Mutual Coupling Reduction in MIMO Patch Antenna Array Using Complementary Split Ring Resonators Defected Ground Structure

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Abstract ─ In this paper, complementary split ring resonators (CSRRs) defected ground structure (DGS) is introduced to suppress surface waves and to reduce the mutual coupling between E-plane coupled two elements of a microstrip patch MIMO antenna array. The CSRRs-DGS is easily etched on the ground plane between the array elements. The CSRRs-based DGS acts as a bandstop filter between the array elements and operates in the same desired frequency band of the array at 9.2 GHz. Significant reduction of the electromagnetic (EM) mutual coupling is achieved between array elements with a reduced edge-to-edge spacing of 7.5 mm (0.22 λo). Experimental results show that more than 30 dB isolation between the array elements is obtained using an array of CSRR-based DGS. Moreover, the antenna array parameters are successfully optimized with a numerical experimentation technique using a 3D full-wave EM simulator. The design of the proposed array is fabricated and measured for verification purposes. The proposed design has been simulated and validated experimentally. Good agreement is found between the simulated and the measured data.

Index Terms ─ Bandstop filter, CSRRs (complementary split ring resonators), DGS (defected ground structure), mutual coupling, surface waves.

I. INTRODUCTION

In recent years, isolation enhancement in antenna array applications poses a strong challenge in the antenna community [1,2]. The mutual coupling or isolation between closely placed antenna elements is important in a number of applications. These include systems depending on array antennas and more recently multiple-input–multiple-output (MIMO) wireless communication systems [3,4]. Surface waves cause many disadvantages for microstrip antennas such as a mutual coupling effect between elements on an antenna array, which exists whenever the substrate has a dielectric permittivity greater than one ($\varepsilon_r > 1$). In an antenna array, the mutual coupling effect will deteriorate the radiation properties of the array. To achieve low mutual coupling between closely spaced antenna elements and to suppress surface waves, several studies have been conducted including defected ground structure (DGS) [5-10]. This idea can be extended to a specific application like reducing scan blindness in microstrip arrays. Many shapes and configurations of DGS have been studied such as rectangular slots [5,6], circle [7], dumbbells [8], polygonal [9], and inter-digital capacitor [10]. Each DGS shape can be represented as an equivalent circuit model consisting of an inductance and a capacitance, which leads to a certain frequency band gap determined by the shape, dimension and position of the defect [7]. DGS gives an extra degree of freedom in microwave circuit design and can be used for a wide range of applications.

Recently, a pioneer research of the complementary split ring resonator (CSRR) has been proposed [11]. It can be derived from the split ring resonator (SRR) structure in a straightforward way by using the concepts of duality and complementariness. This CSRR structure provides a negative effective permittivity [12]. Because of their small size, CSRRs are called sub-lambda structures. Due to this fact, a super-compact reject band structure can be implemented using CSRRs. The CSRRs are etched in the ground plane or the conductor line of planar transmission structures, such as a microstrip line or a coplanar waveguide (CPW), and provide a negative

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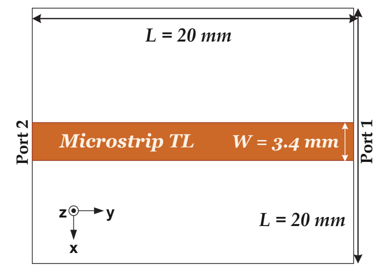
effective permittivity to the dielectric media [13]. The electromagnetic (EM) behaviors of the CSRRs are similar to those of the electromagnetic bandgap (EBG) structures [14,15]. However, it is difficult to design the dimension and to find the equivalent circuits of EBG. Although EBG structures, DGS and CSRR can provide the similar stop-band characteristics, it may be worth pointing out the attenuation property of the CSRR which is better than EBG structures and other DGS shapes. It seems to be good in cognitive radio (CR) systems to reduce the mutual coupling between the sensing antenna and communication antenna in cognitive radio MIMO applications using a simple technique [16].

In this paper, simple designs of bandstop filter using CSRRs-based DGS are proposed to suppress surface waves and to reduce the mutual coupling effect between E-plane coupled antenna array elements [17,18]. The designed microstrip antenna arrays operate at the X-band (9.2 GHz). Usually, the array elements are susceptible to strong mutual coupling due to the surface wave, space wave and near field overlapping. The coupling is stronger in E-plane coupled antennas than in H-plane coupled antennas. Thus, the mutual coupling effect in the E-plane direction is mainly investigated in this work. The CSRRs are etched in the ground plane and occupy a small area allowing for small antenna separation in their use with compact ground planes. Moreover, the radiation properties of the proposed antenna array are also observed and discussed. Simulations results based on a 3D full-wave EM simulator and measurements are presented. In Section II, the structure of the bandstop filter is discussed. Section III presents and illustrates the proposed array design. Section IV is devoted to the comparison of the simulated and measured results.

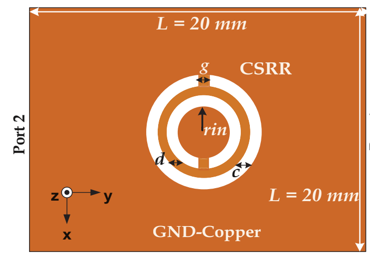
II. CSRR-DGS BANDSTOP FILTER DESIGN

Figure 1 shows the top and bottom 2-D views of the single CSRR-DGS geometry. The CSRR structure is designed to operate at stopband of 9.2 GHz in the same desired band of the antenna array. The dimensions of the CSRR structure are r_{in} = 0.75 mm, and $c = g = d$ = 0.4 mm. The ground plane dimensions are 20×20 mm^2. The substrate is Rogers Ro 3003 with a thickness of t = 1.524 mm, dielectric constant of 3 and loss tangent of 0.0013. The CSRR structure is etched in the ground plane below the center of the microstrip line, which has a width of 3.4 mm. The width of the microstrip line is designed to match the characteristic impedance of 50 Ω. Figure 1 (c) shows the simulated |S|-parameters of the single CSRR. The presented bandstop filter was optimized through simulations using a commercial 3D full-wave analysis software package computer simulation technology (CST) [19].

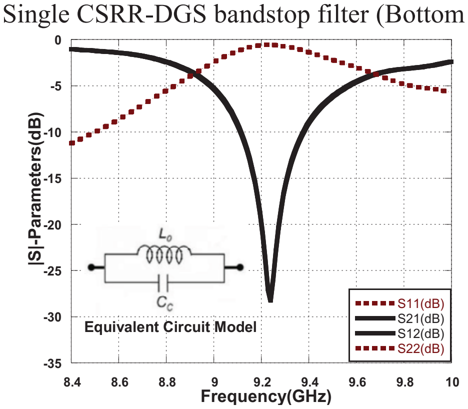
The simulation results show a reject band characteristic at the transmission zero frequency of 9.24 GHz as shown in Fig. 1 (c). Using only a single CSRR structure in the ground plane, we can obtain a wide stop band response with a high rejection level which is difficult to achieve with conventional microstrip resonators.



(a) Single CSRR-DGS bandstop filter (Top view)



(b) Single CSRR-DGS bandstop filter (Bottom view)



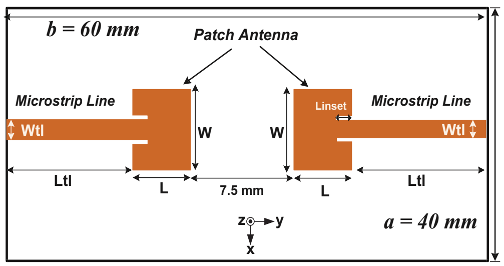
(c) Simulated |S| prameters

Fig. 1. Schematic of the optimized CSRR-DGS bandstop filter and |S|-parameters results.

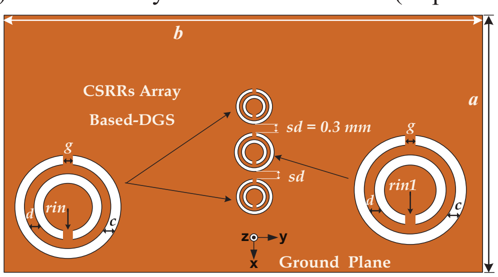
III. PROPOSED MICROSTRIP PATCH ANTENNA ARRAY WITH CSRRs-DGS

The proposed geometry of the antenna array with CSRRs-based DGS and |S|-parameters are shown in Fig. 2. The rectangular patch has dimensions W = 11 mm, and L = 8.7 mm, whereas the feeding microstrip has length L_{tl} = 17.5 mm and width W_{tl} = 3.4 mm which ensure a 50 Ω characteristic impedance. The inset length is L_{inset} = 3.8 mm which in essence provides the necessary impedance matching. The substrate used for this array is the same as that used for the bandstop filter design in Section II. The spacing between the elements is chosen to be 7.5 mm (0.22 λo). The CSRR structures are designed to operate at the transmission zero frequency in the same band of the antenna array. The chosen dimensions of the

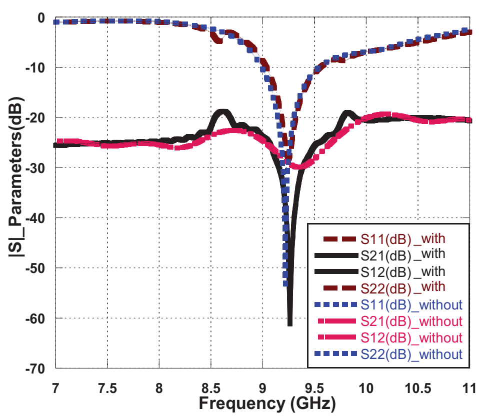
CSRR structures for this frequency of operation are $r_{in} = 0.65$ mm, $r_{in1} = 0.8$ mm, and $c = g = d = 0.4$ mm, respectively after intensive optimization and co-design for the array with the CSRRs-DGS. The bandstop filter affects significantly the array mutual coupling and the isolation between the two elements [17]. However, the proposed design with CSRRs has a very small deviation in the resonant frequency about 0.3% (29 MHz) compared to the conventional array due to the presence of the CSRRs DGS in the ground plane. The proposed configuration produces a mutual coupling about -61 dB better than the conventional array with the same dimensions through simulations as shown in Fig. 2 (c). The total dimensions of the array are $a = 40$ mm and $b = 60$ mm.



(a) Antenna array with 3 CSRRs-DGS (Top view)



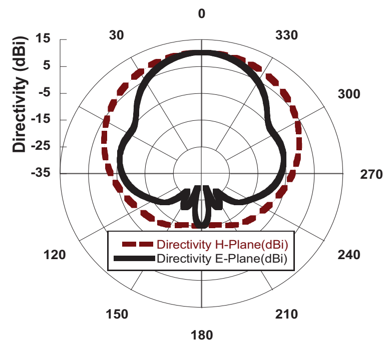
(b) Antenna array with 3 CSRRs-DGS (Bottom view)



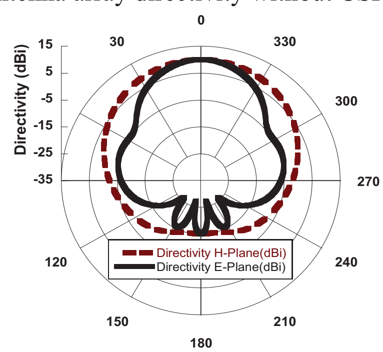
(c) Simulated |S|-parameters of the antenna array

Fig. 2. Antenna array configurations and simulated |S|-parameters with and without CSRRs-DGS.

Figure 3 contains the radiation pattern results of the proposed antenna array with and without 3-CSRRs. It is obvious that the radiation patterns in the E (yz-plane) and H (xz-palne) planes are stable over the operating frequency band. In addition the radiation pattern results show that there is a slight decrease in the main lobe due to the presence of the CSRRs-based DGS, which is acceptable compared to the obtained significant isolation and mutual coupling reduction.



(a) Antenna array directivity without CSRRs-DGS



(b) Antenna array directivity with 3 CSRRs-DGS

Fig. 3. Optimized antenna array radiation pattern results with and without 3 CSRRs-DGS at 9.22 GHz.

Table 1 contains summary of the simulation results of the proposed array with single, two, and three CSRRs-DGS and compared with the conventional array. The coupling reduction has been achieved by optimally positioning the array of two and three CSRRs-DGS between the antenna array elements. It is obvious from Table 1 that the proposed arrays have a significant and a good isolation than the array without CSRRs-DGS where about 33 dB reduction is achieved using an array of three CSRRs-DGS with a less edge-to-edge spacing [20], thus leading to the design of compact MIMO antenna arrays. In addition to this, using more than three CSRRs will not provide better isolation due to the internally mutual coupling between the CSRRs that will change the resonant frequency of the bandstop filter.

Table 2 shows a comparison for different approaches and configurations that were reported and implemented to reduce the mutual coupling. The proposed array exhibits a better isolation and compact size compared to Ref. [10] and Ref. [20] in terms of nearly the same edge-to-edge separation. Compared to other techniques, the proposed array has a significant improvement in the isolation.

Table 1: Performance comparison of the proposed antenna arrays with the conventional

Antenna Structure	Results			
	Mutual Coupling (dB)	Improvement (dB)	Directivity (dBi)	Realized Gain (dB)
Conventional	-28	-	10.23	10.2
Proposed array with CSRR-DGS	-38	10	9.67	9.37
Proposed array with 2 CSRRs-DGS	-42	14	9.7	9.4
Proposed array with 3 CSRRs-DGS	-61	33	10	9.87

Table 2: Performance comparison of the proposed antenna array with other approaches in the literature

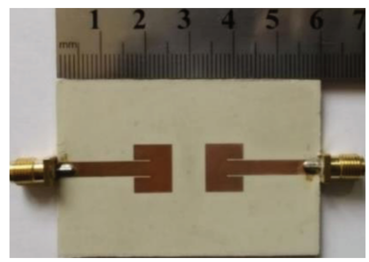
Ref. No.	Approach	Size of the Array in mm^2	Improvement (dB)	Edge-to-Edge Spacing
[4]	Meta-material	300×300	20	0.125 λo (30 mm)
[5]	High order DGS filter	75×50	20	0.2 λo (10.4 mm)
[8]	Dumbbell DGS	140×100	6.19	0.5 λo (18.8 mm)
[10]	Inter-digital DGS capacitor	60×50	17	0.25 λo (9.5 mm)
[14]	Uniplanar-EBG	78.3×78.3	10	0.5 λo (26 mm)
[20]	Slotted CSRR	78×60	10	0.25 λo (15 mm)
Proposed	CSRR DGS	60×40	33	0.22 λo (7.5 mm)

IV. EXPERIMENTAL RESULTS AND DISCUSSION

The proposed antenna array has been fabricated and measured to validate experimentally the approach to achieve a significant isolation and mutual coupling reduction. The photographs of the top and bottom layers of fabricated antenna array with CSRRs-based DGS are shown in Fig. 4. The |S| parameters measurements were carried out using the Agilent N5227A PNA vector network analyzer and the calibration was done with the Agilent N4691B-Ecal module in the RF and microwave laboratory at E-JUST. While the pattern measurements were done at Kyushu University. The Experimental results show a significant reduction in the mutual coupling of 30 dB between the array elements.

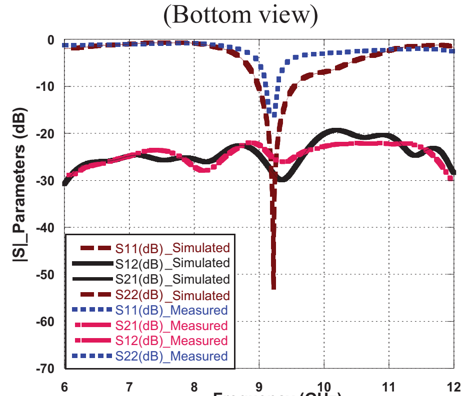
The fabricated antenna array provides a measured mutual coupling of -24 dB and -54 dB at the center frequency of 9.22 GHz for the array with and without CSRRs as shown in Figs. 4 (c), and (d), respectively. In addition, there is a very slight and tolerable shift between the simulated and measured resonant frequencies is found due to the fabrication tolerance. Furthermore, a good agreement between the resonant frequency and the bandstop frequency is observed for the array with and without the CSRRs-DGS.

The measured and simulated normalized radiation patterns of one side element of the proposed antenna array with and without CSRRs-DGS at 9.22 GHz in the E and H-planes are presented in Fig. 5. While the other array element is terminated with a 50 Ω load. Obviously, these results do not show any significant difference between the main lobes patterns. As shown in the plots, the applied technique using CSRRs-DGS has a minor effect on the radiation pattern. Moreover, an excellent agreement is observed.

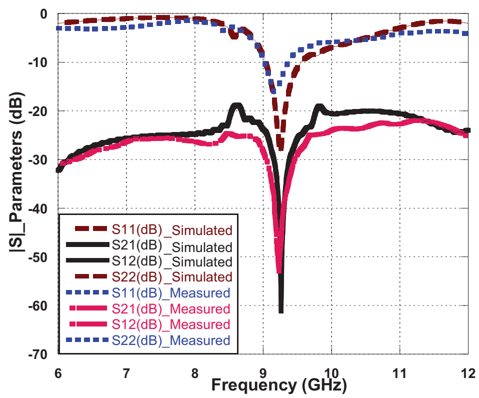


(a) Photograph of the fabricated antenna array (Top view)

(b) Photograph of the fabricated antenna array (Bottom view)

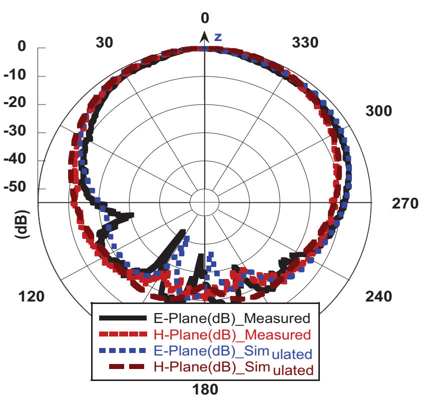


(c) Measured and simulated |S| parameters of the conventional array without CSRRs-DGS

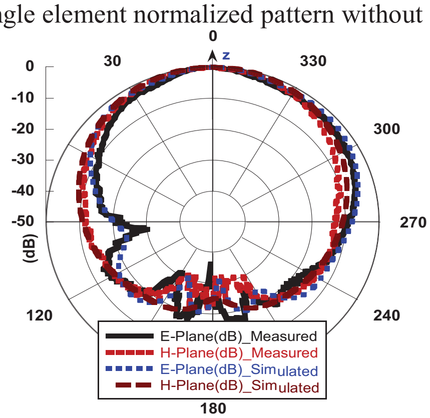


(d) Measured and simulated |S| parameters of the proposed array with 3 CSRRs-DGS

Fig. 4. Photograph of the fabricated array, simulated and measured |S| parameters without and with CSRRs-DGS.



(a) Single element normalized pattern without CSRRs



(b) Single element normalized pattern with 3 CSRRs

Fig. 5. Measured and simulated E and H-planes radiation patterns for single element of the proposed array with and without CSRRs-DGS at 9.22 GHz.

V. CONCLUSION

In this paper, a design of compact antenna array with low mutual coupling has been presented, fabricated and measured for the validation purposes. The approach for isolation improvement is proposed by inserting a bandstop filter composed of an array of three CSRRs-based DGS between the two elements antenna array. In this simple design, the isolation has been significantly improved and the experimental results show that the proposed antenna array can improve the isolation between array elements by 30 dB. Furthermore, the measured radiation patterns are stable over the operating frequency band with and without the CSRRs. The measured and simulation results are in a good agreement. Thus, the proposed antenna array with this better isolation is suitable for MIMO communications.

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