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Design and Development of High Gain, Low Profile and Circularly Polarized Cavity-backed Slot Antennas Using High-order Modes of Square Shaped Substrtae Integrated Waveguide Resonator

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ABSTRACT

In In this paper, two low profile, single fed cavity backed slot antennas providing a circularly polarized (CP) wave are introduced. One of the antennas presents a right-handed CP (RHCP) wave, while the other one offers a left handed CP (LHCP) wave. The proposed antennas consist of a square shaped Substrtae Integrated Waveguide (SIW) cavity incorporatng two couples of radiating slots to radiate two field components with 90° phase difference far from the antennas. A single layer of printed circuit board (PCB) process is employed for both antennas to provide low cost, light weight and also to be compatible with planar circuits. An inset feed line is used to excite two orthogonal modes including TE_{120} and TE_{210} with suitable phase difference for generating CP wave. Antenna structures is numerically evaluated using High Frquency Structure Simulator (HFSS) and a prototype of RHCP antenna is fabricated and its radiation charateristics including reflection coefficient, gain, Axial Ratio (*AR)* and radiation patterns are reported.

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1. INTRODUCTION

In recent years, the design and development of antennas providing high performance radiation properties including low profile, light weight, easy fabrication and compatibility with planar circuits has been progressively emerging due to advances of wireless microwave and millimeter wave communication systems [1]. In addition, using the Circularly Polarized (CP) antennas leads to overcome the limitation of polarization mismatch, which results from wave propagation in certain media such as ionosphere.

Variety of methods has been proposed in literature to design and implement CP antennas using microstrip patches. In literature [2] a wideband aperture coupled multi-layer patch CP antenna is designed and made based on using a crossed slot at the second layer of the structure. The obtained result for impedance bandwidth is 30% for 10 dB return loss and Axial Ratio (*AR*) bandwidth is 12% for *AR* less than 3 dB. In literature [3] CP antenna is introduced by exciting a circular patch using a cross shaped coupling slot with unequal lengths and the measured 2 dB *AR* bandwidth is only 0.65%. The proposed antennas in literature [2, 3] are multi-layer structures and therefore, they suffer from both the difficulty of arrangement of different layers and the complexity of the feeding structure.

In order to avoid those complexities, a single feed line CP patch antenna is presented in literature [4], in which a patch is excited by a coplanar waveguide. The antenna is made using a single layer of substrate and the measured 3 dB *AR* bandwidth is 1.6%. Nevertheless of this low value of bandwidth of the patch antennas, they suffer from surface waves and low radiation efficiency due to their conductor loss especially at high frequencies.

In order to eliminate the drawbacks of patch antennas, cavity-backed slot antennas are presented in literature [5, 6], which exhibit suitable radiation performance including unidirectional radiation patterns. However, due to the large size and three dimensional structure of the conventional metallic cavity, the integration of these antennas with planar microwave circuit is a challenge.

Substrate Integrated Waveguide (SIW) technology

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was firstly proposed in literature [7] to facilitate integration of bulky waveguide with planar circuits. In recent years, the applications of SIW have been widely developed in designing and implementing microwave components and antennas [8, 9]. The cavity-backed slot antenna based on the SIW technology is proposed in [8]. Although using these antennas, the size of the radiating structure is significantly reduced, but they provide narrow bandwidths, especially while thin substrates are used. In literature [9], three crossed slot antennas backed by the SIW cavity for dual frequency, dual linear polarization and CP antennas are presented. The CP antennas proposed in literature [10] produce RHCP and LHCP waves and for both antennas the achieved *AR* bandwidth is nearly 0.8%. In literature [11], two low profile cavity-backed slot antennas are introduced using Half Mode SIW (HMSIW) resonator providing RHCP and LHCP waves. It is shown that the measured impedance and *AR* bandwidth are 8.8% and 1% respectively.

In this paper, using two couples of inclined radiating slots with respect to the diameter of the square cavity, two low profiles, and single fed CP antennas including RHCP and LHCP antennas are proposed. An inset feed line is used to feed the cavity to assist integration with the planar structure. Two antennas are designed, and simulated using the electromagnetic full-wave solver High Frequency Structure Simulator (HFSS). A prototype of one of the proposed antennas providing RHCP wave is fabricated using a single layer of substrate by standard Printed Circuit Board (PCB) process and its radiation characteristics are successfully measured.

2. ANTENNA DESIGN AND CONFIGURATIONS

Two antenna schemes for the proposed RHCP and LHCP antennas and their geometrical parameters are shown in Figure 1. The cavities of both antennas are squares and are realized using the SIW structure. The lengths of the cavities are denoted by L_c. In order to represnt the square SIW cavity equivalent to a conventional metallic resonator, two conditions incluing Equations (1) and (2) have to be satisfied.

$$\frac{d}{p} < 2 \tag{1}$$

$$\frac{p}{\lambda_o} \le 0.1 \tag{2}$$

in which, λ_0 is the free space wavelength, while d is the separation between two adjacent vias and p is the via diameter. The radiating slots of the antennas are etched on the ground plane of the substrate and its length and width are designated by l_s and W_s respectively and they are the same for all four slots. The distances between the radiating slots to the centre of the cavity are labeled as d_1, d_2, d_3 and d_4. The feed line is placed on the top surface of the substrate to avoid parasitic radiation due to feeding line. Geometrical structures of both antennas are the same, except for their distances to the cavity centre which are different. This difference makes them provide opposite circular polarizations.

In order to meet the requirement of planar integration, a single inset feed line is employed, which is located along the diagonal line of the square shaped cavity. A 50 Ω microstrip line is added at the end of the feed line to facilitate adopting SMA connector. The dimensions of the two proposed antennas are listed in Table 1. Also, Ansoft HFSS is used to numerically investigate the radiation performance of the proposed antennas.

A prototype of the proposed antenna for the RHCP one is fabricated using single layer of TLY031 substrate with permittivity of 2.2, loss tangent of 0.001 and a thickness of 0.787 mm and its radiation characteristics are measured and compared with those obtained by simulation process.

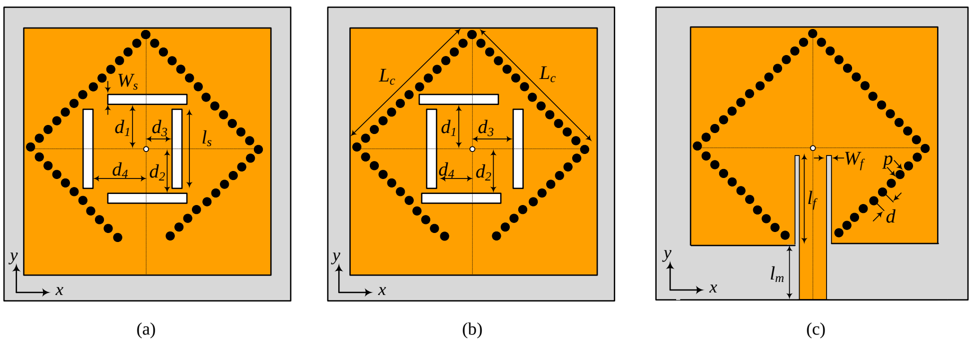


Figure 1. The configurations and the geometrical parameters of the proposed antennas, a) top view of the RHCP antenna, b) top view of the LHCP antenna, c) rear view of both antennas

TABLE 1. The geometrical parameters of the RHCP proposed antenna.

Parameter	Value (mm)
l_s	8.7
L_c	17.8
W_f	0.6
l_m	4
p	1
W_s	1
L_e	26
l_f	12.9
s	1.5
d_1	5.2
d_2	5.2
d_3	2.8
d_4	5.2

3. ANTENNA SIMULATION

3. 1. Field Distribution Figure 2 shows the simulated electric field distribution of the first four modes of the square cavity for a specific side length of 17.8 mm. These are obtained using eigen mode analysis of HFSS. Also, simulated resonant frequency and unloaded Q-facotr of different modes are summerized in Table 2. The two modes, TE_{120} and TE_{210} are orthogonal degenerate modes with same resonant frequency, which can be obtained by Equation (3):

$$f_{m0n} = \frac{c}{2L_{ce}\sqrt{\varepsilon_r}}\sqrt{m^2+n^2} \quad \left.\begin{matrix} m=1,2,3.... \\ n=1,2,3.... \end{matrix}\right\} \tag{3}$$

in which, c is the free space light speed, ε_r is the permitivity of the substrtae and L_{ce} is the effective length of the cavity, which is calcluated by Equation (4).

$$L_{ce} = L_c - 1.052\frac{d^2}{p} \tag{4}$$

According to Figure 2, each mode is formed by two subsections of the cavity and the maximum electric fields of the two modes are perpendicular to each other. Using two couples of radiating slots on the surface of the cavity, as shown in Figure 1, and by adjusting the distance between them, the phase difference between the radiated field components is adjusted 90° and therefore, a CP wave is radiated far from the antenna.

Using an inset feed line, the two TE_{120} and TE_{210} degenerate modes can be simultaneously excited.

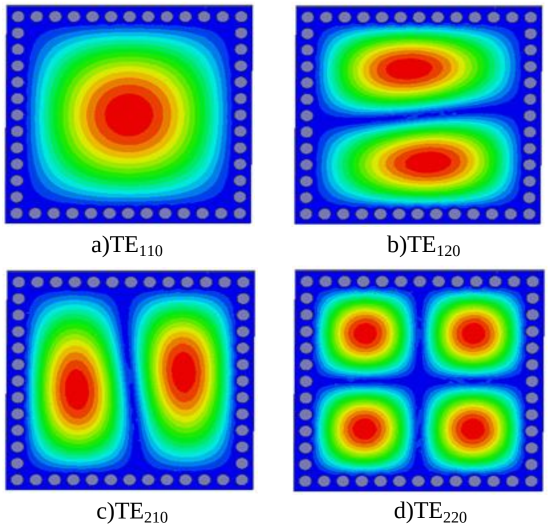


Figure 2. The simulated electric field distribution of the SIW square cavity at first four resonant modes, a) TE_{110}, b) TE_{120}, c) TE_{210}, d) TE_{220}

TABLE 2. The simulated resonant frequency and unloaded Q-factor of the square shaped cavity with L_c =17.8 mm and TLY031 substrate

Mode	Resonate frequency (GHz)	Unloaded Q-factor
TE_{110}	8.3	534
TE_{120}	13.27	740
TE_{210}	13.27	870
TE_{220}	16.6	906

Also, using suitable pair of parallel slots, two components with required phase differences of the radiated field far from the antenna are obtined to produce a CP wave. In addition, due to using two parallel slots along x and y directions, an array of two radiating slots is formed and in turn antenna gain is improved compared to the gain of an antenna with a single radiating slot [12].

3. 2. Parametric Analysis In order to study the effect of the slot distances with respect to the centre of the cavity, a parametric study is performed and AR of the antenna is investigated. The effects of distances d_i for different slots, i=1,2,3,4, on AR of the antenna are shown in Figure 3, in which they are set equal (d=d_1=d_2=d_3=d_4). It can be observed that AR is always greater than 10 dB, which means that the antenna radiates a Linearly Polarized (LP) wave. This is due to that the two subsections, a negative or a positive one, are in such a way that the far fields along the radiating slots are in an opposite direction and in turn, circularly polrized wave is not radiated.

In order to obtain a radiated CP wave, one of four separations between the radiating slots is changed, while the other ones are remained unchanged. Figure 4 shows the effects of d_4 on *AR*, while d_1, d_2, and d_3 are set to be 5.2 mm. It can be seen that in case of d_4=2 mm, *AR* is less than 3 dB, and in turn a CP wave is produced.

Figures 5(a) and 5(b) show the effects of the slot length l_s, on reflection coefficient and *AR* respectively, while d_4=2mm and W_s=1mm. It can be seen that by decreasing the slot length l_s, better impednace matching is obtained, whereas by increasing the slot length, *AR* is increased.

To investigate the effects of the slot width on *AR* of the proposed antenna, a parametric study is also carried out. The simulated results and the variations of S_{11} and *AR* are shown in Figure 6 versus frequency for l_s = 8.7 mm and different values of W_s. It can be concluded that better matching and minimum *AR* are obtained for slot width of W_s =1 mm.

The effects of the inset feed line l_f on reflection coefficient S_{11} and antenna gain for W_s=1 mm are shown in Figure 7. As it can be seen, with increasing the feed line, better matching is obtained and for the length of 9.5 mm best matching condition with acceptable bandwidth is achieved.

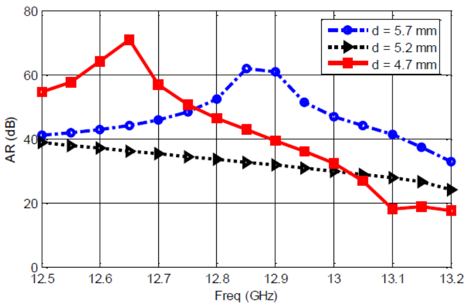


Figure 3. The effects of distance *d*, $d=d_1=d_2=d_3=d_4$ on *AR* of the proposed RHCP antenna

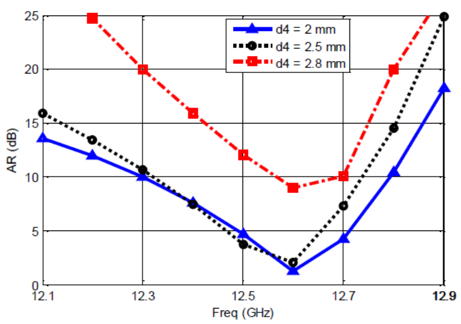
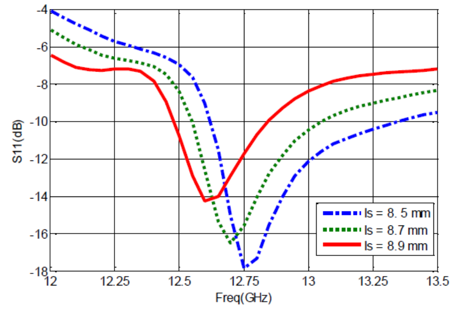
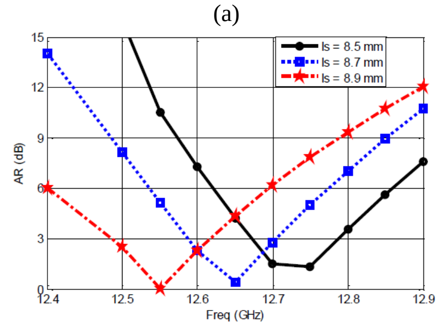


Figure 4. The effects of distance d_4 on *AR* of the proposed antenna, while the other distances d_1, d_2, and d_3 are equal to 5.2 mm

However, referring to Figure 7(b), which shows the effects of l_f on antenna gain for W_s = 1 mm, it can be concluded that with increasing l_f, the antenna gain decreases. As a result, the best value of l_f is 8.9 mm.

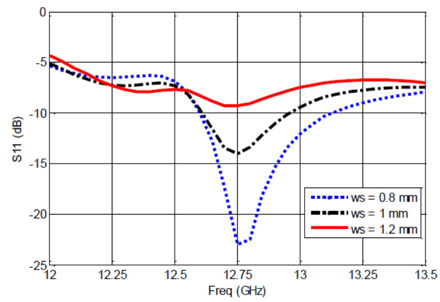


(a)

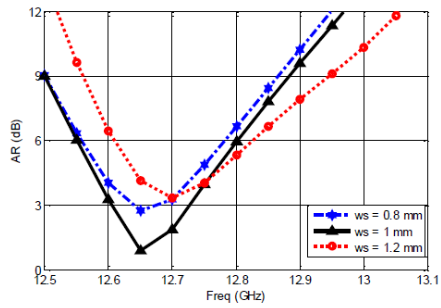


(b)

Figure 5. The effects of the slot length of the proposed antenna with d_4 = 2 mm and slot width of W_s= 1 mm, a) S_{11}, b) *AR*

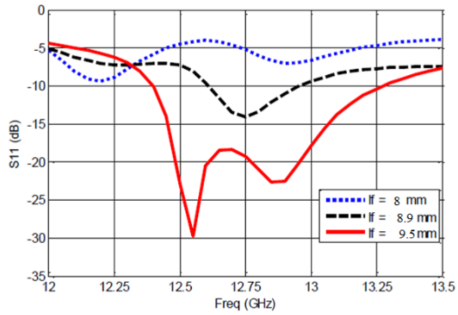


(a)

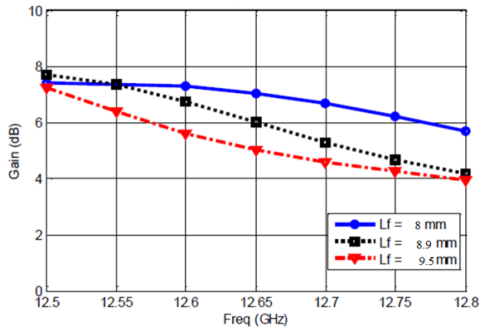


(b)

Figure 6. The effects of slot width W_s of the proposed antenna on a) S_{11}, b) *AR* with l_s = 8.7 mm



(a)



(b)

Figure 7. The effects of the feed line length l_f of the proposed antenna on a) S_{11}, b) antenna gain versus frequency for w_s= 1 mm and different values of l_f

4. MEASURED RESULTS AND DISCUSSION

To validate the design procedure of the proposed RHCP antenna, a prototype of the antenna is made by a single layer of TLY031 substrate using low cost PCB process. The designed antenna is numerically and experimentally investigated and its radiation characteristics are examined. The photo of the fabricated antenna is illustrated in Figure 8. The antenna size is 17.8×17.8 mm^2 and its geometrical parameters are summarized in Table 1.

The simulated and measured results of S_{11} and *AR* are shown in Figure 9. It can be seen that apart from a shift in resonant frequency of the antenna due to fabrication imperfections, there is a good agreement between the measured results and those obtained by simulation.

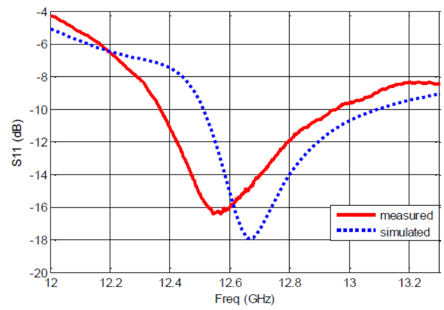
(a) (b)

Figure 8. The photo of the fabricated RHCP proposed antenna. a) top view, b) rear view

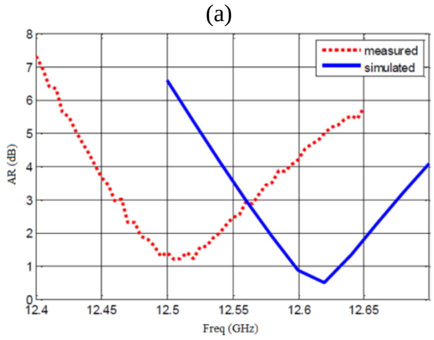
The measured results show that, reflection coefficient is below -10 dB from 12.39 GHz to 12.95 GHz, corresponding to 560 MHz impedance bandwidth. This means that the measured fractional impedance bandwidth is 4.42 %. The measured and simulated *AR* of the antenna are plotted in Figure 9(b). *AR* is considered as the ratio of major axis to the minor axis of the polarization ellipse. *AR* is measured at the backside direction, θ = 180°, versus frequency. Results indicate that minimum *AR* is 0.5 dB at 12.62 GHz, whereas measured fractional *AR* bandwidth is 0.9 % for *AR* values less than 3 dB. Although, the reonant frequency of the square cavity is 13.27 GHz, but adding the radiating slots the resonant frequency at minimum S_{11} occurs at 12.58 GHz and the best value of *AR* is obtained at 12.62 GHz.

The simulated gain of the proposed antenna including the measured results at a few frequencis are depicted in Figure 10(a). Also, the measured gain at minimum value of *AR* is 7.5 dBi, which agrees well with that of the simulation results. In addition, it can be seen that with increasing frequency, the antenna gain is decreased. It is believed that this is due to increasing conductor loss with frequency and in turn, antenna gain is decreased. The simulated radiation efficiency of the proposed RHCP antenna is plotted in Figure 10(b). The simulated radiation efficiency is at least 95% over the frequency range under study.

The simulated electric field distribution of the proposed antenna at 12.62 GHz is shown in Figure 11, while the simulated *AR* is minimum at this frequency.



(a)



(b)

Figure 9. The simulated and measured a) S_{11}, b)*AR* versus frequency

It can be observed that 90° phase difference exists between the two excited modes of the cavity.

The simulated radiation patterns of the proposed RHCP antenna in two planes, φ= 0° and φ =90° at the frequency with minimum *AR* are illustrated in Figure 12. The experimental radiation patterns at φ = 0° plane is also shown in Figure 13. It confirms that a right-hand circularly polarized wave is radiated by the proposed antenna. Also, the LHCP level within half power beamwidth (HPBW) of the antenna is below -20 dB with a front to back ratio (FBR) of 10 dB at φ = 0°. By swapping, the distances d_3 and d_4, then an antenna with LHCP radiating wave is obtained.

A comparison between the measurement results of our proposed antenna and the results of the previously reported CP antennas is summerized in Table 3.

It can be seen that the proposed antenna in this paper provides higher gain compared to that of the antenna published in literature [8].

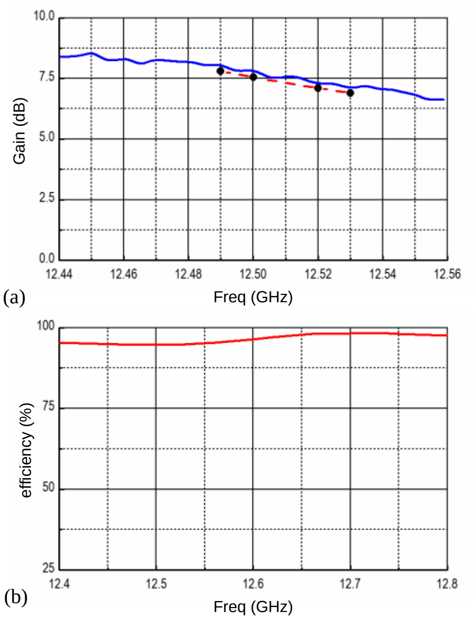


Figure 10. a) The simulated and measured gain of the proposed RHCP antenna, data points masured values, data line simulation results, b) the simulated radiation efficiency of the RHCP antenna

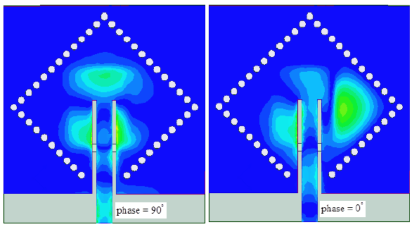


Figure 11. The simulated electric field distribution of the two orthogonal modes of the cavity at 12.62 GHz

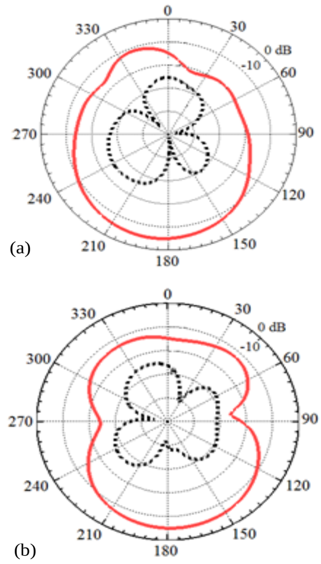


Figure 12. The simulated radiation patterns of the proposed RHCP antenna at 12.62 GHz, a) φ = 0°, b) φ=90°

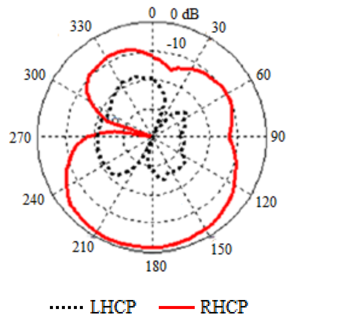


Figure 13. The measured radiation patterns of the proposed RHCP antenna at 12.62 GHz and φ = 0°

TABLE 3. Radiation performance comparison of the proposed RHCP antenna with previously published ones

Number of layer	Feed line	Antenna gain (dBi)	*AR* bandwidth (%)	Impedance BW (%)	ε_r	Substrate thickness	
Single	microstrip	6.3	0.8	3	2.2	$0.017\lambda_o$	Ref. [9]
Two	probe	13	11	15	2.2	$0.32\lambda_o$	Ref. [10]
Single	microstrip	4.88	1	8.8	2.2	$0.033\lambda_o$	Ref. [11]
Single	microstrip	7.5	0.9	4	2.2	$0.033\lambda_o$	This paper

Moreover, compared with that published in literature [11], it is observed that our antenna provides lower gain and lower impedance and *AR* bandwidth. However, the antenna in literature [11] is made up of two layers of substrates. The most important advantages of our proposed antennas is that they provide no parasitic radiation for both antennas.

5. CONCLUSION

In this paper, two new low profile cavity-backed slot antennas for producing RHCP and LHCP wave are presented. Both antennas are made of a square-shaped cavity using SIW technique on a single layer substrate. An inset feed line is used to excite two orthogonal degenerate modes including TE_{120} and TE_{210} of the cavity with 90° phase difference for generating CP wave. Four inclined slots of the same length and width are used to radiate a circularly polarized wave.

By adjusting the distance between different slots, 90° phase shifts between the two radiated components is obtained. The proposed antennas are numerically inspected using HFSS and one prototype of the proposed RHCP antenna is made and its radiation characteristics are measured. It is shown that a very good agreement is obtained between the simulation and measured results. Measured resluts show that the fabricated antenna provides impedance bandwidth of 4%, gain of 7.5 dBi and *AR* bandwidth of 0.9%. The proposed new antennas provide the advantage of conventional metallic cavity backed antenna including high gain, and also offer other advantages of planar antenna including low profile, light weight, low fabrication cost and easy integration with planar circuit.

6. ACKNOWLEDGMENT

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چکیده

در این مقاله، دو آنتن روزنه ای تغذیه شده با حفره تشدید و تحریک با خط انتقال از یک نقطه برای تولید موج با قطبش دایروی معرفی می شوند. یکی از آنتن‌ها دارای قطبش دایروی چپ گرد و آنتن دیگر دارای قطبش دایروی چپ گرد است. آنتن های پیشنهادی از تشدید کننده مربعی با فناوری موجبر مجتمع شده در زیر لایه ساخته شده و همراه با دو جفت روزنه مستطیلی تشعشع کننده، دو مولفه راه دور میدان با اختلاف فاز °۹۰ برای ایجاد قطبش دایروی ایجاد می‌کنند. آنتن ها با استفاده از فرآیند مدار چاپی و از یک زیرلایه دی‌الکتریک طراحی شده‌اند که هزینه ساخت آن‌ها کم، سبک و به‌سادگی با مدارهای صفحه‌ای سازگار است. با استفاده از خط تغذیه میکرواستریپ مُدهای TE_{120} و TE_{210} تشدید کننده مربعی با فاز مناسب تحریک شده و موجی با قطبش دایروی ایجاد می‌شود. ساختار آنتن با استفاده از نرم افزار HFSS شبیه سازی شده و برای یک نمونه ساخته شده، مشخصات تشعشعی آنتن شامل ضریب بازتاب، بهره، الگوی تشعشع و *AR* گزارش می‌شوند.

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