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Isolation Enhancement of Wide-Band MIMO Array Antennas Utilizing Resistive Loading

JUNG-DONG PARK, (Senior Member, IEEE), MUHIBUR RAHMAN, AND HSIANG NERNG CHEN
Division of Electronics and Electrical Engineering, Dongguk University, Seoul 04620, South Korea

Corresponding author: Jung-Dong Park (jdpark@dongguk.edu)

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ABSTRACT In this paper, we propose the use of resistor-loaded paired parallel-coupled resonators (PCRs) for mutual coupling reduction and isolation enhancement in wideband MIMO array antennas. It was shown that the isolation enhancement using a conventional PCR structure was drastically degraded in the middle of the frequency band. By placing an optimally designed resistor between the PCRs, we can improve the isolation considerably, compared with the simple PCR structure. Moreover, it could also improve the diversity parameters, such as envelope correlation coefficient (ECC), diversity gain (DG), and channel capacity loss (CCL). The validity of the proposed resistor-loaded PCR technique was verified with ultra-wideband array antennas with 1×2 and 1×4 patch array configurations, achieving a $0.125\lambda_0$ center-to-center spacing between narrowly spaced patches and isolation better than 25 dB within the range 3–9-GHz without any degradation in its frequency response, radiation patterns, or diversity parameters. The presented results confirm that the proposed technique is suitable in various MIMO systems applicable for wireless local area networks (WLANs), long-term evolution (LTE), and possibly fifth-generation (5G) communication due to the compact size and improved isolation performance.

INDEX TERMS Antenna arrays, multiple-input multiple-output (MIMO), mutual coupling.

I. INTRODUCTION

Multiple-input multiple-output (MIMO) is regarded as an efficient approach for modern telecommunication systems, including wireless local area networks (WLANs), long-term evolution (LTE), and possibly fifth-generation (5G) communication. Recently, there has been an increase in demand for compact MIMO antennas at both mobile terminals and base stations for aesthetic and space-saving reasons [1]. In designing MIMO antennas, mutual coupling reduction is a critical consideration. It is understood that the coupling between two array patches or two wires in a MIMO system depends on their position relative to each other [2].

Numerous techniques have been explored to mitigate mutual coupling. For example, in [3], a dumb-bell shaped defective ground structure (DGS) was proposed, while an electromagnetic bandgap (EBG) structure and a uniplanar compact electromagnetic bandgap (UC-EBG) structure were reported to reduce both antenna size and mutual coupling in [4] and [5], respectively. In addition, slotted combined complementary split ring resonators (SCCSRRs) were placed on the top and the bottom of an antenna to improve isolation with a smaller size in [6]. A waveguide metamaterial (WG-MTM) structure was introduced in [7], while a polarization converter isolator (PCI) was used in [8] to improve cross-polarization performance, and meander line resonators (MLRs) were included to obtain an edge-to-edge spacing of $\lambda/18$ in [9]. Furthermore, a modified meander line slot was implemented in [10] to reduce the mutual coupling between patch array elements designed for WLAN applications. Similarly, ground capacitive loaded loops (GCLLs) and π-shaped resonators were implemented to achieve better isolation within the 3-4 GHz frequency band in [11]. However, it only applies to a very narrow bandwidth (2.64 to 2.68 GHz). However, all of these designs and techniques have been implemented on narrowband antennas.

Recently, a MIMO patch array with two radiating elements and a wide operating frequency range was proposed in [12].

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Mutual coupling was reduced by introducing five parasitic decoupling structures on the rear of the substrate, each with a length of λ/2 at the specific resonance frequency. Due to these resonators, the response of the antenna significantly improved at resonance frequencies, while the frequency response outside of the resonance frequencies remained unaffected. The size issue related to the λ/2 structures was somehow resolved in [13] with the implementation of a novel miniaturized double-layer slit-patch EBG structure for closely spaced patch array elements. Although it offers a simple fabrication process with a compact size, this technique is functional only with the frequency range of 3-6 GHz. Most recently in [21], a wide-band MIMO antenna was designed to reduce mutual coupling between array elements by inserting an inverted F-shaped stub between the array elements, leading to a low envelope correlation coefficient (ECC) and high diversity gain, leading to improved isolation. However, the size of the antenna was comparatively large, and the center-to-center spacing between array elements was almost $1.36\lambda_0$, which would ultimately increase the overall circuit size if applied to higher MIMO configurations such as 1 × 4 or 1 × 8 arrays. It would also generate grating lobes, which arise with spaces larger than $0.5\lambda_0$, in the arrayed beam pattern.

This paper proposes a new technique which efficiently reduces the mutual coupling between two closely spaced MIMO array antennas without degrading its functionality. The coupling between the two array elements can be reduced by introducing a pair of parallel coupled resonators (PCRs). However, doing so degrades the isolation in the middle of the passband and at the resonance frequency of the PCR. To improve the isolat ion of the antenna within the narrow band, we investigated the isolation enhancement of the PCRs by loading a resistor between the resonators, thus improving the overall isolation better than 25dB within the 3–9 GHz frequency range. With this configuration, a smaller center-to-center spacing between the MIMO array elements is achieved compared to [11]. The proposed technique is validated for 1 × 2 and 1 × 4 MIMO patch array configurations. The overall size of the antenna in 1 × 2 configuration is 35mm × 36mm, before and after the isolation enhancement technique. The proposed technique did not increase the size and improve the isolation and antenna diversity parameters within the same circuit size.

The remainder of this paper is organized as follows. Section II describes the configurations and fabricated prototypes of the designed antennas. The proposed decoupling method is discussed and simulation results provided. In Section III, the resistor is optimized for the 1 × 2 and 1 × 4 patch array configurations, while Section IV summarizes the proposed antenna diversity parameters. The measurement of the antenna parameters is performed in Section V, and a comparison of the proposed approach with recent decoupling techniques is discussed in Section VI, followed by a conclusion.

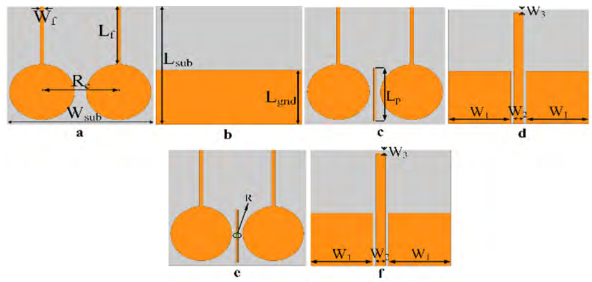

FIGURE 1. Geometrical structure of the implemented antennas: (a) Front view of Ant. 1, (b) Back view of Ant. 1 (c) Front view of Ant. 2 (d) Back view of Ant. 2, (e) Front view of Ant. 3, (f) Back view of Ant. 3.

TABLE 1. Geometrical dimensions of the proposed array antennas.

Symbol	Value	Symbol	Value	Symbol	Value
L_{sub}	35 mm	W_{sub}	36 mm	L_{gnd}	16 mm
R_c	19 mm	L_p	16 mm	L_f	17 mm
W_f	1 mm	W_1	16.5 mm	W_2	2.5 mm
W_3	5.2 mm	R	250 Ω		

II. ANTENNA CONFIGURATIONS

We designed and fabricated three antennas: a reference antenna (Ant. 1), an antenna with PCRs (Ant. 2) and an antenna with the proposed resistor-loaded PCRs (Ant. 3). First, a reference wideband MIMO antenna (Antenna without PCRs and resistor loading) is designed, and its response is observed in terms of isolation, and diversity parameters. To improve the isolation and diversity parameters of the designed reference antenna, we implemented a conventional PCR for mutual coupling reduction between closely spaced antennas. Although this technique is appealing, it creates degradation in the performance due to the resonance nature of the PCRs. Different solutions for its improvement has been reported in the literature [9], [22]–[33]. However, all the reported techniques cannot provide a suitable solution for improving isolation at the resonance of the PCRs. For this purpose, we have developed a PCR with resistive loading between the PCRs and improve the isolation as well as diversity parameters. This technique is quite appealing owing to its simple geometry, ease of optimization and implementation between any closely spaced antennas, consuming much smaller space. The antenna comprised of PCRs with a loaded resistor is termed as a proposed antenna (Ant. 3). All the above antennas were implemented with a RogersRO5880 substrate with a thickness of 31 mils, a relative dielectric constant of 2.2, and a loss tangent of 0.0009. The geometrical dimensions of these antennas are illustrated in Figure 1, while their geometrical dimensions are summarized in Table 1. Prototypes of the fabricated antennas are presented in Figure 2.

III. SIMULATIONS

The performance of the antennas was simulated using the 3-D EM simulator Ansoft HFSS. The simulated isolation

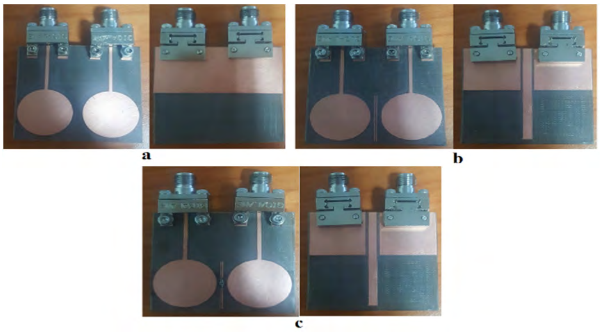

FIGURE 2. Fabricated prototype of the implemented antennas: (a) Ant. 1, (b) Ant. 2 (c) Ant. 3.

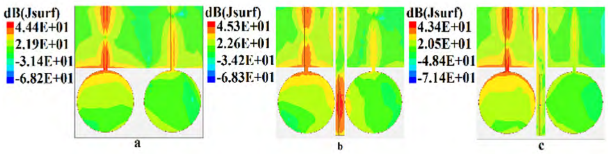

FIGURE 3. Surface current distribution of the implemented antennas in 1 × 2 array configuration (a) Ant.1, (b) Ant.2, (c) Ant.3.

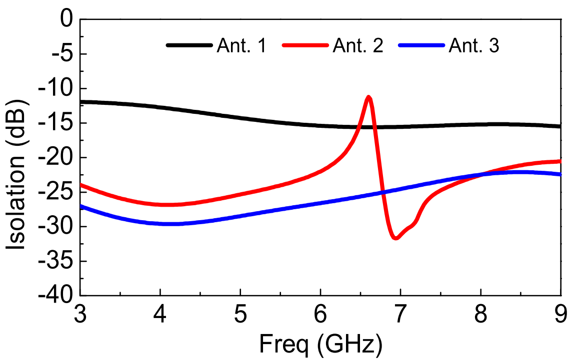

FIGURE 4. Simulated isolation (dB) of the implemented antennas in a 1 × 2 array configuration.

and current distributions of the antennas are discussed for 1 × 2 and 1 × 4 patch array configurations.

A. 1 × 2 PATCH ARRAY CONFIGURATION

The simulated isolation and current distributions of the 1 × 2 patch array antennas are shown in Figures 3 and 4, respectively. Although the isolation of the antenna (Ant. 2) was improved by introducing the PCRs between the two array elements, the isolation within the 6–7 GHz frequency band varied considerably and was lower than that of the reference antenna without PCRs at 6.45 GHz. This adverse effect was relieved by adding a 250-Ω resistor between the PCRs (Ant. 3), which improved the isolation considerably within the 6–7 GHz range. The optimal resistance (250 Ω) was selected using 3-D EM simulation by investigating the worst-case isolation within the passband.

The location of the resistor between the PCRs was also optimized and validated by placing two symmetrical resistors

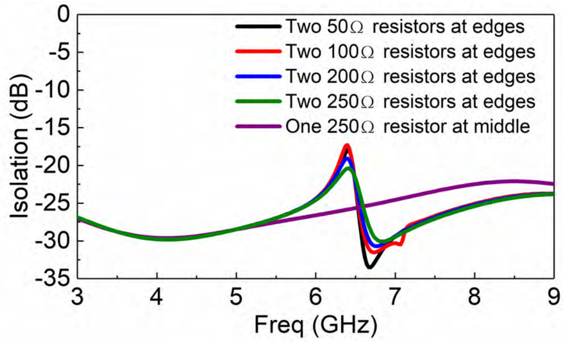

FIGURE 5. Simulated isolation (dB) of 1 × 2 array antenna depending on the resistor configuration in the PCRs.

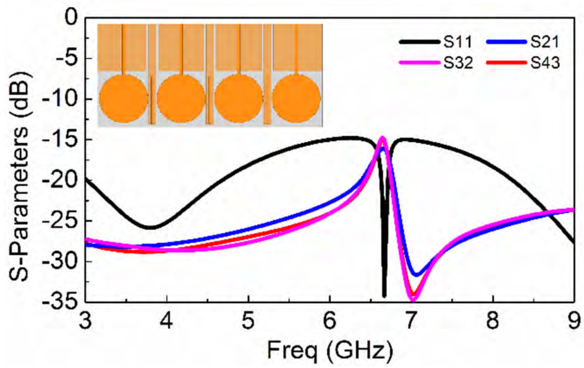

FIGURE 6. Simulated S-parameters of a 1 × 4 array antenna with conventional PCRs.

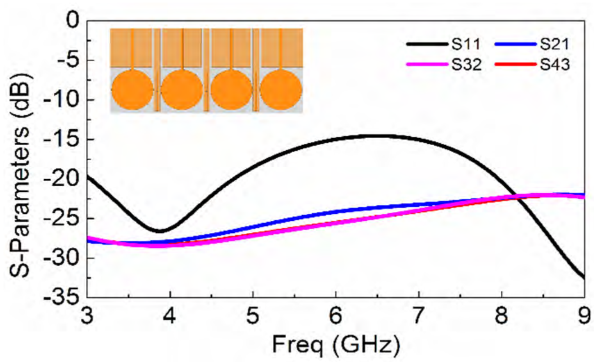

FIGURE 7. Simulated S-parameters of a 1 × 4 array antenna with resistor-loaded PCRs.

on the upper and lower edges of the PCRs and observing the isolation for different resistances. The results are summarized in Figure 5.

B. 1 × 4 PATCH ARRAY CONFIGURATION

The proposed technique was also extended and validated for a 1 × 4 patch array configuration. The simulated S-parameters of the antenna with conventional PCRs in the 1 × 4 configuration are shown in Figure 6, while the proposed antenna with the resistor-loaded PCRs is presented in Figure 7. It is evident from Figure 7 that the proposed technique also operates well in the 1 × 4 configuration, improving the isolation within the 6–7 GHz band. It can also be seen that the mutual coupling between the patch array elements was lower than 25 dB over the entire operating band. Therefore, the proposed decoupling structure enhances the isolation between the patch array elements by more than 10 dB within the 6–7 GHz band compared to conventional PCRs.

IV. EVALUATION OF THE PROPOSED METHOD FOR ANTENNA DIVERSITY

Although destructive interference can occur due to multipath fading, this can be ameliorated by utilizing an appropriate antenna diversity scheme with multiple array elements. Our proposed method is structurally simple and capable of mitigating multipath fading using pattern diversity. We investigated three essential figures of merit – the envelope correlation coefficient, diversity gain, and channel capacity loss [15]–[22] – to evaluate the antenna diversity performance of the reference antenna without any decoupling technique (Ant. 1), the antenna with conventional PCRs (Ant. 2), and the proposed antenna with resistor-loaded PCRs (Ant. 3).

A. ENVELOPE CORRELATION COEFFICIENT

The correlation between array elements was measured using the envelope correlation coefficient (ECC). The ECC measures the similarity between the two antennas' radiation patterns. When ECC = 1, the two radiation patterns are identical. This means that the signal received by both ports are the same. i.e., both ports simultaneously experience the same amount of fading. When ECC = 0, the two radiation patterns are non-overlapping, and the incoming signal is received by the single array element from any direction. It means that a lower ECC is more promising because it indicates that there is little overlap between the two radiation patterns. For acceptable performance, the ECC must be lower than 0.5. The ECC for a pair of antennas can be calculated using the equation in [13]:

$$ECC = \rho_e = |\rho_{ij}| = \frac{|S_{ii}^* S_{ij} + S_{ji}^* S_{jj}|^2}{\left[1 - (|S_{ii}|^2 + |S_{ji}|^2)\right]\left[1 - (|S_{jj}|^2 + |S_{ij}|^2)\right]} \quad (1)$$

The simulated ECCs for the antenna with conventional PCRs (Ant. 2) and the proposed antenna (Ant. 3) are given in Figure 8. Both antenna types had EECs lower than 0.025. The ECCs improved considerably with the use of the proposed technique, indicating the improvement in the isolation within the middle band.

B. DIVERSITY GAIN

Diversity gain (DG) is another essential parameter used to assess the performance of MIMO antenna systems. The approximate relationship between the ECC and DG is presented in [14]:

$$DG = 10 \times \sqrt{1 - |ECC|} \quad (2)$$

Equation (2) can be used to calculate the theoretical DG between monopoles using the ECC. We can also use the above relation to approximate the correlation between two patch array elements. As shown in Figure 9, the DG of the antenna with conventional PCRs (Ant. 2) and the proposed antenna system (Ant. 3) is about 10 dB within the band of operation.

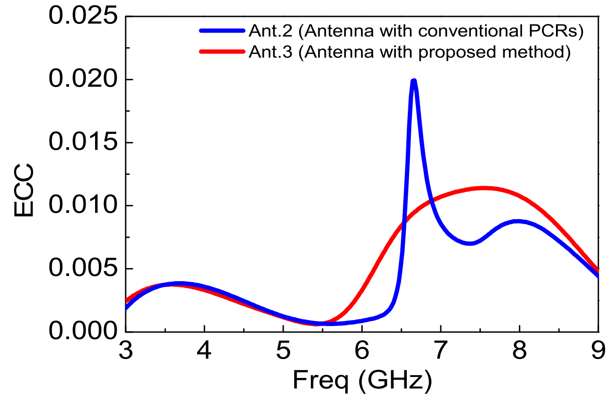

FIGURE 8. Simulated envelope correlation coefficients (ECCs) for the antenna with and without the isolation enhancement technique.

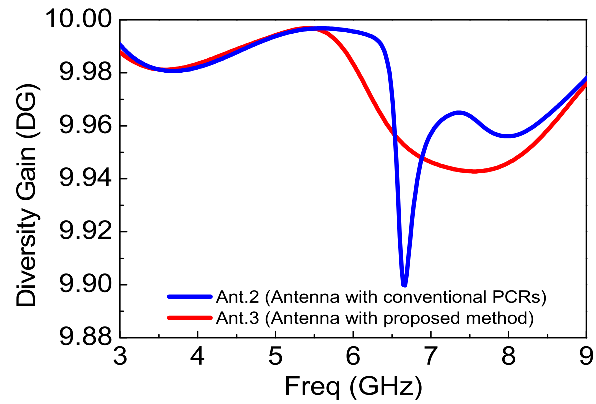

FIGURE 9. Simulated diversity gain (DG) for the antenna with and without the isolation enhancement technique.

C. CHANNEL CAPACITY LOSS

The channel capacity loss (CCL) is also affected by the coupling between multiple antennas, with CCL increasing proportionally with an increase in antenna elements. Because the correlation between patch array elements in a MIMO channel generates CCL, it can be calculated as follows [15]:

$$CCL = -\log_2 \det\left(\psi^R\right) \quad (3)$$

$$\psi^R = \begin{bmatrix} \rho_{11} & \rho_{12} \\ \rho_{21} & \rho_{22} \end{bmatrix} \quad (4)$$

$$\rho_{ii} = 1 - \left(|S_{ii}|^2 + |S_{ij}|^2\right) \quad (5)$$

$$\rho_{ij} = -\left(S_{ii}^* \times S_{ij} + S_{ji}^* \times S_{jj}\right), \quad i \text{ and } j = 1 \text{ or } 2 \quad (6)$$

Compared to Ant. 2, the CCL of Ant. 3, which utilizes the proposed method, had a response below 0.1 bits/Hz/sec over the entire band of operation (Figure 10).

The simulated gain and percentage radiation efficiency of the proposed antenna before and after the isolation technique are provided in Figure 12 and 13, respectively. It is seen that

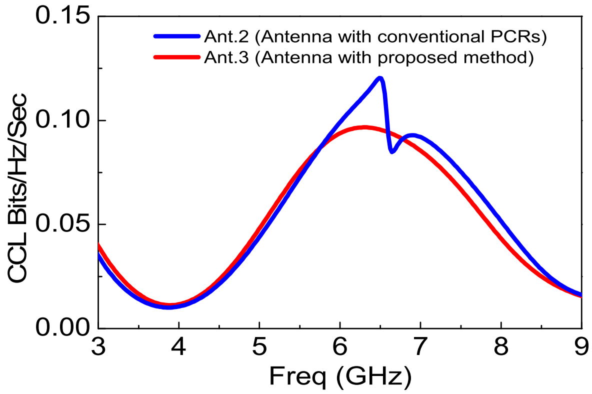

FIGURE 10. Simulated channel capacity loss (CCL) for the antenna with and without the isolation enhancement technique.

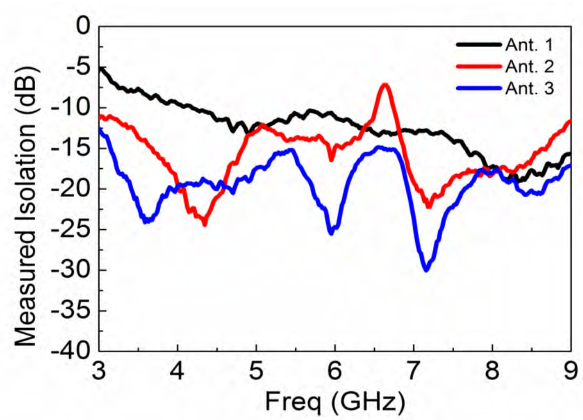

FIGURE 11. Measured transmission characteristics for the fabricated antennas including Ant.1 (Reference antenna), Ant.2 (Antenna with conventional PCRs), and Ant.3 (Antenna with resistor loaded PCRs).

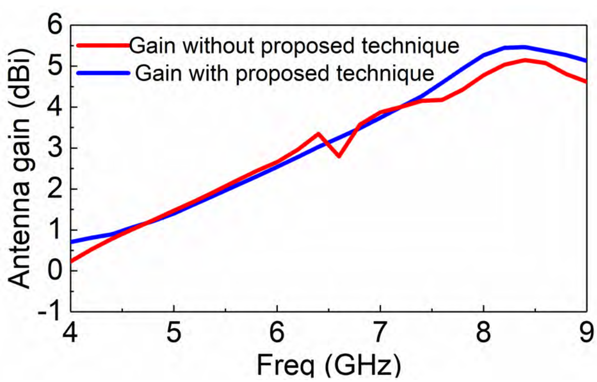

FIGURE 12. Simulated antenna gain (dBi) before (Ant.2) and after the isolation enhancement technique (Ant.3).

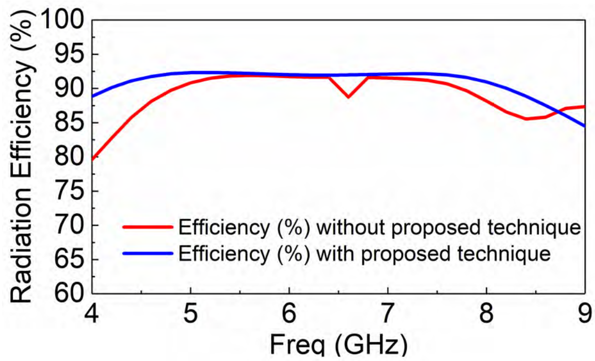

FIGURE 13. Simulated radiation efficiency (%) before (Ant.2) and after the isolation enhancement technique (Ant.3).

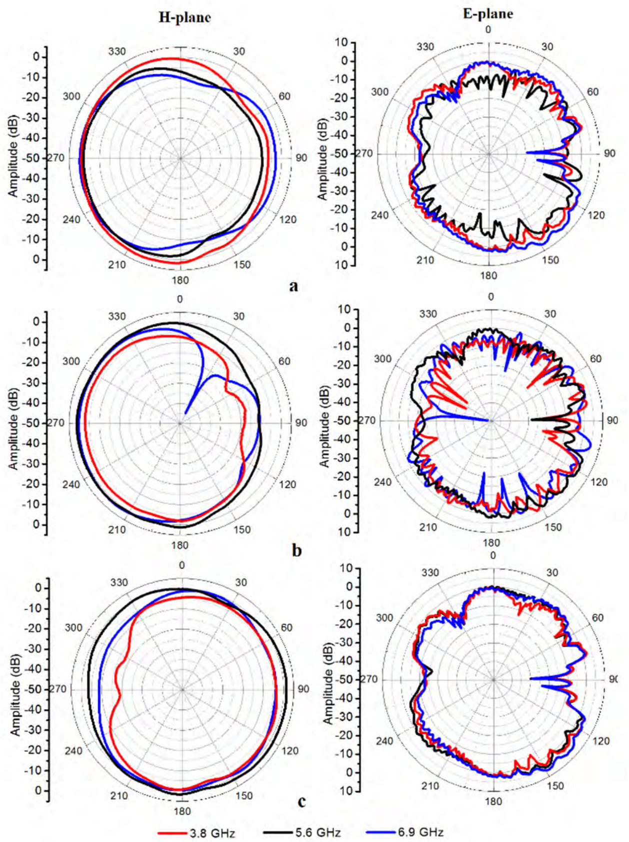

FIGURE 14. Measured radiation patterns of the implemented antennas: (a) the reference antenna (Ant. 1), (b) the antenna with conventional PCRs (Ant. 2), and (c) the antenna utilizing the proposed method (Ant. 3).

the proposed technique did not deteriorate the antenna gain and efficiency as expected. Simulated percentage radiation efficiency varies between 40 % and 95 % within the operating frequency range.

V. MEASUREMENT OF THE FABRICATED ANTENNAS

Prototypes of the antennas were fabricated and tested to confirm the simulation results. The measured isolation of the antennas is presented in Figure 11. Similar to the simulation results, the resistor-loaded PCRs improved the isolation over the entire band. The differences observed between the simulated and measured results were caused by the external coupling between the SMA connectors.

All three fabricated antennas were tested and measured in an anechoic chamber to demonstrate its radiation properties. Figure 14 compares the radiation patterns (on both the E- and H-planes) of the three antennas. The radiation patterns of the proposed antenna had a lower variation in

TABLE 2. Performance of the proposed antenna with previously reported state-of-the-art designs (λ_0 is the free-space wavelength at the center freq.).

Ref.	Technique Used	Frequency (GHz)	Centre to Centre Distance	Antenna Size (mm^2)	Isolation (dB)
[3]	DGS	7.5	0.45 λ_0	36×36	17.43
[4]	EBG	5.56	0.84 λ_0	95×95	4
[5]	UC-EBG	5.75	0.50 λ_0	78.26×78.26	8
[6]	SCCSRR	3.7	0.67 λ_0	74.14×44.14	14.6
[7]	WG MTM	2.44	0.422 λ_0	111.7×60	9
[8]	PCI	5.8	0.39 λ_0	41×32	19.6
[9]	MLR	2.8	0.28 λ_0	63.6×55.6	>14
[13]	Dual Layer EBG	2.0-6.0	0.13 λ_0	60×50	10-20
[21]	F-shaped stubs	2.5-14.0	1.36 λ_0	50×30	>20
[22]	EBG	4-9	0.50 λ_0	70×37	>20
[23]	CRDN	2.4 & 5.2	0.17 λ_0	55×120	>20
[24]	MTM slab	9-10	0.50 λ_0	N/A	>30
[25]	Slot Structure	5.8	0.33 λ_0	27.8×40	>45
[26]	EBG	2.5	0.13 λ_0	N/A	>40
[27]	MTM fractal loading	9.5 & 13	0.50 λ_0	70×37	>35
[28]	Slotted CSRR	4-6	0.25 λ_0	60×45	>30
[29]	DGS Structure	2.35-2.45	0.13 λ_0	60×60	>15
[30]	Meta-surface	8-12.8	0.3 λ_0	70×37	>30
[31]	MTM	8-9.25	0.5 λ_0	70×40	>30
[32]	EBG	5-6	N/A	N/A	>10
[33]	CRDN	2-3	0.22 λ_0	90×55	>20
This Work	Resistor - loaded PCRs	3.0-9.0	0.125 λ_0	35×36	17-25

gain compared with that of the reference and conventional PCR-loaded antennas. The radiation patterns of the antenna with conventional PCRs (Ant. 2) were particularly distorted due to strong mutual coupling between the two antennas at the resonance frequency of the PCRs, while the proposed antenna (Ant. 3) achieves the most uniform radiation pattern of the three fabricated antenna types. Figure 12 shows how the proposed technique is worthy over conventional PCRs technique in terms of radiation performance. The nulls arise in conventional PCRs technique have been diminished by utilizing the proposed isolation technique.

VI. COMPARISON WITH OTHER ISOLATION ENHANCEMENT METHODS

The proposed antenna (Ant. 3) was then compared with recently proposed state-of-the-art structures in the literature (Table 2). The isolation enhancement method proposed in this work achieved better isolation over a broader operating band even with the closer center-to-center distance, while also offering a straightforward implementation.

The diversity parameters of the proposed antenna were also compared with recently proposed structures and the conventional PCR-loaded antenna (Table 3). The proposed technique exhibited a lower ECC, better DG, and lower CCL, all of which are advantageous for use in MIMO antenna schemes.

TABLE 3. Performance comparison of the proposed antenna with other state-of-the-art designs proposed in the literature in terms of diversity parameters.

Ref.	ECC	DG (dB)	CCL	Antenna Size (mm^2)
[17]	<0.5	NA	NA	50×30
[18]	0.04	NA	NA	32×32
[19]	0.20	NA	NA	26×40
[20]	<0.1	>8.2	NA	25×40
[21]	<0.04	>7.4	NA	50×30
Ant. 2	<0.025	>9.8	<0.125	35×36
This Work	<0.010	>9.9	<0.10	35×36

VII. CONCLUSION

A wide-band MIMO array antenna with resistor-loaded paired PCRs that achieved an isolation of more than 25 dB over the 3–9 GHz range was presented in this study. The proposed antenna demonstrated better isolation over a broader operating bandwidth and offered a smaller center-to-center distance at 0.125 λ_0 between the two antennas. The improved performance using the proposed antenna was validated by comparing the isolation, radiation patterns, and diversity parameters such as the ECC, DG, and CCL with a reference antenna and an antenna with conventional PCRs. With its enhanced isolation, this method successfully reduced gain variation in comparison to both the conventional PCR array structure and the array without an isolation-enhancement approach.

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JUNG-DONG PARK received the B.S. degree in EE from Dongguk University, Seoul, South Korea, in 1998, the M.S. degree from the Gwangju Institute of Science and Technology (GIST), Gwangju, South Korea, in 2000, and the Ph.D. degree in EECS from the University of California at Berkeley, in 2012.

From 2000 to 2002, he was a Researcher with the Institute for Advanced Engineering (IAE), Yongin, South Korea, where he designed 35-GHz radar/radiometer transceivers. From 2002 to 2007, he was a Senior Researcher with the Agency for Defense Development (ADD), Daejeon, South Korea, where he was responsible for the development of millimeter-wave (mmW) passive/active sensors and related mmW modules. From 2007 to 2012, he was with the Berkeley Wireless Research Center (BWRC), where he researched silicon-based on-chip antennas and RF/millimeter-wave/terahertz circuits and systems. From 2012 to 2015, he was with Qualcomm, Inc. He is currently an Associate Professor with the Division of Electronics and Electrical Engineering, Dongguk University, Seoul, South Korea. His current research interests include phased array antenna systems, remote sensors, microwave electronics, and various types of antenna.

MUHIBUR RAHMAN received the bachelor's degree in electrical (communication) engineering from the University of Engineering and Technology, Peshawar, Pakistan, in 2014, and the M.S. degree in electrical (telecommunication) engineering from the Military College of Signals, National University of Sciences and Technology (NUST), Islamabad, Pakistan, in 2016. He is currently with Dongguk University, Seoul, South Korea. His current research interests include microwave electronics, non-linear transmission lines, and MIMO antennas.

HSIANG NERNG CHEN received the bachelor's degree in telecommunication engineering from the Asia Pacific University of Technology & Innovation, Kuala Lumpur, Malaysia, in 2016. He is currently pursuing the master's degree in electronics and electrical engineering with Dongguk University, Seoul, South Korea.

His current research interests include microstrip patch antennas and dielectric resonator antennas.