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RESEARCH ARTICLE

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Single layer CPSSA array with change polarization diversity in broadband application

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Abstract

The present study proposes a novel broadband circularly polarized (CP) multiple-input multiple-output antenna array designed for C-band applications. The first step was the introduction of a reconfigurable circularly polarized square slot antenna (CPSSA) capable of changing polarization diversity, which could cover impedance bandwidth (BW) from 4.48 to 8.21 GHz with 1.9 GHz of −3 dB axial ratio (AR) BW. Then, a feed network composed of 90° and 180° couplers, a crossover, and delay lines was presented. The CPSSA with two metalized via-holes adopted with two ports polarization diversity fed the networks. A number of reconfigurable CP array antennas using the polarization diversity technique have been presented so far. However, given that the proposed layout designed in a single layer had advantages of reduced antenna size and increased antenna gain and ARBW, this approach has received due attention over recent years. Another promising feature of this approach is its capability to change the polarization diversity by rotation of phases in the array feed network using PIN diodes.

KEYWORDS

broadband, circularly polarized and square slot antenna, MIMO antenna array

1 | INTRODUCTION

One of the significant problems in satellite and wireless communications is the incorporation of several requests into a single compact system.[1–4] Regarding this fact and taking into consideration that each request operates at a different frequency band and has distinct polarization and radiation characteristics, such complex systems require different antennas. As the physical size of these systems plays a constraining role, it is not practical to create separate antennas for each application. To solve the mentioned problem, a single multifunctional antenna such as polarization diversity multiple-input multiple-output (MIMO) antenna has been made so that switching to the required polarization can eliminate the need for complex systems with different antennas.[5–7] Circularly polarized array antenna (CPAA) with high gain, good directivity, and extensive coverage areas can be regarded as one of the most central methods to provide MIMO features.[8–11] However, CPAA mostly suffers from inability to change the polarization without changing the array feed network. Up to the present, some studies have been devoted to solve this problem. For example, in Refs. 10–13, a polarization diversity circularly polarized (CP) reconfigurable antenna was achieved by expanding the reconfigurable structures. A 2 × 2 Vivaldi linearly polarized array elements arranged in a square or rectangular grid configuration was presented in Ref. 12 which resulted in increasing antenna size and decreasing 3 dB axial ratio (AR) bandwidth (BW) and gain. A cylindrical cavity backing a multilayer structure was also reported in Ref 13. However, the proposed technique also suffers from large antenna size and fabrication problems. As it is well known, right-hand circularly polarized (RHCP) and left-hand circularly polarized (LHCP) are isolated from each other. Therefore, designing an antenna capable of changing polarization diversity with broadband BW and high gain can have many applications to prevent utilization of multiband processors. In the present study, a reconfigurable CP MIMO array antenna has been achieved combining four (2 × 2) reconfigurable CP

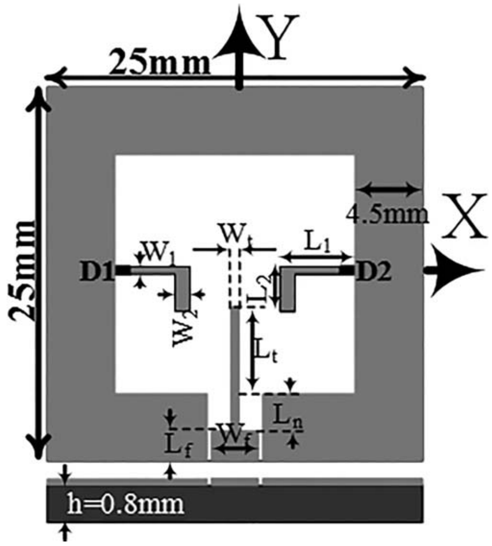

FIGURE 1 Configuration of reconfigurable CPSSAA ($W_f = 3.1$, $W_1 = 0.5$, $W_2 = 1$, $W_t = 0.5$, $L_n = 2.5$, $L_t = 5.8$, $L_f = 2$, $L_1 = 5$, $L_2 = 3$) (All values are presented in mm.)

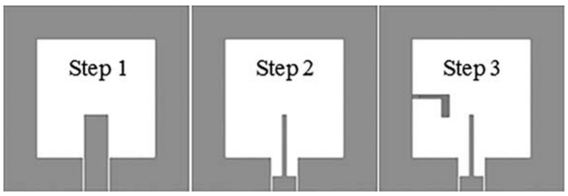

FIGURE 2 Three steps of designing the proposed single-element antenna

antennas. The proposed single element is a CPW- fed circularly polarized square slot antenna (CPSSA) that covers C-band applications. The proposed single element with compact size switches between RHCP and LHCP by microwave PIN diodes. The projected array feed network consists of two 90°/3dB branch-line couplers and one 180°/3dB rat-race coupler. A novel crossover coupler has been also designed to isolate two array input ports. Furthermore, transient mechanism between microstrip feed network array and CPSSA is

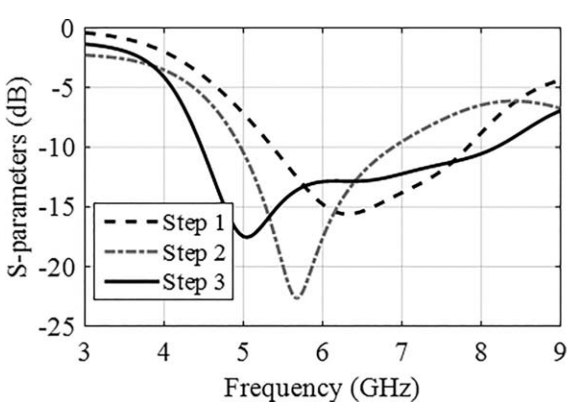

FIGURE 3 Simulated S_{11} on the basis of three steps of designing a single-element antenna

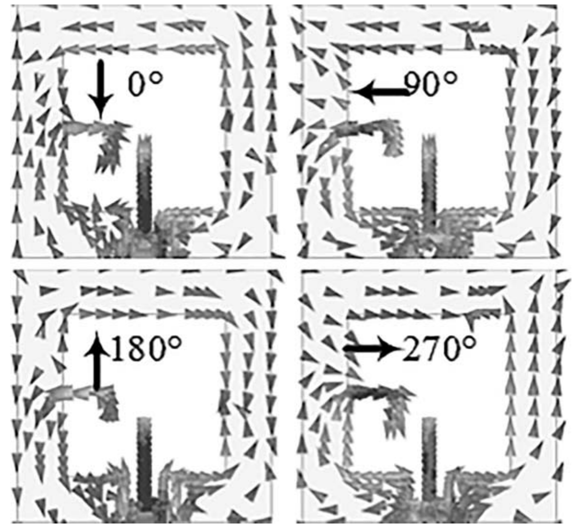

FIGURE 4 Distribution of current flow at 5.5 GHz

based on metalized via-holes. The effect of these via-holes on array antenna properties such as BW and gain is also discussed in the present study. Although a good number of studies[10–13] are formerly reported in this field, the main purpose of designing the proposed antenna was to create a single-layer broadband MIMO antenna which could provide

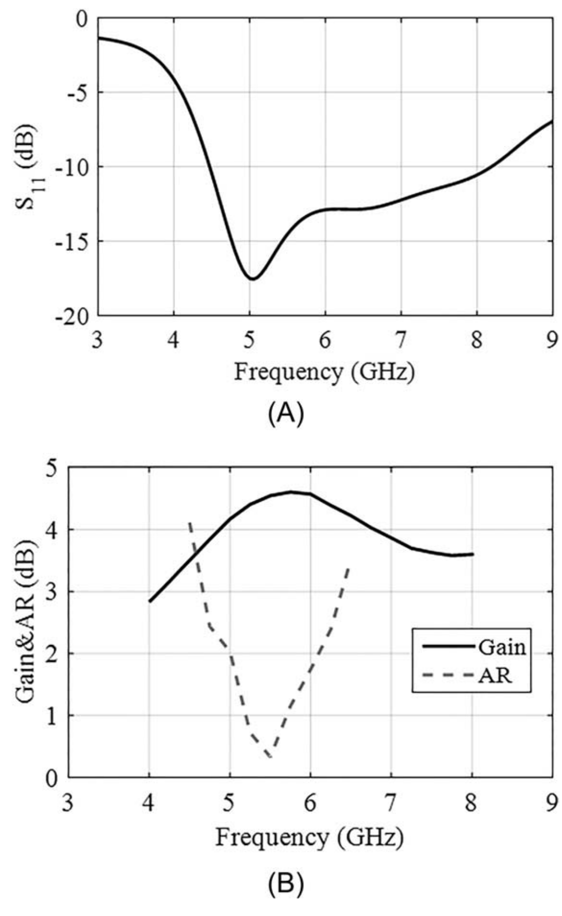

FIGURE 5 Simulation results of reconfigurable CPSSA; (A) S_{11} and (B) gain and axial ratio

TABLE 1 Simulated states of the proposed antenna

State	Diode 1	Diode 2
1	ON	OFF
2	OFF	ON

high gain and wide band AR covering C-band applications. Additionally, utilization of novel structures such as reconfigurable CPSSA, which arranges the feeding network, leads to the presentation of specific innovations in the antenna structures and offers mentioned results in this field.

2 | ANTENNA ELEMENTS

Geometry of the proposed reconfigurable circularly polarized square slot array antenna (CPSSAA) is displayed in Figure 1. The CPSSAA with side length of L was printed on a FR4 substrate with relative permittivity of (ε_r=) 4.4 and loss tangent of (tan δ=) 0.02. Two identical L-shaped metallic stubs were protruded from the ground loop to the slot center, both of which were connected to the ground loop by PIN diodes. To achieve a 50Ω input impedance to feed the antenna, the study made use of a CPW with a protruded signal strip having a signal strip of width W_f and a gap of spacing g between the signal strip and the ground plane.

The antenna can radiate RHCP and LHCP fields depending on the position of L-shaped stub in the ground loop. In fact, a reconfigurable CPSSA with polarization diversity applications is presented. When diode 1 is on and diode 2 is off, the left L-shaped stub is connected, and the right L-shaped stub is disconnected from the ground plane; therefore, RHCP can be obtained in the front side. Similarly, if diode 1 is off and diode 2 is on, LHCP can be obtained. Switching PIN diodes (SC79-PIN diode) are controlled by the DC-bias circuit on the other side of antenna. Two inductances (i.e., Li_1 and Li_2 of μH) are used to block the RF signal. A resistor R_L of Ω is used as a limiting resistor to protect

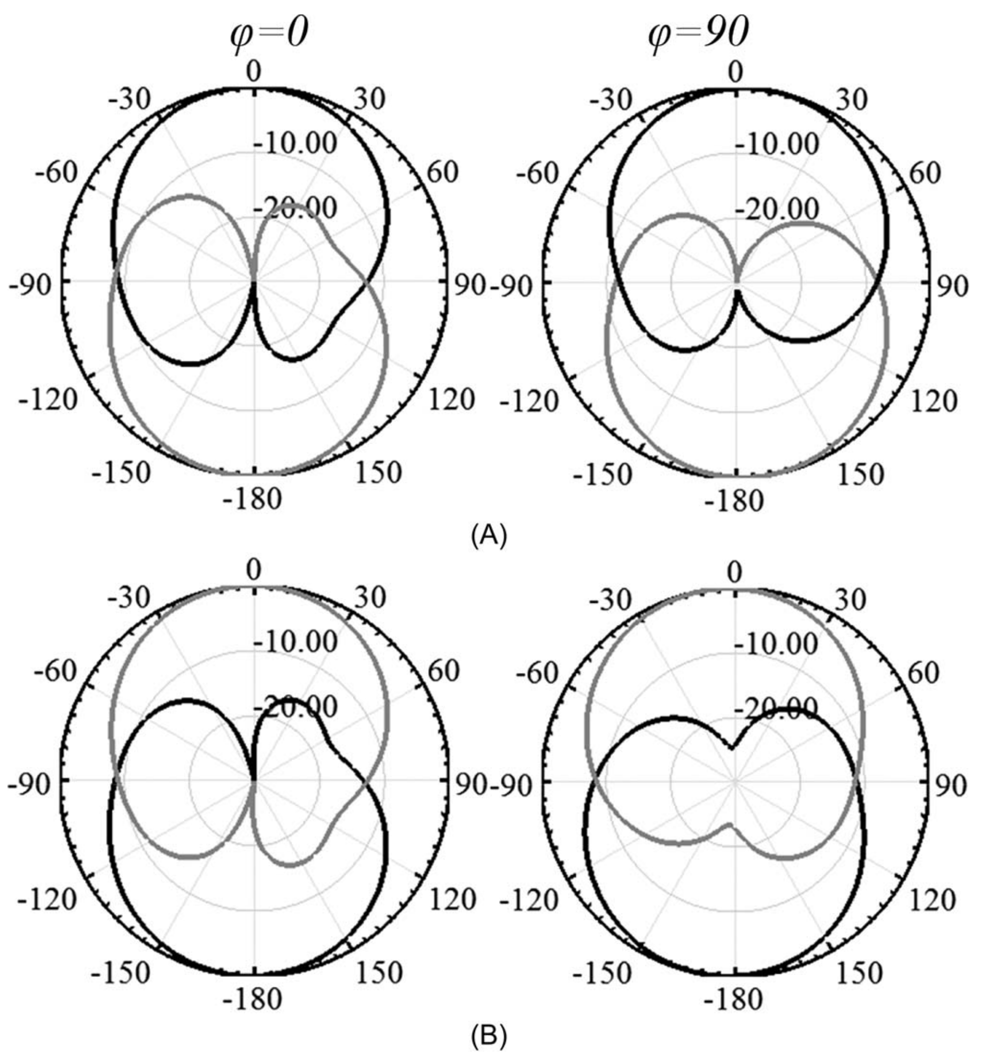

FIGURE 6 Normalized simulated radiation pattern of the proposed single element at 5.5 GHz; (A) state 1 and (B) state 2 (Gray line is LHCP and black line is RHCP.)

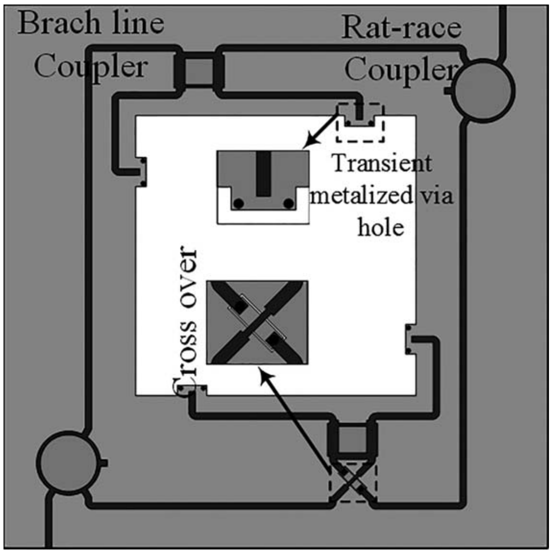

FIGURE 7 Structure of the proposed CP diversity feed network

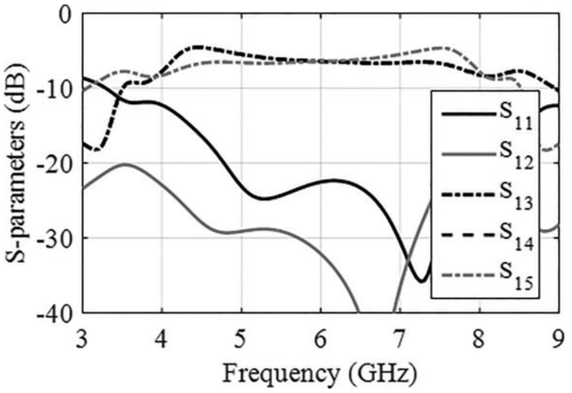

FIGURE 8 The simulated magnitude of scattering parameters of the proposed feed network

the diodes.[6] The proposed single element antenna was designed in three steps (Figure 2). In step 1, antenna consisted of a CPW fed and a square ground loop. When antenna was excited by the input port, two problems occurred. One was impedance mismatching in the broad band, and the second related to future of CP. In step 2, feed of single element matching was almost improved with some modifications (as seen in Figure 3); however, the problem of CP generation still remained unsolved. To design a CPSSA, current rotation in the ground loop played a significant role. In the proposed antenna, surface currents of the ground loop did not eliminate their effect by embedding an L-shaped stub. Therefore, surface current could be rotated in the ground loop within the broadband region. Surface current of the proposed single element is displayed in Figure 4.

The simulated results for the S_{11}, gain, and AR of the antenna are illustrated in Figure 5. The simulated results reveal that the proposed antenna generated the same results in the two states presented in Table 1, except for the change of polarization diversity. As shown in Figure 5. The impedance BW range is 4.48-8.21 GHz with 1.9 GHz ARBW. When D1 =ON and D2 = OFF, the antenna radiates an RHCP field (Figure 6A), and when D1 = OFF and D2 = ON, an LHCP field is radiated (Figure 6B).

3 | ARRAY FEED NETWORKS

The proposed feed network consists of two 180-degree rat-race couplers, two 90-degree branch-line couplers, and a novel low-loss crossover. The proposed crossover was designed on a layer substrate, in which one of the intersecting lines in the point of overlap was transferred to the other side of the substrate (metalized ground plane) by using a metalized via-hole (Figure 7). Using a 0.2 mm gap between the line and ground, the line was isolated from the ground. To compensate for phase response delay in the output of crossover, the two lines with different widths were selected, which caused a change in phase velocity in two crossed lines and consequently reached the same phase response delay in two outputs of the crossover. As clearly indicated in Figure 7, after crossing 180° hybrid ring rat-race couplers, the signal was divided into two equal −3 dB magnitude and 180° phase shifting and entered in branch-line hybrid couplers, and repeatedly, the signal energy was divided to two paths.[12–14] To achieve a sequential phase rotation between the ends of one side of the rat-race couplers and branch-line coupler, a crossover was utilized.

A line length placed on the other side of the crossover was used to rectify the phase shift caused by the crossover. Table 2 shows the phase results obtained from each output port of the network for the selected input port in the proposed feed network. Simulated results for scattering parameters of the proposed feed network are demonstrated in Figure 8.

TABLE 2 Distribution of phase differences between CPSSA elements against each input port and the type of generated diversity

P = port	Output P1	Output P2	Output P3	Output P4	Diversity
Input P1	0°+θ°	90°+θ°	180°+θ°	270°+θ°	RHCP
Input P2	270°+θ°	180+θ	90°+θ°	0°+θ°	LHCP

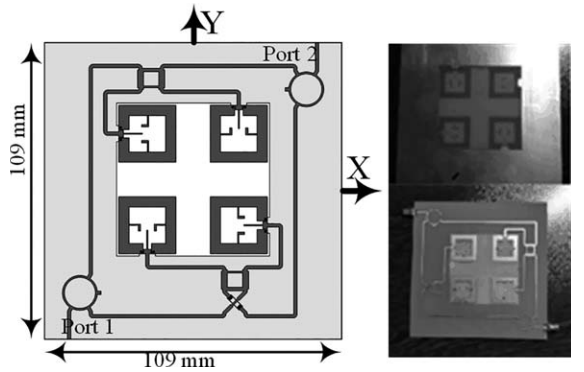

FIGURE 9 Schematic and fabricated photograph representation of CPSSA diversity array antenna

4 | RESULTS AND DISCUSSION

Configuration of the proposed array is presented in Figure 9. The proposed array antenna was fabricated and measured using R&S®ZNB Vector Network Analyzer. The obtained results confirmed that the radiation property of the CP array antenna was able to switch between LHCP and RHCP by selecting input ports of the array antenna feed network. As proved in Ref. 9, acceptable results were obtained by

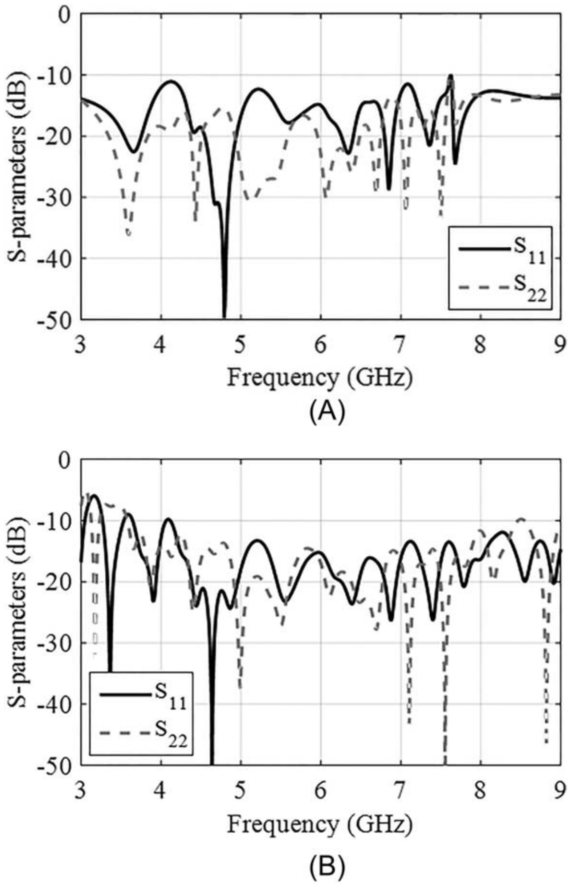

FIGURE 10 Comparison between the simulated and measured S_{11} and S_{22} of the proposed antenna; (A) simulated and (B) measured values

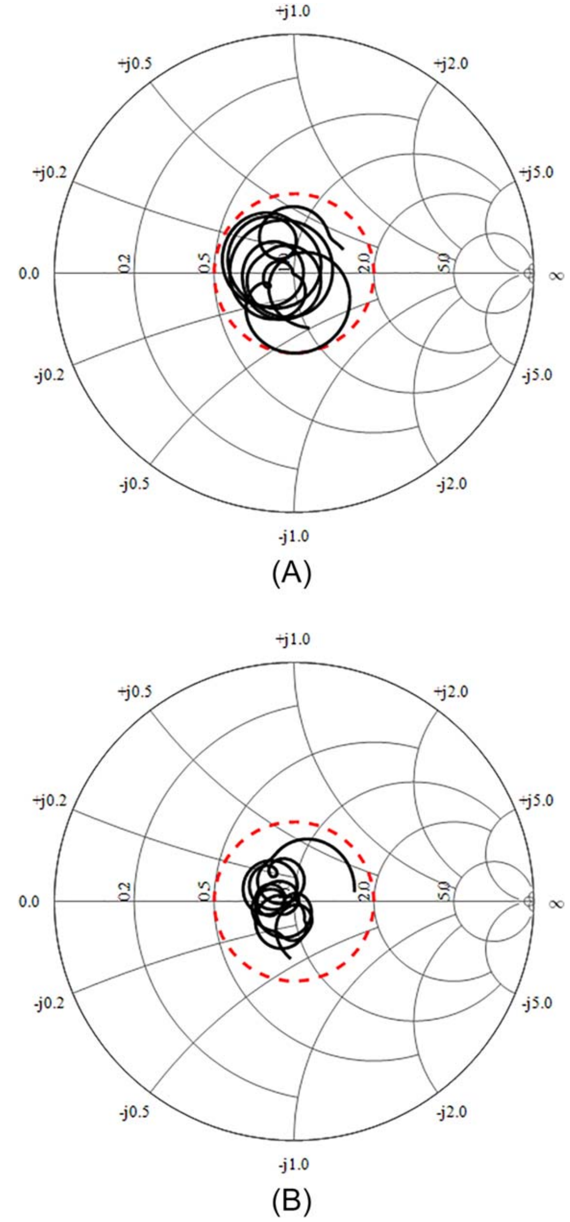

FIGURE 11 Simulated impedance matching diagram (Smith chart) of the proposed array antenna for input ports; (A) port 1, and (B) port 2

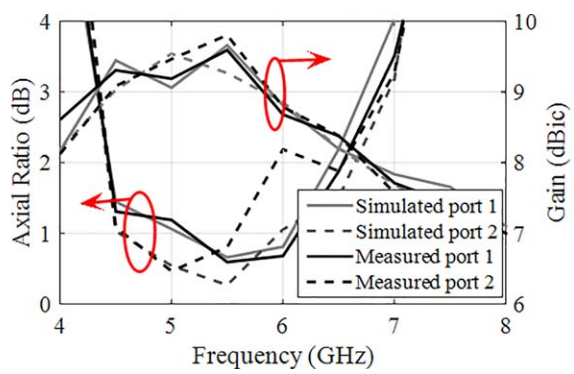

FIGURE 12 Comparison between simulated and measured gain and AR of the proposed antenna in states 1 and 2

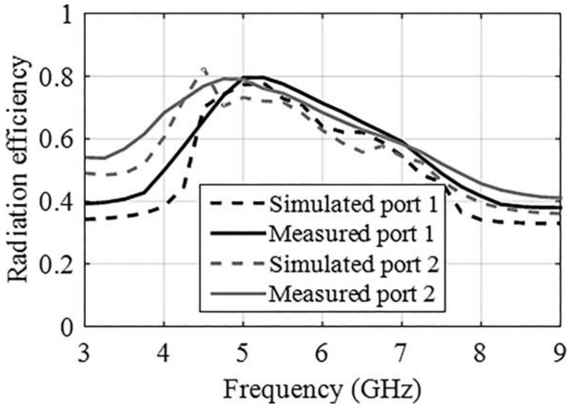

FIGURE 13 Comparison between simulated and measured radiation efficiency of the proposed antenna in states 1 and 2

selecting matched diversity between rotation phase of array feed and radiation elements. Table 2 displays array antenna states. In Figure 10, the comparison made between simulated (Figure 10A) and measured (Figure 10B) S_{11} and S_{22} for the proposed array antenna is provided. By matching diversity of feed network phase rotation with single elements, the simulated impedance BWs of the antenna obtained for ports 1 and 2 inputs were 6 GHz (3-9 GHz). Moreover, the measured impedance BWs of the antenna for ports 1 and 2 were 5.33 GHz (3.67-9 GHz) and 5.38 GHz (3.62-9 GHz), respectively. Utilization of metalized via-holes in transient mechanism between array feed network and elements led to increased inductance effect in the antenna and its radiation resistance. To prove this hypothesis, simulated Smith chart of the proposed array antenna for input ports 1 and 2 is displayed in Figure 11. The underlying significant reason for the minor difference observed between simulated and measured S_{11} and S_{22} could be proved by resorting to minor differences present between substrate characteristics. In addition, such differences can be attained by fabrication and measurement of errors. The radiation patterns and AR were

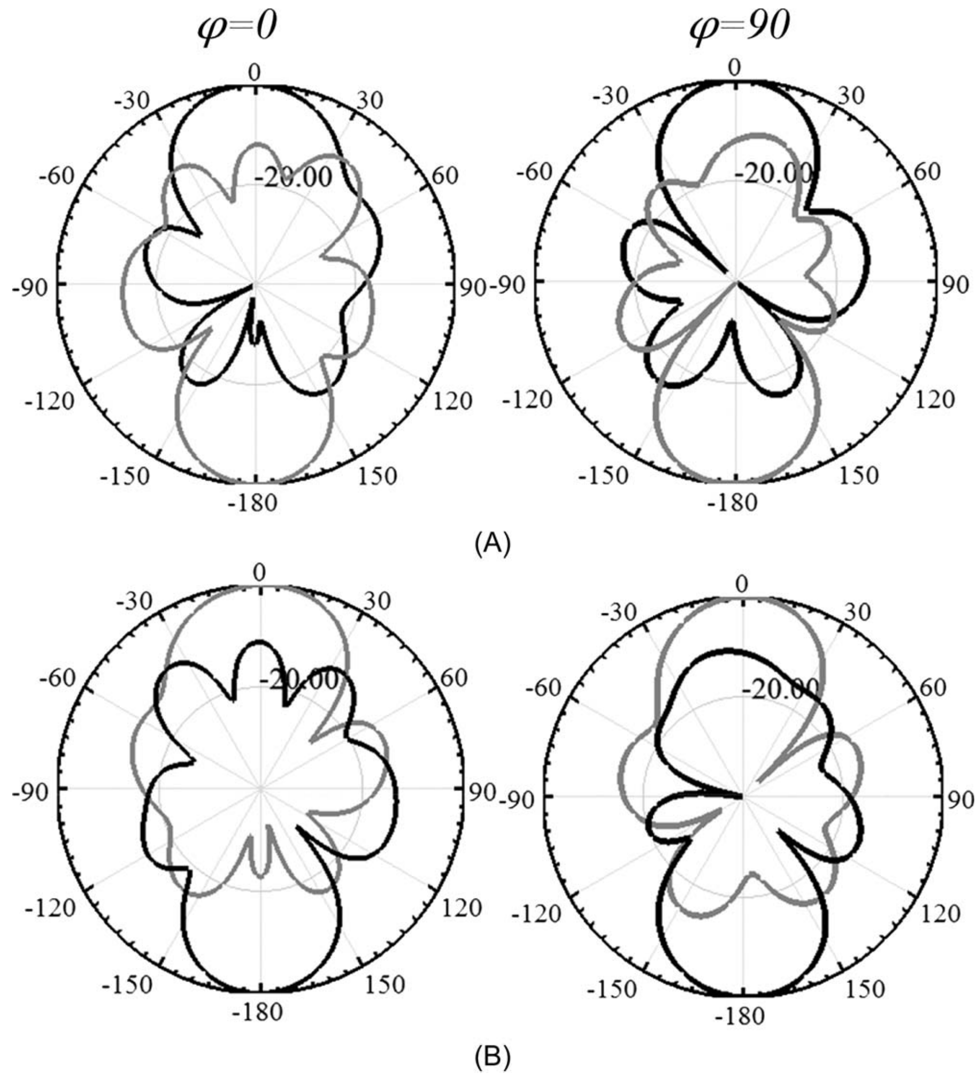

FIGURE 14 The normalized measured radiation patterns of the proposed array antenna at a frequency of 5.5 GHz in states 1 and 2; (A) state 1, and (B) state 2

TABLE 3 Comparison between the proposed array antenna and conventional array antennas BW is the frequency range, where the VSWR ≤ 2, ARBW is the -3 dB axial-ratio bandwidth, and MePD is the method of polarization diversity

Ref.	Size (mm)	PG (dBic)	ARBW (GHz)	BW (GHz)	Number of elements	MePD
[10]	100 × 100 × 5	~8	0.31 (1.76–2.07)	0.82 (1.55–2.37)	4	PIN diode
[11]	Not mentioned	~7	0.01 (2.07–2.08)	0.11 (2.03–2.14)	2	PIN diode
[12]	90 × 85 × 68	~13.9	1.36 (4.81–6.17)	3.58 (4.26–7.84)	4	Input port
[13]	85 × 73 × 12	14.8	3.02 (4.41–7.43)	2.73 (4.45–7.18)	4	Cavity back-PIN diode
This work	109 × 109 × 0.8	9.8	2.6 (4.31-6.91)	5.38 (3.62-9)	4	CPSSA-PIN diode

measured in an anechoic chamber by Agilent PNA E8362A vector network analyzer. The comparison made between simulated and measured AR and gain of antenna in two states is illustrated in Figure 12. A 3 dB ARBWs of the antenna for ports 1 and 2 were measured in the direction of peak gain. The measured 3 dB ARBW for ports 1 and 2 were 2.45 GHz (4.31-6.76 GHz) and 2.6 GHz (4.31-6.91 GHz), respectively. As indicated in Figure 12, the proposed array had peak gain of 9.78 and 9.8 dBic at 5.5 GHz for excitation ports 1 and 2, respectively. Antenna gain varied between 7 and 9.8 dBic across the frequency band. A standard linearly polarized horn antenna was used to measure the total gain characteristics.

As already mentioned, utilization of metalized via-holes in transient mechanism led to an increase in radiation impedance in the array antenna. This increase caused enhancement of radiation efficiency of the proposed antenna and consequently increased the gain. Simulated and measured radiation efficiency values of the proposed antenna is demonstrated in Figure 13. As illustrated in this figure, the antenna with about 79% peak of radiation efficiency can provide high gain. The normalized measured radiation patterns of the proposed array antenna at a frequency of 5.5 GHz in states 1 and 2 are shown in Figure 14 for ports 1 and 2, respectively (as demonstrated in Table 2). The antenna HPBWs in state 1 was about 31° for RHCP and 29° for LHCP. In state 2, it was about 30° for LHCP and 28° for RHCP.

Comparing the proposed array with the previous polarization diversity array structures is presented in Table 3. The proposed antenna design revealed notably increased impedance BW and 3-dB ARBW. Using CPW slot antenna and a good impedance matching with microstrip feed line, which was created with metalized via-holes, led to an increase in impedance BW. Moreover, as shown in Table 3, utilization of this technique also led to an increase in -3 dB ARBW. Evidently, an increase in antenna BW reduced its gain. In contrast, tapered element antenna in Ref. 12 despite increasing antenna gain, suffered from large size; moreover, its BW and 3-dB AR had to be decreased to use linear polarization antenna. In Ref. 13, a three-layered antenna including a cylindrical cavity backed and a top layer polarizer are the reasons behind high gain and 3-dB ARBW. Similar to Ref. 12, the size was increased and BW of antenna was reduced in the present study. However, in comparison with Refs. 12 and 13, designing the proposed antenna with wider impedance and 3-dB ARBW within a single layer makes such antennas more interesting.

5 | CONCLUSIONS

In the present study, a CP MIMO array antenna capable of changing polarization diversity in elements and feeding the network in C-band applications was proposed. To achieve polarization diversity in single elements, a new feed network structure was introduced. Two input and four output ports were used to switch the PIN diodes embedded in the single element structure and polarization diversity feature of array feed network. In comparison with traditional similar designs, the proposed antenna array and feed network design achieved a significant enhancement in impedance BW, A-3 dB ARBW, and the average gain of the antenna. As already mentioned, the proposed antenna can change the polarization diversity by selecting the inputs of the feed network with matched polarization state of the diodes used in the single antenna structure.

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REFRENCES

[1] ItohHaddad TG, Harvey J. *RF Technologies for Low Power Wireless Communications*. New York: Wiley; 2001.

[2] Sung YJ, Jang TU, Kim YS. Reconfigurable microstrip patch antenna for switchable.pb5 polarization. *IEEE Microwave Wireless Compon Lett.* 2004;14(11):534–536.

[3] Shokri M, Rafii V, Karamzadeh S, Amiri Z, Virdee B. Miniaturised ultra-wideband circularly polarised antenna with modified ground plane. *Electron Lett.* 2014;50(24): 1786–1788.

[4] Karamzadeh S, Rafii V, Kartal M, Ucan ON, Virdee BS. Circularly polarised array antenna with cascade feed network for broadband application in C-band. *Electron Lett.* 2014;50(50):1184–1186.

[5] Fries MK, Grani M, Vahldieck R. A reconfigurable slot antenna with switchable polarization. *IEEE Microwave Wireless Compon Lett.* 2003;13(11):490–492.

[6] Chen YB, Jiao YC, Zhang FS. Polarization reconfigurable CPW-fed square slot antenna using pin diodes. *Microwave Opt Technol Lett.* 2007;49(6):1233–1236.

[7] Karamzadeh S, Rafii V, Kartal M, Virdee BS. Modified circularly polarised beam steering array antenna by utilised broadband coupler and 4 × 4 butler matrix. *IET Microwave Antennas Propag.* 2015;9(9):975–981.

[8] Vaughan RG. Polarization diversity in mobile communications. *IEEE Trans Veh Technol.* 1990;39(3):177–186.

[9] Ahn CH, Oh SW, Chang K. A dual-frequency omnidirectional antenna for polarization diversity of MIMO and wireless communication applications. *IEEE Antennas Wireless Propag Lett.* 2009;8: 966–970.

[10] Cao W, Zhang B, Liu A, Yu T, Guo D, Pan K. A reconfigurable microstrip antenna with radiation pattern selectivity and polarization diversity. *IEEE Antennas Wireless Propag Lett.* 2012;11:453–456.

[11] Tsai JF, Sh. Row J. Reconfigurable square-ring microstrip antenna. *IEEE Trans Antennas Propag.* 2013;61(5): 2857–2860.

[12] Karamzadeh S, Kartal M. Circularly polarised MIMO tapered slot antenna array for C-band application. *Electron Lett.* 2015;51(18):1394–1396.

[13] Karamzadeh S, Rafii V, Saygin H, Kartal M. Polarisation diversity cavity back reconfigurable array antenna for C-band application. *IET Microwave Antennas Propag.* 2016;10(9):955–960.

[14] Karamzadeh S, Rafii V, Kartal M, Saygin H. Compact UWB CP square slot antenna with two corners connected by a strip line. *Electron Lett.* 2016;52(52):10–12.

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Vahid Rafiei, was born in Naghadeh, IRAN in 1986. He is author and coauthor more than a dozen articles about CP array and beam steering antenna. He is selected as top Iranian young research in 2014-2016. Now, he is worked with advance Electromagnetics, Microwave and Antenna research group at Istanbul Aydin University and at the same time as faculty member of Istanbul Aydin University. His main areas of interest in research are Microstrip array antenna, beam steering and beam shaping feed networks, computational methods, Microwave passive and active circuits Graphene base Nano structure microwave and antenna application, and RF MEMS.

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