent two antennas are terminated with 50 Ω impedance which is shown in Figure 13.

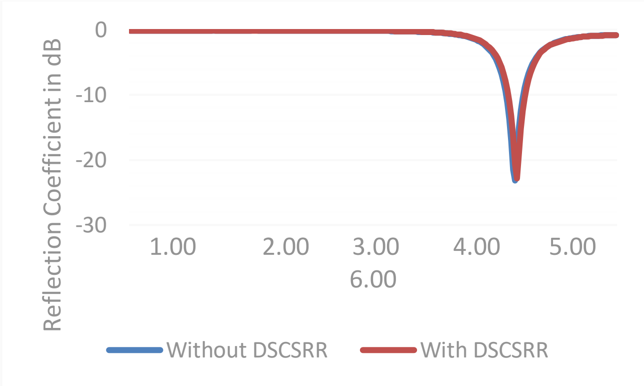

Figure 11. Return loss (S11) of four patch with CSRR and without CSRR

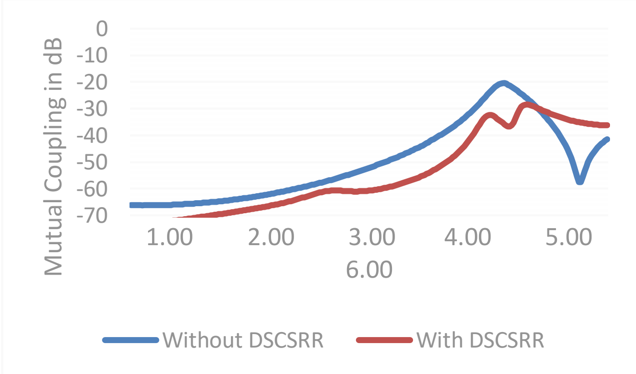

Figure 12. Mutual coupling between four patch antennas with and without CSRR

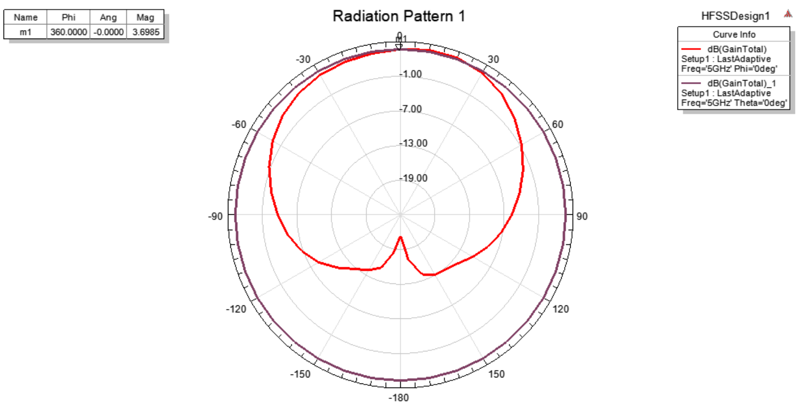

Figure 13. Radiation pattern with DSCSRR

The comparison of four port array without any periodic structure and with SRR, DSCSRR is shown in Table 1. Return loss i.e. reflection coefficient of antenna has very less effect due to addition of periodic structures as it varies from -23.16dB for simple antenna to -22.9 dB for DSCSRR structure. Since periodic structures are part of ground and does not come exactly under radiating element, gain and radiation pattern of antenna is preserved. Significant improvement can be seen in mutual coupling which reduces from -20.44 dB for simple array antenna to-27.24dB for SRR structure and -36.2 dB for DSCSRR structure.

Table 1. Comparison of different parameters for four port array

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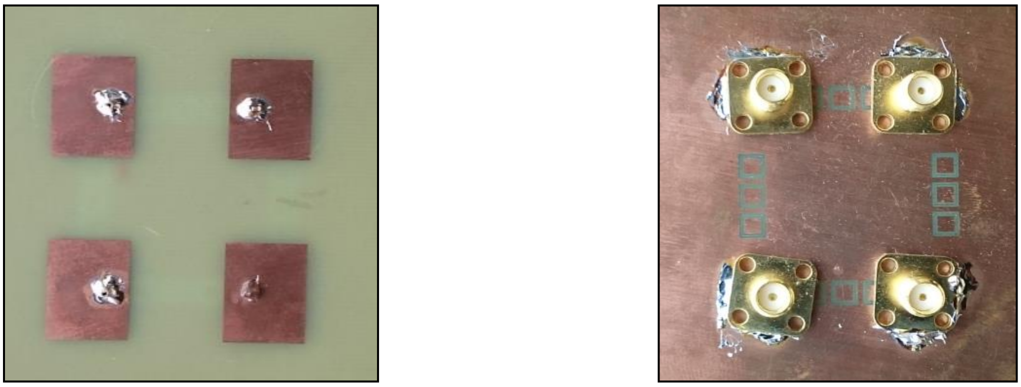
Sr. No.	Parameters	Simulation Results in dB		
		Simple Array	With SRR	With DSCSRR
1	Return loss	-23.16	-18.04	-22.9
2	Mutual coupling	-20.44	-27.24	-36.2
3	Gain	3.60	3.56	3.7

4. Fabrication and VNA (Vector Network Analyzer) Testing Results



(a) (b)

Figure 14. Fabricated antenna (a) Top view (b) Bottom view

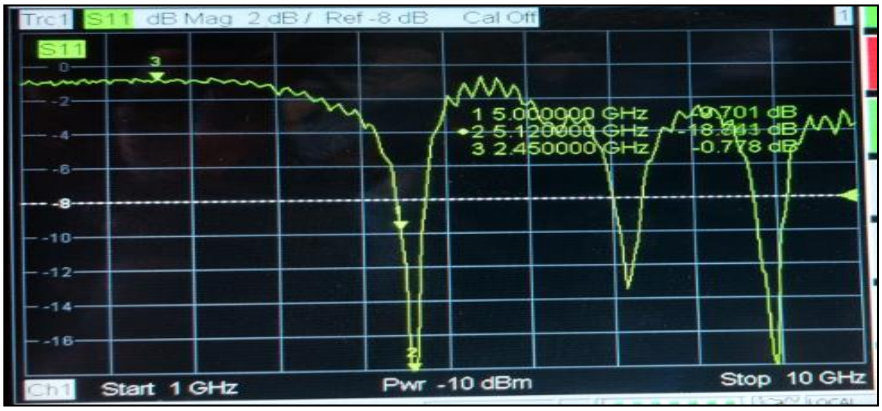


Figure15. Reflection Coefficient observed on VNA

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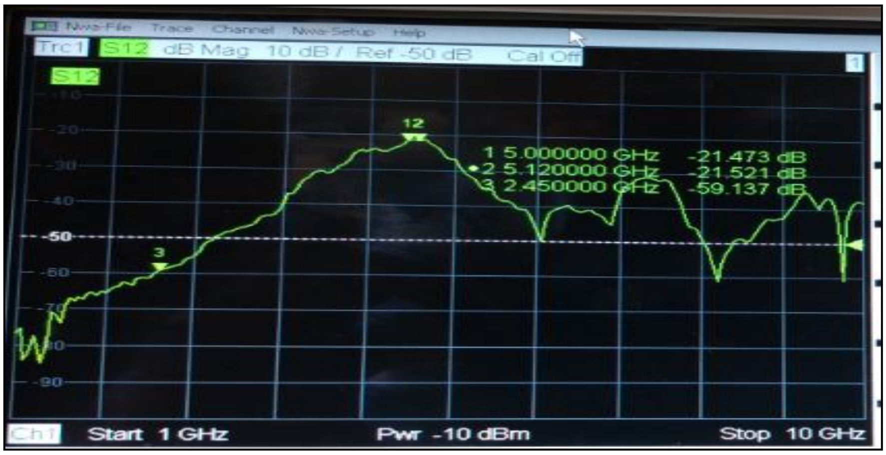

Figure 16. Mutual Coupling For SRR structure in ground

Figure 14 shows the photos of top and bottom view of antenna with DSCSRR and its measured reflection coefficient results are shown in Figure 15. Reflection coefficient graph closely follows S_{11} graph simulated in HFSS. Mutual coupling is measured by measuring S_{12} also in agreement with simulated results as shown in figure 16 and 17 for SRR and DSCSRR respectively. Minor deviation observed in simulated and practical results because of imperfect soldering, antenna fabrication losses and no fixed slot for keeping antenna while testing.

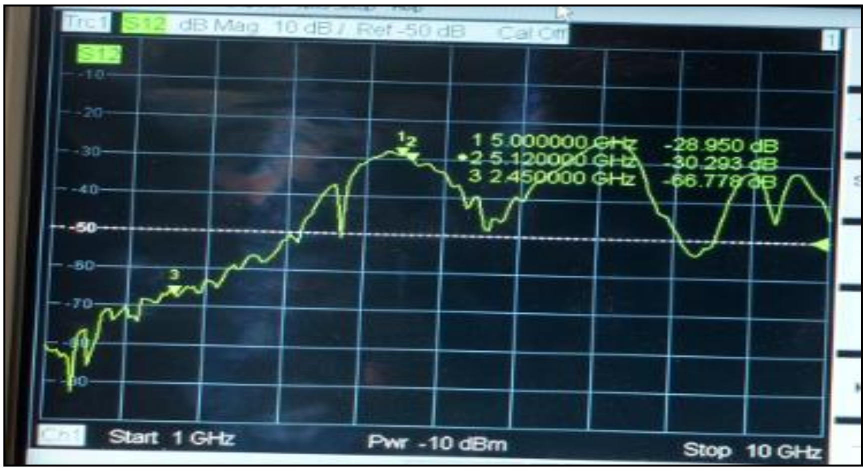

Figure 17 . Mutual coupling for DSCSRR structure in ground

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Table 2: Comparative Results of four-port antenna array with DSCSRR

Sr. No.	Parameter	Simulation Results	Measured Results
1	S parameter (Return Loss)	-22.9 dB	-19.72 dB
2	Mutual coupling/Isolation	-36.23 dB	-30.29 dB

Table 3: Comparison with other techniques and structures

Paper	Decoupling Structure	Number of layers	Plane of structure	Maximum Mutual Coupling reduction
1	PCI and DGS	1	Patch	-22.3 dB
2	MPR wall	multiple	Perpendicular to patch	-8dB to -14 dB
5	slits	1	ground	-10dB
6	Shape modification	1	NA	-10 to -15 dB
8	Circular CSRR	1	Patch	-14 dB
9	GCLL	multiple	Perpendicular to patch	-7.15dB
11	line resonators	multiple	patch	-12dB
12	SCSRR	1	ground	-10 dB
This paper	DSCSRR	1	ground	-36.23dB

5 . Conclusion

Addition of periodic structures in antenna reduces mutual coupling from -20.44 dB to -36.23dB without affecting other parameters like impedance matching, return loss and gain. Double Slit Complementary Split Ring Resonator structure is more efficient than simple Split Ring Resonator in suppressing surface waves as evident from reduced mutual coupling from -27.4 dB to -36.23dB . Hence it can be fairly concluded that resonating structures, generally used to actively radiate or cancel interfering frequencies can be reduce mutual coupling between elements of array antenna. These structures are etched out of ground material hence no additional cost or space is required. This paper only discusses about 4 element i.e. 2 X 2 array. Further investigations can be made with higher order arrays to verify proposed theory.

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