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RESEARCH ARTICLE

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A novel circularly polarized cavity backed SIW antenna with capability to change polarization diversity by a reconfigurable polarizer structure

Saeid Karamzadeh[1,2] | Vahid Rafiei[2] | Hasan Saygin[1]

[1] Application & Research Center for Advanced Studied, Istanbul Aydin University, Istanbul, Turkey

[2] Department of Electric and Electronics Engineering, Istanbul Aydin University, Istanbul, Turkey

Correspondence
Saeid Karamzadeh, Department of Electric and Electronics Engineering, Istanbul Aydin University, Istanbul, Turkey.
Email: karamzadeh@itu.edu.tr

Abstract

This article examines a substrate integrated waveguide (SIW) cavity-backed circularly polarized diversity antenna. In the proposed novel antenna, parasitic patch and reconfigurable diodes are used to change polarization diversity from left hand to right hand and vice versa, respectively. In addition to, what makes distinctive proposed antenna in compared with similar works, is ability to change linear polarization from a SIW slot to circularly polarization by a parasitic patch. Chopping off two diagonally opposite corners makes the resonance frequency of the mode along this diagonal to be higher than that for the mode along the unchopped diagonal. By exciting parasitic patch with a slot along axes of it the orthogonal modes are generated which causes to CP. The comparison between simulation and measurement results validate antenna design. The measured impedance BW (VSWR < 2) for state 1 and 2 are 22.18% (11.86-14.82 GHz) and 21.68% (11.88-14.77 GHz), and The measured 3-dB AR BW for states 1 and 2 are about 11.46% (11.43-12.82 GHz) and 11.23% (11.43-12.79 GHz), respectively. Finally, the measured maximum gain is 9.81 dBic.

KEYWORDS

circularly polarized antennas, cavity-backed, substrate integrated waveguide

1 | INTRODUCTION

Circularly polarized antennas popularly are used in radar and satellite communication to resolve problems such as polarization mismatch and interference which are generated by Faraday and multipath effects in wireless channels, respectively. There are key components of many existing and developing wireless communication systems. The general requirements for satellite antennas are light weight, stabilized gain, good return loss characteristics, and a compatible radiation pattern to narrow/wideband electromagnetic interferences caused by unexpected aerospace environmental phenomena. Despite the printed aperture antennas are commonly used, as they can provide aforementioned features and also wideband CP radiation,[1–3] they usually suffer low radiation gain due to the bidirectional radiation properties. Therefore, the CP aperture antennas backed by a metal reflector or cavity have been proposed to offer unidirectional radiation.[2,3] Substrate integrated waveguide (SIW) to have their benefits such as: the merits of low loss, high power capacity, high Q-factor and lower cost than conventional waveguide, has been able to allocate a special place in cavity backed antenna structures.[4–7] Hitherto, many works using SIW cavity backed techniques to attain CP feature at planar antenna have been reported.[6–9] But, they suffer from inability to change polarization diversity. Polarization diversity technique is very valuable method to reduce the unfavorable fading loss caused by multipath effects.[1] The reconfigurable polarization diversity antennas because they can change their polarization features in real time, have been created in the spotlight of researchers.[1,3] In this work, a novel two-layers antenna with ability to change polarization diversity, is presented. What makes distinctive proposed antenna in compared with similar works, in addition to changing diversity, is capability to change linear polarization to circularly polarization by a parasitic patch. Erenow, no the same methods to change polarization diversity and also convert LP to CP in real time have been reported. The bottom layer of

TABLE 1 Comparison of measured characteristics of proposed antenna with those of previously reported similar antennas (ARBW is 3-dB axial ratio bandwidth and A2CPD is ability to change polarization diversity)

Reference	Size (in ?$_{\text{guide}}$)	B.W. (%)	ARBW	Gain (dBic)	A2CPD
5	1.23 λ_g×1.87 λ_g	18.74	2.3%	5.75	Not available
6	No mentioned	3	0.8%	6.3	Not available
7	No mentioned	6	0.66%	4.2	Not available
8	0.85 λ_g×0.79 λ_g	10	1%	6.8	Not available
9	1.65 λ_g×2.13 λ_g	14.42	2.34%	7.79	Not available
10	No mentioned	2.7	0.6%	8.9	RHCP LHCP
11	No mentioned	2.4	1%	5.7	RHCP LHCP
12	0.74 λ_g×0.74 λ_g	1.6	—	4.2	Vertical Horizontal
This work	1.01 λ_g×1.22 λ_g	21.68	11.46%	9.81	RHCP LHCP

antenna consists of a cavity backed SIW which slot of it radiates linear polarization. The top layer of offered antenna includes a reconfigurable rectangular patch with etching four diagonal corner. Chopping off two diagonally opposite corners makes the resonance frequency of the mode along this diagonal to be higher than that for the mode along the un-chopped diagonal. The patch is fed along the central axis so that the orthogonal modes are generated. To obtain CP diversity, each of diodes, pairwise in diagonal of rectangular patch changes to ON and OFF states, respectively. To evaluate the ability of the proposed antenna with almost similar works in recent years, comparative Table 1 is presented. As seen, the proposed antenna from every aspect is prominent.

2 | ANTENNA ARCHITECTURE AND FORMULATION

The configuration of reconfigurable SIW CP antenna is presented in Figure 1. The proposed antenna consists of two-substrates which one of them created on top of the other. To improve features of slot, the bottom substrate is selected a low value of relative permittivity. To reduce capacitance effect and to enhance impedance BW between radiation slot and parasitic radiation patch, a high relative permittivity substrate is used.

Therefore, air gap and high permittivity substrate when series connected with together cause to produce a low value

TABLE 2 States of antenna

State	D1	D2	D3	D4
#1	ON	OFF	ON	OFF
#2	OFF	ON	OFF	ON

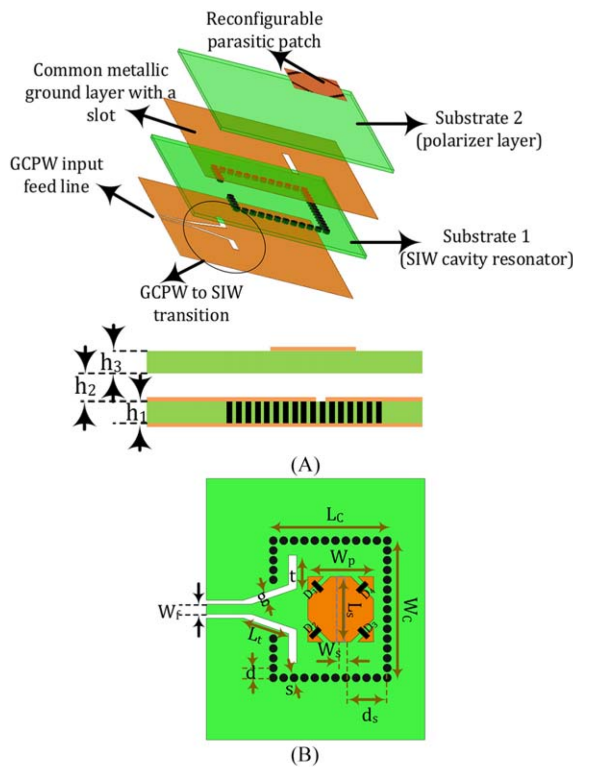

FIGURE 1 configuration of proposed antenna structure. (A) Perspective and side view; and (B) Dimensions and configuration of proposed antenna

effective permittivity and consequently, a lower capacitance effect produced (see formula 4). Therefore, can be said gap and upper substrate play a role as lower relative permittivity.

With attention to aforementioned principles, the lower and upper layers are printed on Rogers 4003 substrate (with relative permittivity (ε_r) of 3.38, loss tang (tan δ) of 0.002, and thickness (h) of 0.508 mm). The total dimensions of two layers are $W \times L$. The bottom layer composes of three main sections. First section includes a grounded coplanar waveguide (GCPW) fed line with width of $W_f = 1.1$ mm to attain 50 Ω input impedance. Second section includes GCPW-to-SIW transition. A single tapered grounded coplanar waveguide (GCPW), is located at the end of GCPW feed line to match impedance between GCPW and SIW cavity. Finally, the third section consists of a SIW cavity backed, with length of $L_c = 13.8$ mm and width of $W_c = 16.8$ mm, and a rectangular slot. The rectangular slot is etched on the ground plane metal surface ($l_s \times w_s$). The radiation of antenna at each operating frequency is determined by a single cavity mode. The formula (1)[6] can be utilized to develop relations between operating frequencies and geometrical parameters in cavity back as follows:

$$f_{\mathrm{mnp}} = \frac{1}{2\sqrt{\mu_r \epsilon_r}} \sqrt{\left(\frac{m}{L_{\mathrm{eff}}}\right)^2 + \left(\frac{n}{W_{\mathrm{eff}}}\right)^2 + \left(\frac{p}{h}\right)^2} \tag{1}$$

$$L_{\mathrm{eff}} = L_c - \frac{1.08s^2}{d} + \frac{0.1s^2}{L_c},$$

$$\mathrm{W}_{\mathrm{eff}} = \mathrm{W}_c - \frac{1.08s^2}{\mathrm{d}} + \frac{0.1s^2}{\mathrm{W}_c} \tag{2}$$

where m, n, and p are integers.

To achieve the highest radiation efficiency, the slot must be resonant at the desired operating frequencies. The length of slot can be calculated by using following equation:

$$L_s = \frac{1}{2f_{\mathrm{mnp}}\sqrt{\mu_r \epsilon_{\mathrm{eff}}}} \tag{3}$$

where $\varepsilon_{\mathrm{eff}}$ is an equivalent permittivity of the slot.

The top layer of antenna consists of a rectangular parasitic patch which is reconfigured by eliminating four small isosceles right triangular patches from the diagonally opposite corners of the square patch, as shown in Figure 1B.

As seen in Figure 1, there is an air separation between the ground plane and the substrate which hold the patch. For this case an effective permittivity is used[13]

$$\epsilon_{\mathrm{eff}} = \frac{[\epsilon_2 . \epsilon_{\mathrm{air}}(h_3 + h_2)]}{\epsilon_2 . h_2 + \epsilon_{\mathrm{air}} . h_3} \tag{4}$$

and then the length of path can be calculated using (5).

$$W_p = \frac{\lambda_0}{2\sqrt{\epsilon_{\mathrm{eff}}}} \tag{5}$$

(λ_0 is wavelength in free space at center operation frequency.)

To attain RHCP or LHCP, each of diodes which are embedded in a diameter of parasitic patch are turned ON or OFF simultaneously. Other optimized parameters values of antenna are: $L = 32$, $L_s = 8$, $L_f = 4.6$, $L_{\mathrm{cpwg}} = 5.8$, $L_t = 5.6$, $L_c = 16.8$, $W = 26.6$, $W_f = 1.1$, $W_c = 13.8$, $W_s = 1$, $W_p = 8$, $s = 1$, $d = 1.2$, $t = 1.9$, $h_1 = 0.508$, $h_2 = 0.5$ *and* $h_{\mathrm{air}} = 1$. (all values are in mm).

3 | EQUIVALENT CIRCUIT

To study effects of each parameter, calculate input impedance and each section of antenna impedance and also antenna performance to attain good results of improved values study of a transmission model of antenna is necessary. The first step is to find the input impedance of the slot. When the transmission line is terminated by a stub length, the input impedance is simply put under the rectangular waveguide supposition and this result is added as series reactance, X. The total impedance is then:

$$Z_{\mathrm{slot}} = Z_c \frac{2R}{1-R} + \mathrm{X} \tag{6}$$

the impedance of an SIW, Z_0, can be calculated by[14]:

$$Z_0 = \frac{\frac{h}{w}\eta}{\sqrt{1-\left(\frac{\lambda}{\lambda_c}\right)}} \quad \text{and} \quad \eta = \frac{120\pi}{\sqrt{\epsilon_r}} \tag{7}$$

where Z_c is the characteristic impedance of transmission line and R is voltage reflection coefficient. Second step of realize transmission line model is implementation of reconfigurable patch.

In this model, the antenna is presumed to excite TM_{10} and TM_{01} modes concurrently to achieve circular polarization. While considering the TM_{10} mode, the current flow on the patch is assumed to be in horizontal direction over the large diameter length "a" of the patch whereas during TM_{01} mode, the current flow is taken over the small diameter length "b" of the patch. Correspondingly, we suppose two antenna elements as referred in Figure 2, that each one has impedance L_a, R_a, and C_0 characteristic impedance and propagation constant k_a whereas the other having characteristic impedance L_b, R_b, and C_0 and propagation constant k_b. All these values can be calculated using equations in Refs. 14–16. As seen in Figure 2, if diodes 1 and 3 turn ON generated polarization is RHCP and if diodes 2 and 4 turn ON it changes to LHCP.

The matching circuit design technique is based on the RLC-equivalent impedance behavior of a patch antenna near its basic resonant mode.[16,17] The RLC-equivalence displays the input impedance to be inductive below the center frequency, and capacitive above the center frequency. The slot used to feed the patch (see Figure 1) adds another series

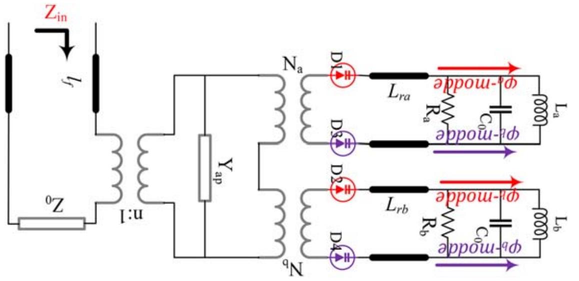

FIGURE 2 Equivalent circuit of the proposed antenna

impedance (inductive effect) to the input impedance. This series impedance has the equivalent effect of the addition of a transmission line section to the antenna. This causes the impedance as function of frequency to be asymmetrical with regards to the center frequency rotated on the Smith chart (as will show in Figures 3 and 4), depending on the length of the slot feed to the patch), at the feed point in the ground plane of the antenna. Moving away from the feed point in the ground plane (the SIW cavity slot indicated in Figure 1) the symmetry in the real and imaginary impedance values around the center frequency can be restored. At this specific position the addition of a parallel resonant circuit with an impedance behavior that can equally well cancel the lower and higher sequence imaginary impedances will improve the impedance behavior of the antenna.

4 | RESULT AND DISCUSSION

The proposed antenna was simulated and optimized by Ansoft HFSS ver.14. Any changes in the values of the each of parameters significantly played effective role on antenna results. In the Figure 3, effect of the parasitic patch, in the

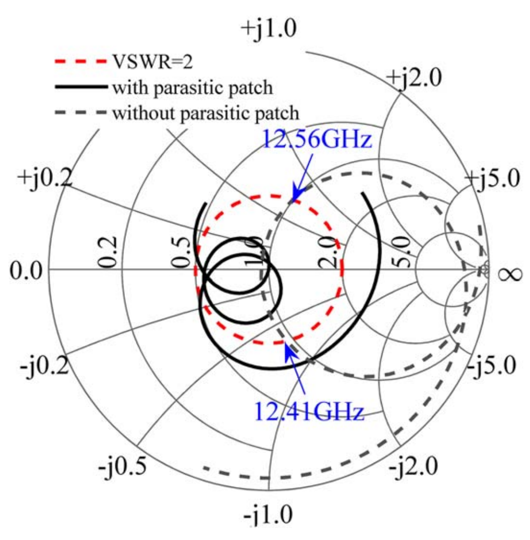

FIGURE 3 simulated S_{11} of antenna with and without using parasitic patch

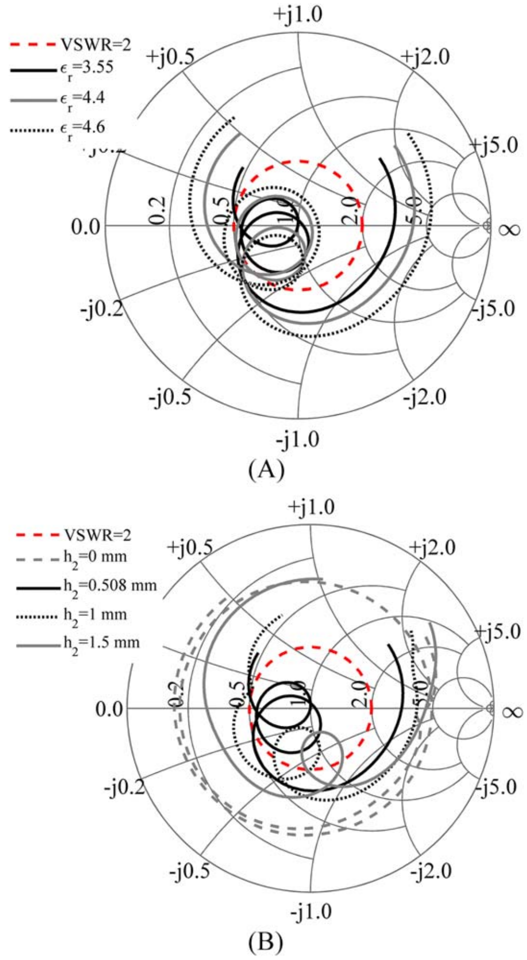

FIGURE 4 simulated S_{11} of parametric study at different values of L_s and W_p versus frequency

presence and absence of it, in simulated results of smith chart is displayed. As seen, when a slot line is only used (without parasitic patch) the antenna is capable to cover frequency range from 12.41 GHz to 12.56 GHz with a resonance. By embedding top layer (with parasitic patch) another resonance at about 14 GHz is occurred. Use of the parasitic patch causes to creation a capacitance effect and it leads to generate a resonance at 14 GHz. Therefore, adjacent of two resonance causes to increase of impedance bandwidth. To realize parametric study of proposed antenna, the values of one parameter are varied and other parameters are held fixed to optimize.

Here two parameters: (1) ε_r of top substrate; and (2) gap distance between two layer (h_2); which play important role in antenna impedance matching are discussed. In Figure 4A effect of relative permittivity (ε_r) is displayed. As seen, by increasing value of ε_r at top substrate capacitance effect is decreased. Reason of it is behind in this fact that two layers that have a distance between themselves, behavior such as two series capacitance. Therefore, by changing each of ε_r and h_2 values, capacitance effect will be affected. With

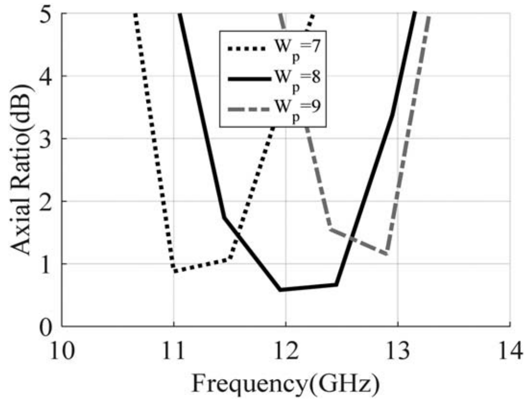

FIGURE 5 simulated axial ratio of parametric study at different value of W_p versus frequency

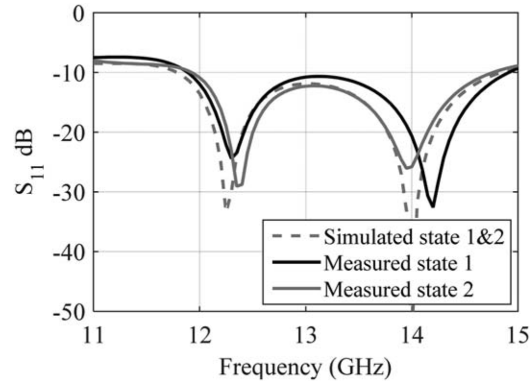

FIGURE 7 Comparison between measured and simulated S_{11} of proposed CP cavity backed SIW antenna at different states

aforementioned reasons by changing h_2 capacitance effect must be varied according to what is shown in Figure 4B.

The optimum values of slot length (L_s) and width of parasitic patch (W_p) are obtained as $W_p = 8$ and $L_s = 8$ mm. As displayed in Figure 5, the 3-dB axial ratio BW is strongly depended on width of parasitic patch dimension (W_p). Figure 5 obviously shows in lower and upper value of $W_p = 8$ mm, 3-dB axial ratio BW decreases and range of covered frequency BW changes. Main reason to change AR by W_p is variation of capacitance effect in top and bottom layers to reach impedance matching.

Besides converting LP to CP by parasitic patch, another advantage of proposed antenna is ability to change polarization diversity. It provides the possibility of changing polarization diversity from left-hand circular polarization (LHCP) to right-hand circular polarization (RHCP). When D_1 and D_3 are turned ON the polarization with attention to pattern and E-field magnitude is RHCP and when D_2 and D_4 are turned ON the polarization diversity could be changed to LHCP. To prevent balance disruption of electromagnetically coupled of SIW slot by high value of DC current, it must be employed a diode by minimum value of bias voltage. The Schottky barrier diode, however, relies on a semiconductor–metal junction that results in a much lower junction capacitance, allowing operation at higher frequencies. Schottky diodes are often biased with a small DC forward current, but can be used without bias.[18]

The antenna polarization is changed by applying a bias voltage of 0.1 V to four Schottky diodes (MZB600-CS12/B11) using a constant-current circuit. The diode exhibits an ohmic resistance of 0.8 V in the forward state and a capacitance of 0.2 pF in the reverse-biased state. The reconfigurable diodes with a size of 0.94 $\times$0.18 mm^2 were inserted into the gaps of 0.73 mm to control the antenna performance and polarization diversity. The equivalent circuit of Schottky diode is presented in Figure 8.

Current vector distributions of the CP cavity backed SIW antenna in two states of the diodes are given in Table 2, Figure 6. As seen from Figure 6A, in state 1, the antenna radiates a RHCP or clockwise field. From Figure 6B, it is proved that a LHCP or counterclockwise field is obtained, while state 2 is performed. To confirm the simulated performance of the antenna, prototypes of the antenna was fabricated using the printed circuit board process. The scattering parameters (S_{11}) of the proposed antenna have been measured using an N5225A PNA Microwave Network Analyzer. Figure 7 shows a comparison of measured and simulated S_{11} at different state of the proposed antenna. Worthy impedance matching of measured and simulated S_{11} is obtained. the

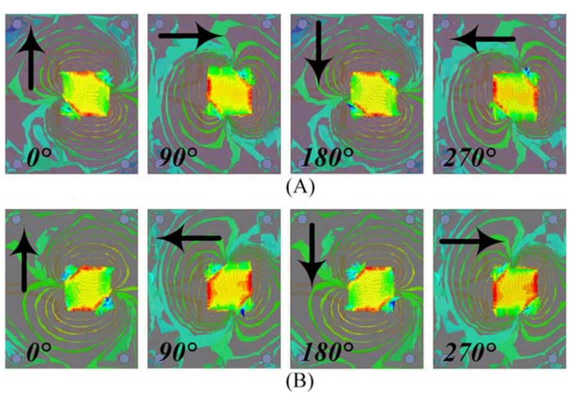

FIGURE 6 Current vector distributions of proposed antenna. (A) RHCP (state 1); and (B) LHCP (state 2)

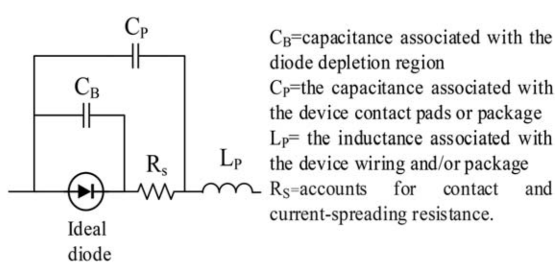

FIGURE 8 The equivalent circuit of Schottky diode

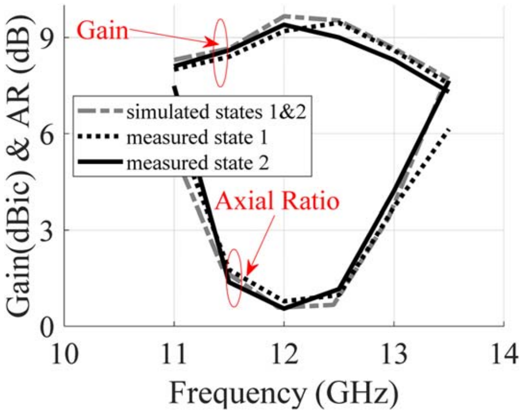

FIGURE 9 Measured and simulated AR and gain of proposed Antenna

measured impedance BW (VSWR < 2) for state 1 and 2 are 22.18% (11.86-14.82 GHz) and 21.68% (11.88-14.77 GHz), respectively, with respect to the center frequency at 12 GHz.

Figure 9 illustrates the measured gain and AR of the proposed antenna against frequency for states 1 and 2. As seen from the figure, the maximum gain of antenna at states 1 and 2 are 9.81 and 9.76 dBic, respectively. In fact, parasitic patch causes to increase gain of antenna. The reason for this is that electric wave is applied perpendicular to the surface of the conductor. Thus, parasitic patch on top of the slot prevents the dispersion of the electromagnetic wave and causes to increase of gain by focusing it.

As aforementioned, the parasitic patch causes circular polarization (CP) in states 1 and 2. Indeed, the parasitic patch plays the role of a circular polarizer which converts linear polarization to CP. The measured 3-dB AR BW for states 1 and 2 are about 11.46% (11.43-12.82 GHz) and 11.23% (11.43-12.79 GHz), respectively.

Simulated and measured radiation efficiency values of the proposed antenna for two states is displayed in Figure 10. As seen in this figure, the antenna with about 79% peak of radiation efficiency can provide high gain. In addition to, near two resonance frequency, antenna has a radiation efficiency ratio which it proves good impedance matching with high value of radiation resistance.

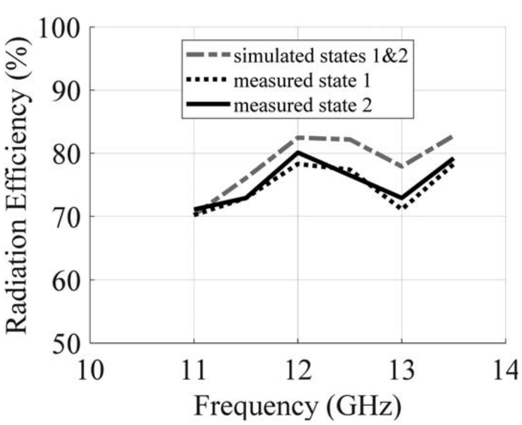

FIGURE 10 Measured and simulated Radiation efficiency of proposed Antenna

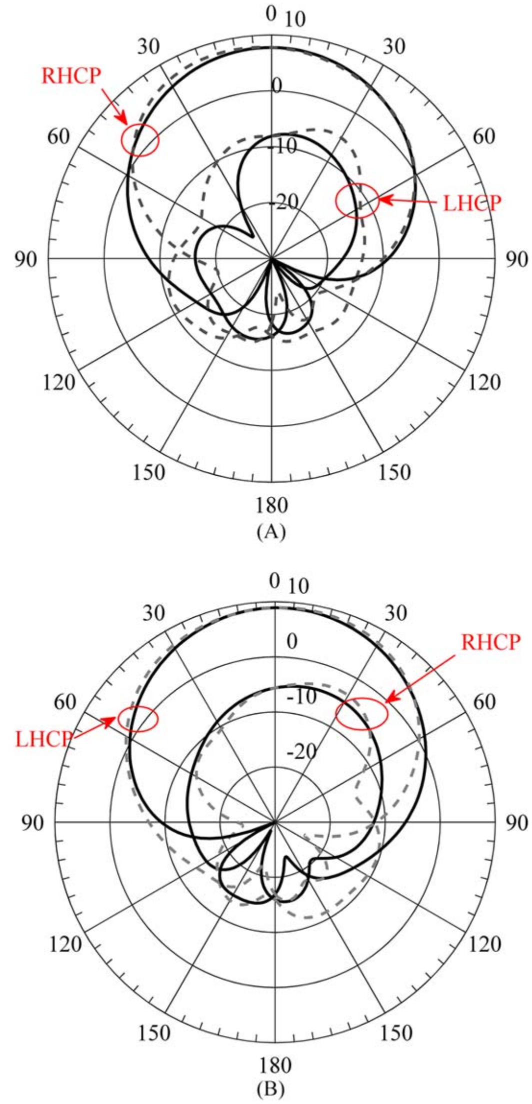

FIGURE 11 Measured RHCP and LHCP patterns of proposed CP antenna (Solid line is $\varphi = 0°$ and dash line is $\varphi = 90°$) (A) RHCP (state 1); and (B) LHCP (state 2)

In Figure 11, the measured radiation patterns of the proposed antenna at $\varphi = 0°$ and $90°$ planes (*XZ*- and *YZ*- planes) are displayed in the center frequency of 12 GHz. The CP performance was measured using a rotating linearly polarized transmitting dipole antenna. In state 1, the antenna

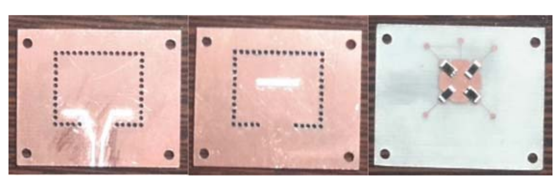

FIGURE 12 Prototype of fabricated proposed antenna

polarization is RHCP and by changing to state 2, the polarization of the antenna is altered to LHCP. The proposed antenna can cover a wide range of HPBW at two states. For state 1 and 2 HPBW are 64-degree and 67-degree, respectively. Photograph of fabricated antenna is shown in Figure 12.

5 | CONCLUSION

A novel two-layers substrate integrated waveguide (SIW) cavity-backed circularly polarized antenna has been presented. The antenna with a parasitic patch which all four corner of it are etched, is able to change the circular polarization diversity from left hand to right hand and vice versa. From significantly features that distinguishes proposed antenna in compared with similar works is ability to produce CP from a LP slot antenna. 22.18% (11.86-14.82 GHz) Impedance BW, 11.46% (11.43-12.82 GHz) 3 dB ARBW, and 9.81 dBic gain are realized by optimizing the antenna parameters. Obtained results show that the proposed design offers really improved antenna performance compared with other similar plans.

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AUTHOR BIOGRAPHIES

Saeid Karamzadeh received his MS and Ph.D. degrees in Department of Communication Systems, Satellite Communication & Remote Sensing program at Istanbul Technical University in 2013 and 2015 respectively. He won the most successful PHD thesis award of Istanbul Technical University. Currently, he is an assistant professor in the Istanbul Aydin University, Department of Electrical and Electronics Engineering. He is also with Application & Research Center for Advanced Studies in the Istanbul Aydin University, Turkey. His research interests include remote sensing, radar, microwave, and Antenna design.

Vahid Rafiei was born in Naghadeh, IRAN in 1986. He is author and co-author 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.

HASAN SAYGIN Professor of Engineering, specializing in Applied Sciences, and Advisor to the Chairman of the Board of trustees at the Istanbul Aydin University. He received his PhD. from École Polytechnique de Montréal, Institut de génie énergétique at the Université de Montréal, and his MSc in Nuclear Energy from Istanbul Technical University. His working area are Nuclear Energy, Thermodynamic, Computational Fluid Mechanics, Energy Policy, microwave and Antenna application.

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