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A MIMO Dielectric Resonator Antenna in single DRA Element with Reduce Mutual Coupling

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Abstract

16 A multiple input multiple output (MIMO) dielectric resonator antenna
(DRA) 32 reduced mutual coupling is presented in the paper. The
antenna resonates at dual frequencies of 4.91 GHz and 6.5 GHz with
a coupling of less than -35 dB. Unlike other DRA MIMO antennas,
the design proposed in this work implements a single DRA to cover
both antenna elements. The mutual coupling compensation is done
using a DRA with a Z-shaped hole at the 9 bottom of the DRA. Two
slots were etched on the ground plane for impedance matching of the
antenna. Analysis of the optimization of the DRA structure is pre-
sented with each of the findings presented in detail. A comparison

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of the energy density of the proposed DRA structure with a conventional DR structure indicates that introducing a Z-shaped hole inside the DRA reduces the coupling between the antenna elements. MIMO antenna performances such as envelope correlation coefficient, diversity gain, channel capacity and total active reflection were presented with all values that are justifiable for MIMO applications. The proposed DRA show an ideal DRA MIMO antenna with a less complicated design.

Keywords: Antenna and propagation, Dielectric Resonator Antenna, MIMO, Mutual coupling.

1 Introduction

Multiple Input Multiple Output (MIMO) antenna technologies have been considerably improving the efficiency of communication systems, particularly in enhancing the channel capacity and signal transmission rate [1, 2]. In a MIMO system, multiple antennas are used. The distance between antennas becomes a great concern as an antenna's radiation will interfere with the adjacent antenna, which may deteriorate the antenna performance. The interaction between antenna elements is measured by mutual coupling. Due to the space-constrained and compactness of current devices, the antennas should be placed as closely as possible.

Numerous approaches have been developed to eradicate the mutual coupling impact for a closed-spaced MIMO antenna, such as slot and parasitic elements [3–5], EBG structure [6, 7], complementary split ring resonators [8, 9], neutralization line [10, 11], and defected ground structure [12]. Together with mentioned techniques, adding extra structure to the antenna, for example, metamaterials and dielectric resonators, are other alternative methods used to minimize the effect of mutual coupling with additional benefits such as wide bandwidth and high gain. All these methods manipulate the coupling by blocking or minimizing the current flow between adjacent elements.

Dielectric resonator antenna has become one of the popular methods owing to its high gain, low loss, large impedance bandwidth [13], easily integrated with printed board [14], and flexibility excitation schemes ¹⁵ such as microstrip feed lines, coaxial feed probes, aperture coupling, proximity feed, and co-planar waveguides [1, 15–17]. Therefore, extensive research on the dielectric resonator antenna (DRA) MIMO antenna has been published, focusing on mutual coupling reduction [1, 13, 16, 18–24]. A few methods adopted from previous studies on the reduction of mutual coupling for DRA MIMO system were metamaterial polarization-rotator wall [18], metasurface shield [22], modified DRA shaped [13, 24], metallic vias and strips [16, 21], varying the DRA excitation mode [1] and dielectric superstrate [19].

These proposed approaches may reduce the mutual coupling. However, the additional complexity in the design and decoupling of structures yield hassle and increase the design process. Most of the MIMO DRA needs two (2) or more DRA structures [1, 15–17, 23–26], which contribute the extra structure and cost to the antenna.

In this proposed work, a 1×2 DRA MIMO is presented using a single DRA structure. A slot inside the DRA is introduced ³⁵ to reduce the mutual coupling while wider ¹⁹ the impedance bandwidth of the antenna. The paper is organized as follows. Section 2 outlines the antenna geometry. Antenna design and optimization ²⁶ with simulation results are discussed in Section 3, while a comparison of the simulated and measured results is presented in Section 4. MIMO antenna performances are explained in Section 5 prior to the conclusion in Section 6.

2 Antenna Geometry

Figure 1 shows the proposed square DRA with dielectric constant $\epsilon_r = 10$ placed on the center of a 100×100 mm ground plane. The antenna is modeled using the CST Microwave Studio. The Rogers RT5870 with $\epsilon_r = 2.33$ is used as the substrate, where the antenna is fed by two rectangular patches. The edge-to-edge of the patch is at 0.18λ . A rectangular-shaped slot is created on the ground plane right under the DR element. In addition, the Z-shaped hole is made on the DR to lessen the coupling effect between the Multiple Input Multiple Output (MIMO) port. Based on the intensive parametric analysis, the optimized design dimension is tabulated in Table 1.

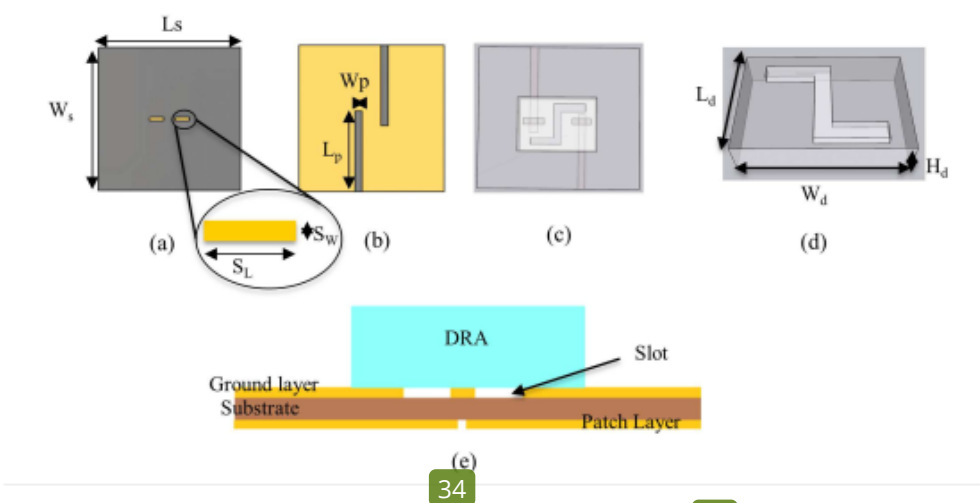


Fig. 1 The proposed DRA antenna. (a) bottom view, (b) side view, (c) top view with transparent DRA, (d) bottom view of DRA and (e) side view of the antenna.

Table 1 The proposed DRA antenna parameters

Parameter	Parameter detail	Size in mm
$L_s \times W_s$	Substrate length $\times$ width	100×100
$L_p \times W_s$	Patch length $\times$ width	53×4.99
H	Substrate thickness	1.57
T	Patch thickness	0.035
$L_d \times W_d$	DRA length $\times$ width	44×44
H_d	DRA height	17
Slot ($S_L \times S_W$)	Slot length $\times$ width	10×2

3 Antenna Design and Optimization

In this section, the antenna design and optimization procedures are discussed in detail. The performance of the DRA excited by a rectangular patch with and without a DR slot is explained and compared. In the proposed design, a Multiple Input Multiple Output (MIMO) antenna is designed with a single dielectric resonator structure. The slots are calculated using Equation 1 and Equation 3, where the slots are located in the center of the ground plane with a gap of 0.18λ .

$$S_L = \frac{0.4\lambda_0}{\sqrt{\epsilon_{\text{eff}}}} \quad (1)$$

where ϵ_r is the effective permittivity calculated using permittivity of DRA (ϵ_r) and substrate (ϵ_s),

$$\epsilon_{\text{eff}} = \frac{\epsilon_r + \epsilon_s}{2} \quad (2)$$

$$S_w = 0.2 \times S_L \quad (3)$$

The length and width of the slots are calculated at λ_0 of 61.86 mm with DRA and substrate permittivity of 10 and 2.33. The calculated value of S_w is 2 mm, S_L is 9.96 mm, and after optimization, the value of S_L is 10 mm. For all designs, the shape and size are kept the same, with alteration done on the bottom of the DRA.

3.1 Unslotted DR Antenna (DRA1)

The square solid DRA is placed on top of the ground plane with two slots etched on the ground plane, as shown in Figure 2. In this initial design, the two slots of $10 \times 2 \text{ mm}^2$ were etched on the ground plane to assist the flow of current to the DRA. This resulted in the antenna resonating at 4.87 GHz and 6.51 GHz, with -11 dB and -15.6 dB return loss, as depicted in Figure 4(a).

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However, -11 dB and -6 dB of S_{21} can be observed at both lower and upper frequencies, showing that stronger coupling between the patch elements.

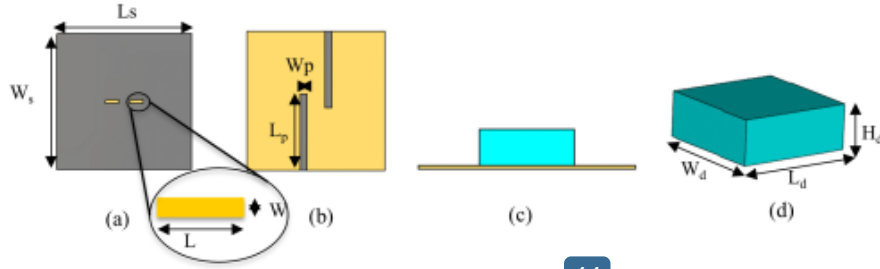


Fig. 2 The DRA1 (a) bottom view (ground plane,) (b) front view (patch layer), (c) side view and (d) DRA perspective view.

3.2 Rectangular slot on DR Antenna (DRA2)

The DRA1 is optimized by proposing a rectangular hole etched at the bottom of the square DRA (DRA2) while keeping the same ground plane and patch structure from DRA1, depicted in Figure 3(b). The hole size dimension is $7 \times 5 \times 15 \text{ mm}^3$. This improves the S_{11} and reduces the mutual coupling at a lower frequency, as shown in Figure 4(a). The percentage bandwidth is increased up to 11.3, where the antenna resonates from 4.66 GHz to 5.12 GHz. The S_{21} also decrease to -15.5 dB showing a better mutual coupling from the DRA1, shown in Figure 4(b).

3.3 Z-shaped slot DR Antenna (DRA3)

The DRA2 is further optimized by introducing a Z-shaped hole etched at the bottom of the square DRA (DRA3) while keeping the same ground plane and patch structure from DRA1, as shown in Figure 3(c). The Z-shaped is in the middle DRA with a size of $37 \times 30 \times 15 \text{ mm}^3$. Significant improvement can be observed in the S_{11} and S_{21} , as shown in Figure 4. A 3.6% and 1.53% increase in percentage bandwidth with a deeper S_{11} at both lower and upper

resonating frequencies is noted in DRA3 result. On top of that, ⁴the mutual coupling is reduced to -38.5 dB and -37.5 dB compared to -11 dB in DRA1 and -15 dB for DRA2. The excitation mode of DRA is typically done using a slot on the ground plane, which is also being implemented in the proposed design. Moreover, a hole inside the DRA is introduced to elevate ¹⁰the isolation between the antenna elements using a single DRA. ⁹The improvement of the result is depicted in Figure 4, where the better performance of DRA2 can be observed compared to DRA1. A greater output is captured when a Z-structure hole is proposed in DRA3 as better impedance matching and wider bandwidth is achieved. The performances of the antenna are summarized in Table 2.

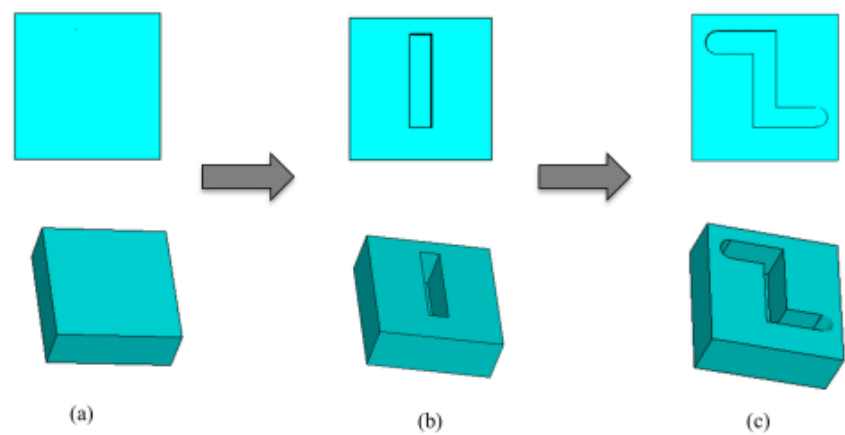


Fig. 3 Optimization of the DRA structure (a) DRA1 (b) DRA2 (c) DRA3.

Table 2 Performance comparison for different stages of DRA

Design	DRA1	DRA2	DRA3
Lower f_c (GHz)	4.87	5.01	4.91
S_{11} (dB)	-11	-26	-20.7
% lower BW	2.67	11.3	6.27
Lower $f_{\min} - f_{\max}$ (GHz)	4.80 – 4.93	4.66 – 5.12	4.68 – 4.98
S_{21} (dB)	-11.0	-15	-38.5
Upper f_c (GHz)	6.51	-	6.51
S_{11} (dB)	-15.6	-	-16.7
% upper BW	0.31	-	1.84
Upper $f_{\min} - f_{\max}$ (GHz)	6.50 -6.52	-	6.43 – 6.55
S_{21} (dB)	-6	-	-37.5

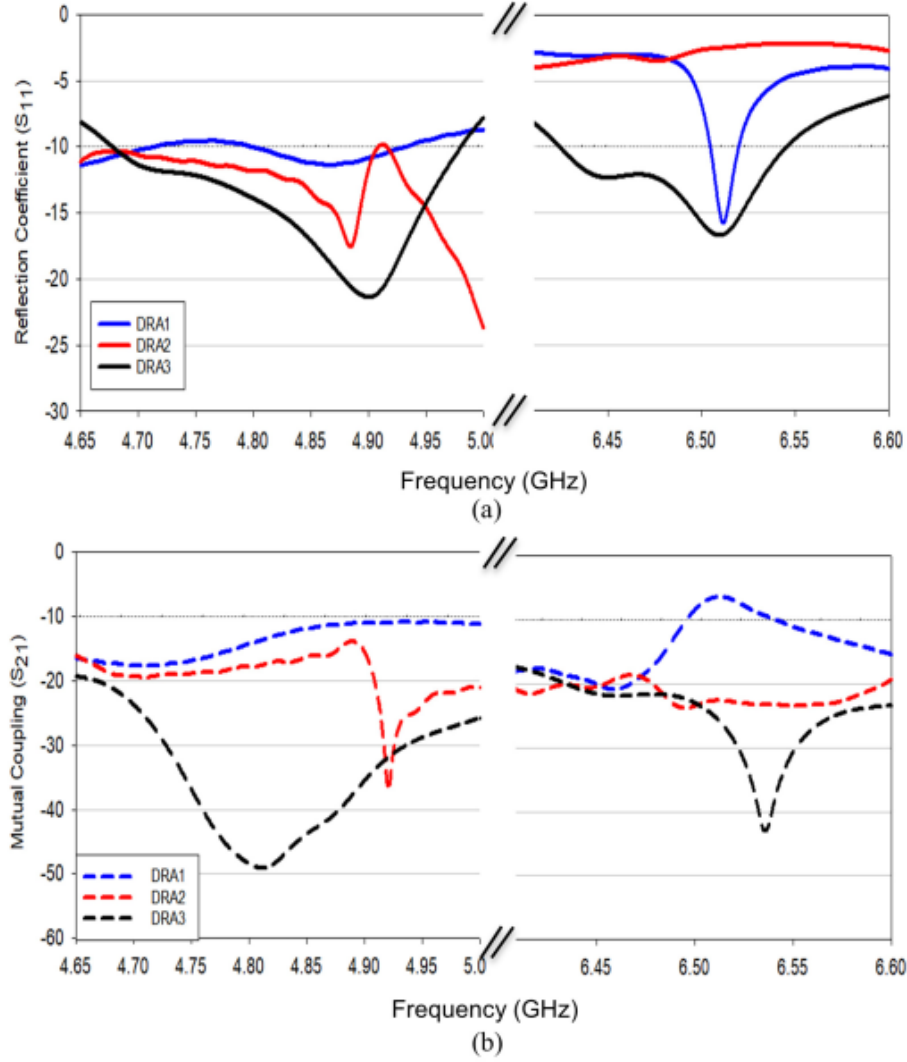


Fig. 4 S -parameter comparison (a) Reflection Coefficient (S_{11}) (b) Mutual Coupling (S_{21}).

Additionally, the achieved mutual coupling shown in Figure 4 is fortified by the given electrical energy density given in Figure 5. Here, Figure 5(a) shows a strong coupling between patch 1 and patch 2 when the patch is excited. Conversely, different energy densities can be observed in the proposed DRA3, where the introduction of a Z-hole inside the DR structure isolates the electromagnetic wave flow on the antenna elements, as shown in Figure 5(b). Note that the air gap inside the DR structure segregates the radiated wave from different ports. The magnetic (H-field) distributions show the higher-order modes $TE_{3\delta 1}^y$ and $TE_{5\delta 1}^y$ at both lower and upper frequencies, depicted in Figure 6.

The higher order modes help broaden the antenna’s impedance bandwidth and directivity [27]. Apart from that, the 3D radiation pattern of the proposed antenna is shown in Figure 7, where the simulated gain is 7.34 dBi and 7.26 dBi at its resonating frequencies of 4.9 GHz and 6.5 GHz.

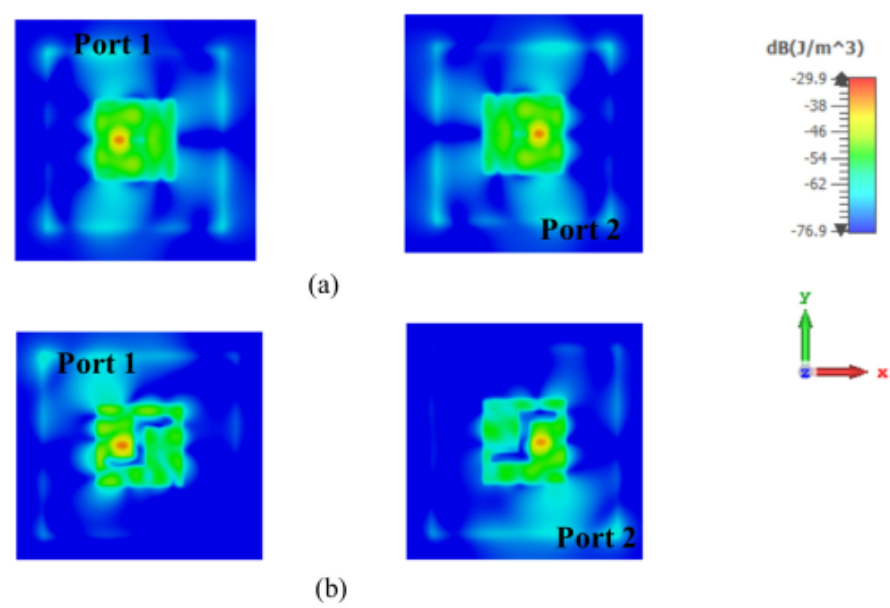


Fig. 5 Electrical energy density for (a) DRA1 and (b) DRA3.

4 Simulation and Measurement Result

Based on the parameters given in Table 1, the proposed 1×2 Multiple Input Multiple Output (MIMO) DR antenna is fabricated and measured to validate the simulated result. The prototype is manufactured by etching the Rogers board with relative permittivity of 2.2, a thickness of 1.57 mm with a loss tangent of 0.001. A Z-shaped hole is etched at the bottom of DR with a depth of 15 mm. The photographs of the prototype are shown in Figure 8. On the other hand, Figure 9 shows photographs of the measurement for the proposed DRA. *S*-parameters were measured using a dual port vector network analyzer

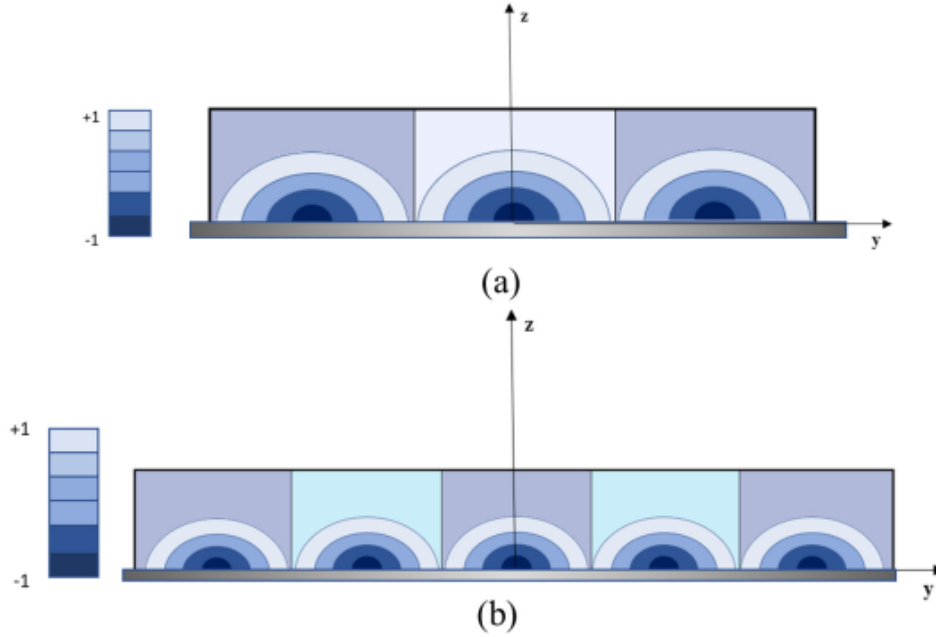


Fig. 6 TE mode of the DRA3 at (a) 4.9 GHz, $TE_{3\delta 1}^y$ and (b) 6.5 GHz, $TE_{5\delta 1}^y$.

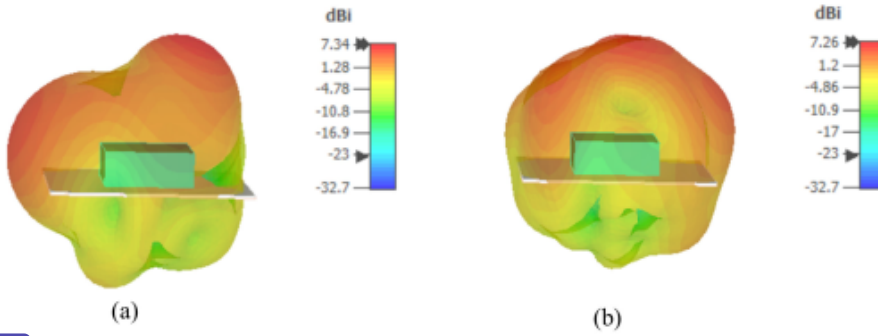


Fig. 7 Radiation Pattern of the proposed DRA antenna at (a) 4.9 GHz and (b) 6.5 GHz.

(VNA) as in Figure 9(a), while the measurement in the chamber was carried out to measure the prototype's radiation pattern, shown in Figure 9(b).

A good agreement between the simulated and measured radiation patterns has been observed for both S -parameters and the pattern of the proposed DRA. As can be seen in Figure 10, the measured S_{11} shifted to 0.02 GHz, where it resonates at 4.88 GHz, while 4.9 GHz in simulation. The operating range changed from 4.75 to 5.03 GHz compared to 4.68 to 4.98 GHz in simulation, with a measured bandwidth (BW) of 7% less than simulated. For good measure, the mutual couplings are about the same at 4.9 GHz, which is

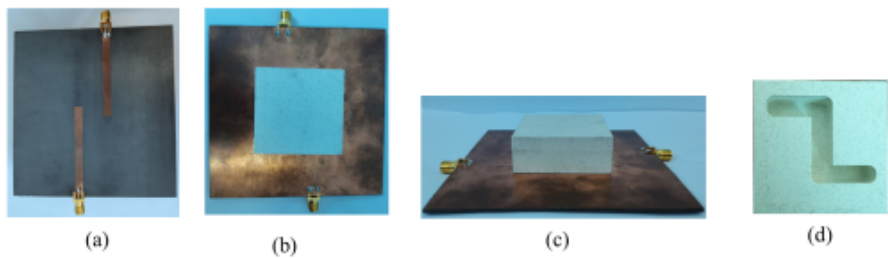


Fig. 8 Fabricated DRA, (a) front view (patch), (b) bottom view (ground), (c) side view and (d) bottom view of DRA.

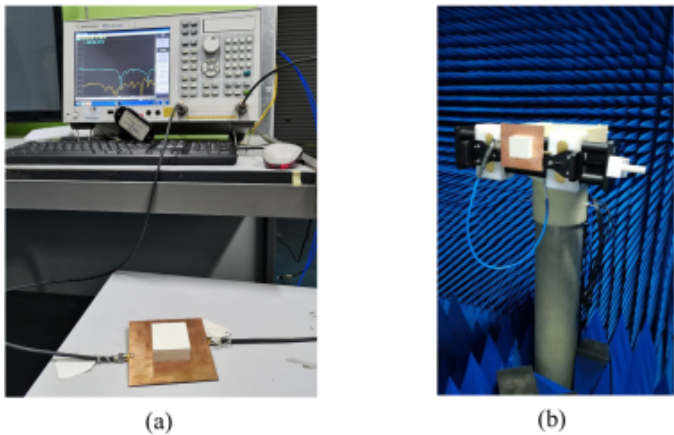


Fig. 9 Measurement of the Proposed DRA (DRA3), (a) s-parameter measurement and (b) radiation pattern measurement in an anechoic chamber.

-38.5 dB. The reasonable agreement can be seen in the proposed DRA’s measured and simulated 2D radiation patterns, which indicate an omnidirectional pattern at 4.9 GHz. In contrast, a more directional pattern can be seen at a higher frequency, as illustrated in Figure 11.

5 MIMO antenna performance

The diversity parameters of the proposed Multiple Input Multiple Output (MIMO) antenna are evaluated to validate the MIMO performance. The parameters such as the envelope correlation coefficient (ECC), diversity gain (DG), channel capacity loss (CCL) and the total active reflection coefficient (TARC). To obtain a MIMO with high channel capacity, the MIMO should have low correlation characteristics.

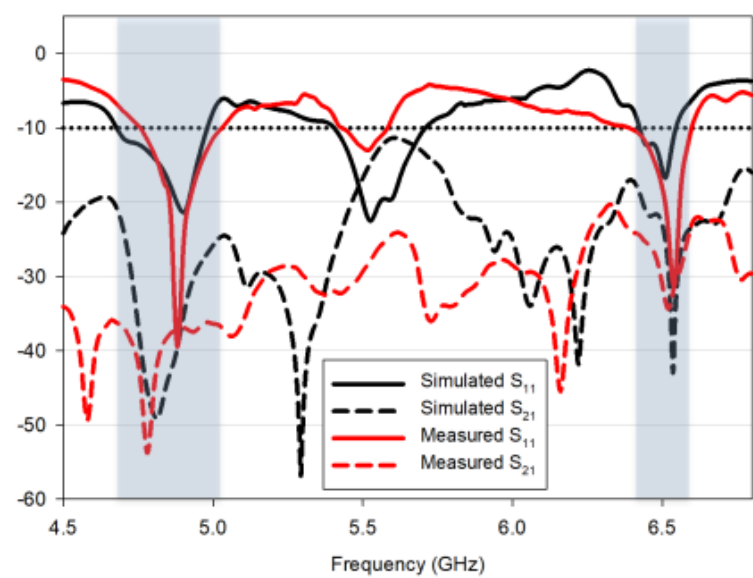


Fig. 10 Simulated and measured S-parameter results.

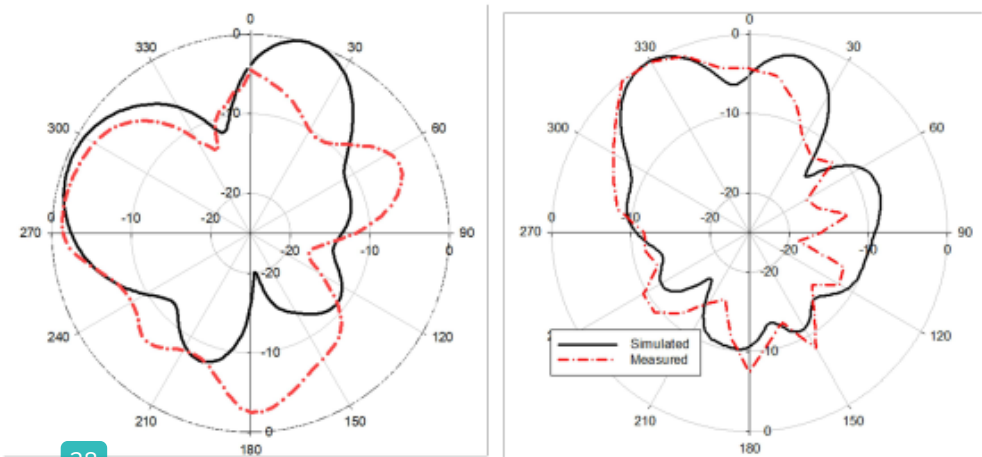


Fig. 11 Simulated and measured radiation pattern at (a) 4.9 GHz and (b) 6.5 GHz.

5.1 Envelope Correlation Coefficient and Diversity Gain

The correlation between antenna elements is described by the ECC (ρ_e) and the DG. They are used to evaluate the correlation levels of the channels [29]

and are calculated using Equation 4, as follows:

$$\rho_e = \frac{\left| \iint \vec{E}_i(\theta, \phi) \vec{E}_j(\theta, \phi) d\Omega \right|^2}{\iint |\vec{E}_i(\theta, \phi)|^2 d\Omega \iint |\vec{E}_j(\theta, \phi)|^2 d\Omega} \quad (4)$$

Minimal correlation between antenna elements is indicated by the low value of ECC. Ideal case, the value of ECC should be 0, indicating uncorrelated antenna elements. However, in practice, the $ECC < 0.5$ is acceptable. This low ECC leads to high diversity gain (DG). Meanwhile, the DG measures the dependency of a spatial correlation coefficient between the patch elements. The ECC and DG are related by equation 5, as follows:

$$DG = 10\sqrt{1 - \rho_e^2} \quad (5)$$

Figure 12 shows the simulated and measured ECC and DG of the proposed DRA. The ECC for both simulated and measured showed are < 0.01 , showing a good decoupling of MIMO structure. In addition, convincing results on DG values of above 9.9 dB in the simulated and measured reading verified the positive side of MIMO characteristics.

5.2 Channel Capacity Loss and Total Active Reflection Coefficient

Alternatively, CCL is the maximum expected message transmission, which can take place without any loss in the communication channel. Therefore, the acceptable rate should be less than 0.4 bits/s/Hz. CCL can be calculated using S -parameter values as in Equations 6 to 8, and the result is presented in Figure 13(a). Apart from that, it is observed that the proposed MIMO exhibits

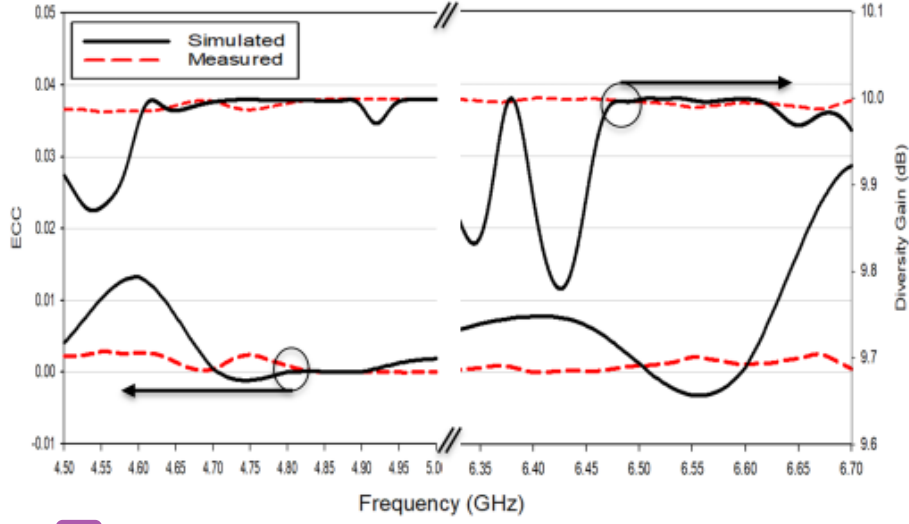


Fig. 12 Simulated and measured ECC and diversity gain of the proposed DRA.

acceptable CCL at the respective operating frequency.

$$CCL = -\log_2 \det(\alpha) \quad (6)$$

where

$$\alpha = \begin{pmatrix} \alpha_{11} & \alpha_{12} \\ \alpha_{21} & \alpha_{22} \end{pmatrix} \quad (7)$$

and

$$\begin{aligned} \alpha_{ii} &= 1 - \left(\sum_{j=1}^2 |S_{ij}|^2 \right) \\ \alpha_{ij} &= -|S_{ii}^* S_{ij} + S_{ji}^* S_{jj}| \end{aligned} \quad (8)$$

A further evaluated parameter for a MIMO antenna is TARC, defined as the ratio of reflected and incident power for a MIMO antenna system. For a two-port MIMO antenna, TARC is calculated using Equation 9 and must be below -0 dB. Besides, for the proposed MIMO antenna at both operating frequencies,

the TARC are below -10 dB, as seen in Figure 13(b).

$$TARC = \frac{\sqrt{|S_{11} + S_{12}e^{j\theta}|^2 + |S_{21} + S_{22}e^{j\theta}|^2}}{\sqrt{2}} \quad (9)$$

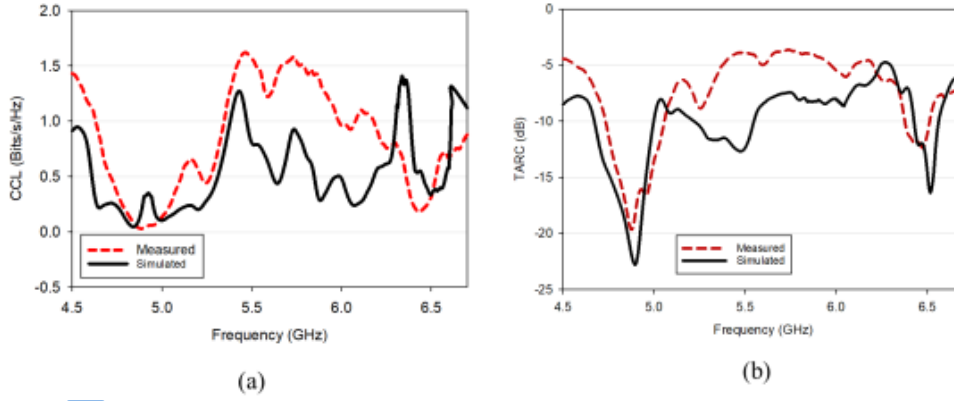


Fig. 13 Simulated and measured (a) channel capacity loss (CCL) and (b) TARC of the proposed DRA.

A comparative study on different approaches to reducing mutual coupling is presented in Table 3. It compares the performance of the proposed antenna against that of previous works by the number of DRA elements, isolation technique, spacing, isolation, gain and impedance BW in percentage. For example, the DRA proposed by [1] and [22] achieved high isolation above 40 dB. However, the design and techniques required to obtain the performance were complex. In contrast, the proposed MIMO DRA attained good isolation of 35 dB by a simple method, without any complicated structure with a single DRA element.

6 Conclusion

In this paper, a multiple input multiple output (MIMO) based on a single DRA element is presented with a new method of mutual coupling compensation.

Table 3 The proposed antenna parameters

Ref	Technique	No of DRA	Frequency (GHz)	Edge to edge (λ)	Impedance BW (%)	Isolation (dB)	Gain (dBi)	Complexity
[1]	Varying excitation Mode	2 rectangular shapes	5.25	NA	10.2	-40	7.8	Medium
[21]	metallic vias, 180° feed	2 rectangular shapes	26	0.07λ	7.7	-22.7	6.3	Low
[16]	metal strips at the DRA edge	2 rectangular shapes	2.4	0.15λ	5.83	-31	5.6	Medium
[22]	Meta-surface shield (SRR array)	2 circular shapes	60	0.5λ (c-c)	9.2	-46	7.9	High
[18]	Meta-material polarization rotator	2 circular shapes	57-64	0.5λ (c-c)	11.7	-22	-	High
[13]	Periodic Defected Ground Structure	2 Maltese-shaped dielectric resonator	3.6-12.6	0.18λ	111	-18	6	High
[24]	Defected Ground Structure	2 Surya Yantra shaped DRA	3.1-9.4	0.18λ	101	-15	4.4	High
Prop	Slot inside DRA	1 with a Z-shaped slot	4.9, 6.5	0.13λ	6.2, 1.84	-35	6.34, 4.39	Low

A rectangular DRA with a Z-shaped hole inside the ¹⁰structure is introduced to isolate the coupling between the antenna elements. Furthermore, analysis done from conventional rectangular DRA structure to Z-shaped hole in DRA strengthens the findings that the introduction of hollow structure to DRA assists on MC reduction with broader impedance matching of the antenna. Observation of the measurement and simulation results show that both design and fabrication structure is a good match.

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