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The Circularly Polarized Sandglass-shaped Dielectric Resonator (DR) Antenna with Cross-shaped Slot

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Abstract: A new circularly polarized (CP) dielectric resonator (DR) antenna is addressed in this research. A cross-shaped slot embedded on the ground plane is used as a feed of a sandglass-shaped dielectric resonator (SSDR). An analytical method is also proposed to determine the initial dimensions of the proposed SSDR. The performance of the DR antenna is investigated using two electromagnetic (EM) full-wave simulators, including CST Studio Suite and Ansys HFSS. To this end, the most important antenna parameters such as the antenna gain, reflection coefficient, radiation pattern, total efficiency and axial ratio are reported. The numerical results show that the introduced DR antenna provides 600MHz (12.25%) impedance bandwidth from 4.6-5.2 GHz at the operation frequency of 4.9GHz. Correspondingly, the proposed antenna provides the axial ratio bandwidth (AR< 3dB) range of 320MHz (6.5%) from 4.85-5.17 GHz and high gain around 7.3dBi with more than 94% total efficiency. The designed antenna is suitable for wireless systems such as Wi-Fi and Wi-Max.

Index Terms: Cross-shaped Slot, Dielectric Resonator Antenna, Sandglass-shaped

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I. INTRODUCTION

Wireless communication devices are becoming smaller and increasingly multifunctional. Regarding dimension limitation, port-to-port coupling, the traditional solution of using two or more radiation elements to realize multifunction or diversity schemes might be not feasible. Using the dielectric resonator antenna with several functions is a feasible candidate with low overall size and cost for the mentioned purpose [1-3]. One of the most attractive features of dielectric resonator antennas is that DR shapes can be tailored to fit specific requirements.

Recently, some dielectric resonator antenna with various configurations for instance stair-shaped [4], trapezoidal [5] and different feeding types such as microstrip feed-line [6], coaxial cable [7] and rectangular waveguide [8] have been focused. Among different types of DR antennas, the DR antennas with circular polarization have an important role in wireless communication systems such as Wi-Fi, Wi-Max and radar systems [9]. Circular polarization because of creating flexibility to orientation between transmitter and receiver antenna has an advantage over linear polarization [10].

In the recent researches, advanced designs of DR antennas regarding to achieve circular polarization have been reported [11]. A high gain omnidirectional circularly polarized slot array antenna by applying the slot array to the cylinder structure has been proposed in Ref [12]. In this article, left-hand and right-hand circularly polarized ports are assigned. This antenna operates at 5.2-5.9GHz with the peak gain of 5dBi. Ref [13] have proposed a rectangular stair-shaped dielectric resonator antenna with circular polarization by feeding a narrow slot that supports multiple resonances. A parametric study on the physical parameters of the proposed antenna has been performed and the antenna was produced with a wide 3dB-axial ratio bandwidth of 10.6%. In Ref [14], by using the new technique of hybrid dielectric resonator antenna in the antenna design process, the designed antenna has generated 26.66% axial ratio bandwidth. A CP cylindrical DR antenna exited by dual conformal strips with axial ratio of 20% is investigated.

In this paper, a circularly polarized DR antenna with high gain, high efficiency and compact size is introduced. In order to achieve circular polarization, a cross-shaped slot is applied on the proposed antenna ground and the physical parametric study on the structure is done. Two numerical methods are used to analyze the performance of the designed antenna and the 10dB impedance bandwidth, radiation pattern, efficiency and axial ratio of the structure are investigated.

This research article is divided into five main units. In the first unit, an analytical method is proposed, which can be used to initial design of the sandglass-shaped dielectric resonator. The geometry of the designed structure is described in the second section. In the third section, the numerical results are reported. The effect of physical parameters of the proposed structure on

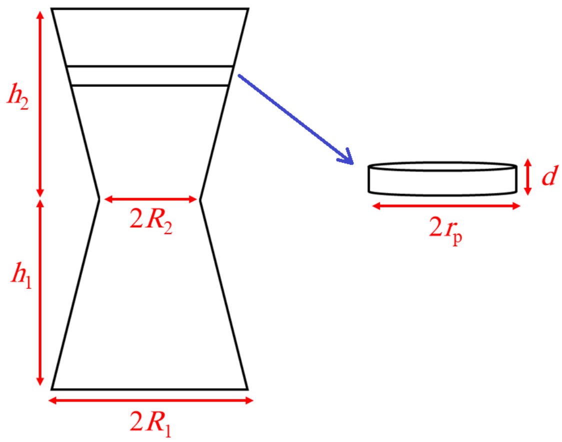


Fig. 1. The geometry of the sandglass-shaped DR

the antenna performance such as axial ratio bandwidth and polarization is performed in the fifth section.

II. ANALYSIS OF SANDGLASS SHAPED DIELECTRIC RESONATOR ANTENNA

In this section, an analytical method is proposed to study a sandglass-shaped dielectric resonator (SSDR). As shown in figure (1), the sandglass-shaped DR is divided into *P* number of equi-length of the cylindrical DR, with each cylindrical DR having constant permittivity.

According to the magnetic wall model [15], the side wall of SSDR can be considered as a Perfect Magnetic Conductor (PMC). By ignoring the feed, each cylindrical DR is considered as a cylindrical waveguide with PMC walls. The TE mode will be investigated and the similar procedure can be done for the TM mode. From the microwave theory, the phase constant γ and impedance Z_p of a cylindrical waveguide can be expressed as follows [16]:

$$\gamma_p = \alpha_p + j\beta_p \tag{1}$$

$$\beta_p = \sqrt{\omega^2 \mu\varepsilon - \left(\frac{x_{nm}}{r_p}\right)^2} \tag{2}$$

$$\alpha_p = \frac{\omega^2 \mu\varepsilon \tan\delta}{2\beta_p} \tag{3}$$

$$Z_p = \frac{\omega\eta\sqrt{\mu\varepsilon}}{\beta_p} \tag{4}$$

where μ, ε, x_{nm}, and tanδ are the magnetic permeability, electric permittivity, *m*th root of the derivative of the Bessel function of the first kind, and loss tangent of dielectric, respectively. Each transmission line (TL) with the specified phase constant and characteristic impedance can be described by a transmission matrix T. The transmission matrix T of each cylindrical DR is defined as [16]:

$$T_p = \begin{bmatrix} \cosh(\gamma_p d) & Z_p \sinh(\gamma_p d) \\ \sinh(\gamma_p d)/Z_p & \cosh(\gamma_p d) \end{bmatrix} \tag{5}$$

The total transmission matrix of a series of TLs can be calculated by multiplying the transmission matrix of each segment. So, the total transmission matrix of the SSDR can be determined as:

$$T_{\text{total}} = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} = \prod_{p=1}^{P} T_p \tag{6}$$

The normalized scattering parameters of the SSDR can be calculated as follows [16]:

$$S_{11} = \frac{T_{11} + T_{12} - T_{21} - T_{22}}{T_{11} + T_{12} + T_{21} + T_{22}} \tag{7}$$

$$S_{12} = \frac{2(T_{11}T_{22} - T_{12}T_{21})}{T_{11} + T_{12} + T_{21} + T_{22}} \tag{8}$$

$$S_{21} = \frac{1}{T_{11} + T_{12} + T_{21} + T_{22}} \tag{9}$$

$$S_{22} = \frac{-T_{11} + T_{12} - T_{21} + T_{22}}{T_{11} + T_{12} + T_{21} + T_{22}} \tag{10}$$

It should be noted that the radius of top and bottom surfaces of SSDR are equal. It is desired that the pumped energy into the structure propagates into the air completely. This condition can be defined as S_{11}=0, S_{12}=0, S_{21}=1, S_{22}=0. These equations lead to a nonlinear system of equations as follows:

$$\begin{cases} S_{21} = 1 \\ S_{11} = 0 \\ S_{12} = 0 \\ S_{22} = 0 \end{cases} \rightarrow \begin{cases} T_{11} + T_{12} + T_{21} + T_{22} = 1 \\ T_{11} + T_{12} - T_{21} - T_{22} = 0 \\ T_{11}T_{22} - T_{12}T_{21} = 0 \\ -T_{11} + T_{12} - T_{21} + T_{22} = 0 \end{cases} \tag{11}$$

The nonlinear system of equations has four equations with four unknowns R_1, R_2, h_1, and h_2. To design a sandglass-shaped DR, and for the given dielectric permittivity and resonant frequency, the dimensions of SSDR can be calculated by solving the established nonlinear system of equations (11). The above equation shows a no-linear system of equations. So, an iterative/numerical technique or algorithm-based methods such as genetic algorithm (GA) or particle swarm optimization (PSO) must be employed to solve it. It should be noted that the proposed method can be used to estimate the initial values of the dimensions for the given resonant frequency and dielectric permittivity. The best response can be obtained using the optimization process by a full-wave simulator.

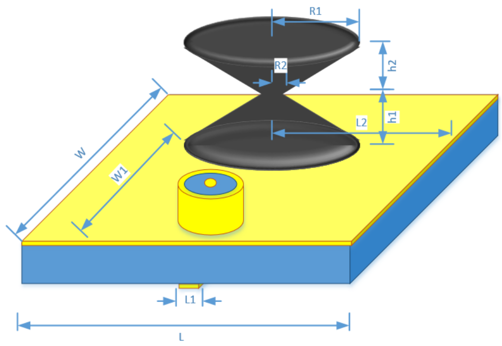


Fig. 2a. 3D view of the proposed structure

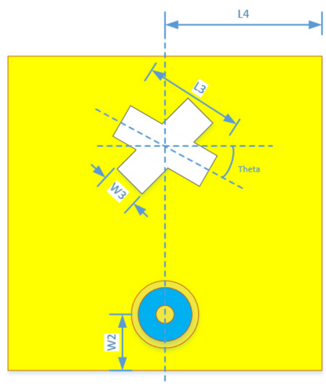


Fig. 2b. Top view of the proposed structure

There is no unique way to determine the value of the number of segments P. But we can estimate the value of P using the discretization concept in the numerical techniques in electromagnetic. Our studies show that by choosing $P=\lambda_0/20$, the accuracy will be acceptable. If the losses of dielectric are high, it affects the axial ratio and polarization too. But there is no clear relationship or analytical method between the dielectric, conductor, and radiation losses. Only using the full-wave simulation, the effect of losses can be studied on axial ratio and polarization changing. However, by employing a low loss dielectric, the influence of losses can be minimized.

In this work, the circularly polarized sandglass-shaped DR antenna is proposed and the geometrical configuration of this antenna is shown in Fig. 2(a). The dielectric resonator is fabricated on Rogers RO3210 material with relative permittivity ε_r=10.8 and dielectric loss tangent 0.0027 which is placed at the top of the ground with thickness of 0.035mm. To obtain the circular polarization, the cross-shaped slot is applied on the antenna ground plane (Fig. 2(b)). According to Babinet's principle, a cross-shaped slot is a complementary pair of a crossed-dipole [17]. If (W_l, L_l) and (W_r, L_r) be the dimensions (width and length) of a crossed-dipole, to achieve a circularly polarization, the following equation should be regarded [18]:

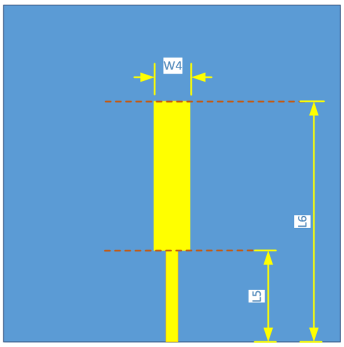


Fig. 2c. Bottom view of the proposed structure

$$\frac{L_l}{W_l} = \frac{L_r}{W_r} \tag{12}$$

It should be noted that to obtain a circular polarization, two orthogonal surface currents with 90-degree phase shift is required. A cross-shaped slot can satisfy the mentioned condition. It is shown in [18] that by using two unequal length and width of a crossed-dipole, two orthogonal surface currents with 90-degree phase shift can be met.

Hence, in this work, the width and length of the cross-shaped slot are the same. The proposed antenna is placed on the Rogers RO4003 substrate with permittivity of ε_r=3.55, dielectric tangent loss of 0.0027 and thickness of 0.508 mm. As shown in Fig.2(c), the microstrip line with the length of $L_{f1}+L_{f2}$ and the widths of W_{f1} and W_{f2} is printed on the bottom side of the substrate and the SMA connector is used as a feed antenna (with inner radius of 0.485mm and outer radius of 2.295mm). The values of the dimensions of the designed antenna are specified in Table 1.

III. RESULTS AND DISCUSSION

The electromagnetic performance of the designed antenna is investigated in this section. In this regard, two numerical methods (Method of Moment and Finite Element Method) were used to study the antenna parameters such as radiation pattern, axial ratio, efficiency, reflection coefficient and antenna gain. Also, a parametric study is done to obtain the wider bandwidth for circular polarization. A plot of the frequency response of S_{11}-parameter is provided in Fig. 3. As shown in Fig. 3, the proposed antenna operates at 4.9GHz with 10dB impedance bandwidth of 600MHz (4.6-5.2GHz). The gain of the antenna is demonstrated in Fig.4. As it is observed in Fig. 4, the peak gain at the passband is about 7.3dB. Pattern of the antenna at resonance frequency is plotted in Fig.5.

Table 1. Sizes of the Proposed Antenna in mm

L	48	L_5	15
W	52	L_6	43
h	0.508	W_1	43.6
h_1	10	W_2	2.78
h_2	8	W_3	9
L_1	1	W_4	5.2
L_2	24	R_1	18
L_3	34	R_2	3
L_4	24	Theta	16°

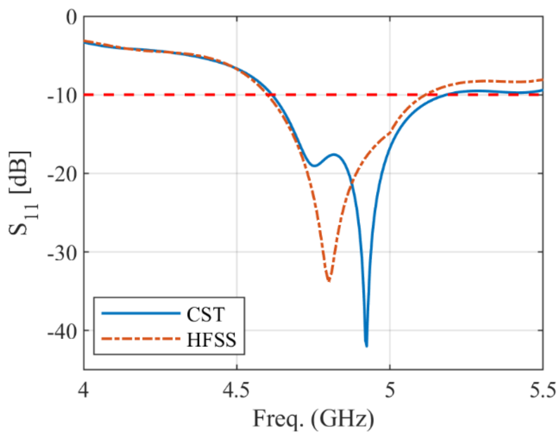


Fig. 3. The reflection coefficient of the proposed dielectric resonator antenna

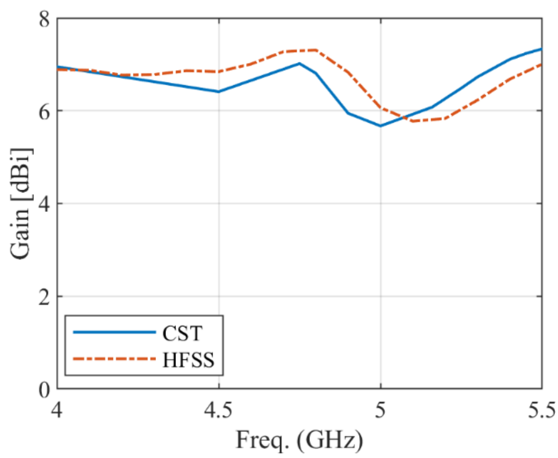


Fig. 4. The gain of the proposed dielectric resonator antenna

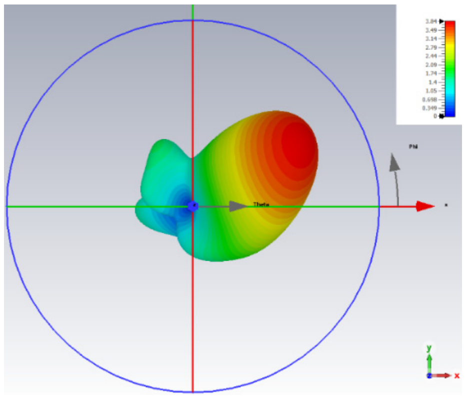


Fig. 5a. The 3D radiation pattern of the proposed antenna at 4.9GHz (CST)

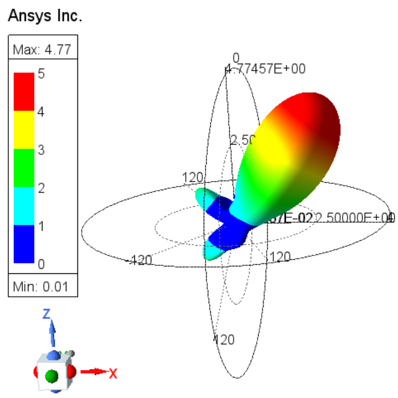


Fig. 5b. The 3D radiation pattern of the proposed antenna at 4.9GHz (HFSS)

Fig. 6 indicates the total and radiation efficiency curves of the antenna. As it is shown in Fig. 6, the antenna provides a high efficiency of 94% at the resonant frequency band. The 3dB axial ratio bandwidth of 400MHz in frequency range of 4.8-5.2GHz is obtained that completely overlaps the 10dB impedance bandwidth (Fig. 7). Obviously, in all results a good agreement between two numerical methods (MoM and FEM) has been obtained.

Fig. 8 represents the antenna radiation patterns at 4.9GHz frequency in the xz (φ=0°) and yz (φ=90°) plane. With reference to Fig. 8, the left-hand (LHCP) and the right-hand (RHCP) radiation patterns are shown and in φ=0°, the LHCP field is stronger than RHCP field and also, in φ=90°, the RHCP field is stronger than LHCP field.

To obtain the wider axial ratio bandwidth and optimum dimensions of the antenna, the parametric study on some physical parameters of the antenna has been performed. In this regard, the dimensions of the cross-shaped slot need to be adjusted suitably. This study incorporated the length and width of the cross-shaped slot. The variation of the length of the cross-shaped slot is shown in Fig. 9. According to the behavior of the curves shown in Fig.9 at different slot lengths, by increasing the length of the slot, the 3dB axial ratio bandwidth improves and also,

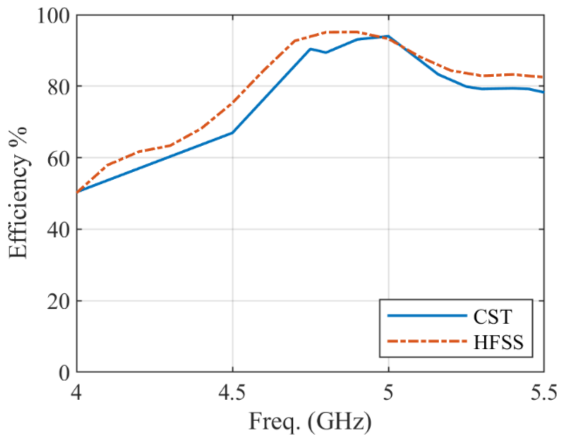


Fig. 6. The efficiency curves of the DR antenna

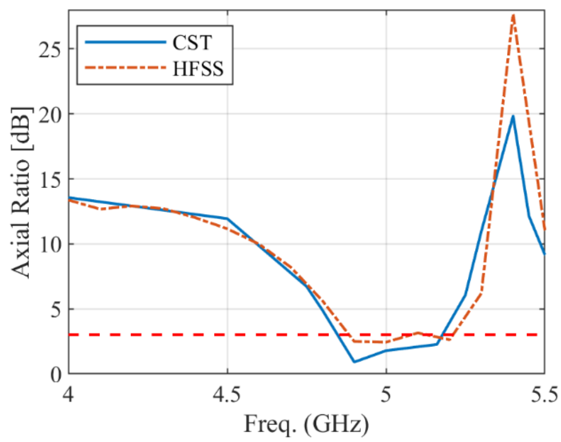
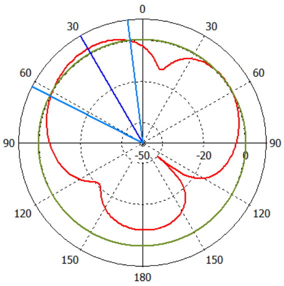


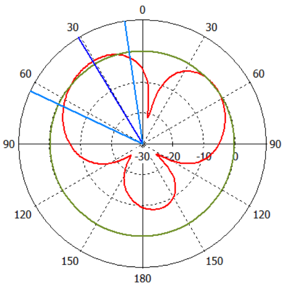
Fig. 7. The axial ratio versus frequency of the antenna

with L_{slot}=17mm the best result can be obtained. By increasing the L_{slot}, other radiating features such gain, radiation efficiency and also the return loss get worse. Hence, increasing the value of L_{slot} doesn't provide the better performance for the proposed structure. Furthermore, the effect of various widths of cross-shaped slots on operation of the designed antenna was investigated in Fig. 10. As W_{slot} is increased, the wider axial ratio bandwidth is achieved.

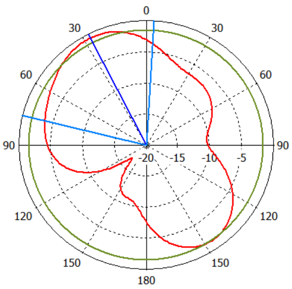
The comparative study of the designed antenna with some of the earlier circularly polarization DR antenna in the context of 10dB Impedance Bandwidth (IB) in MHz, 3-dB Axial Ratio Bandwidth (ARB) in MHz, gain (G) in dBi, and Total Efficiency (TE) in % is done in Table 2 [19-21]. It can be seen that the proposed antenna compared to other existing structures, has higher antenna gain and provides wider 10dB impedance bandwidth and 3dB axial ratio bandwidth. Also, the designed antenna has a higher efficiency and exhibits improved performance.



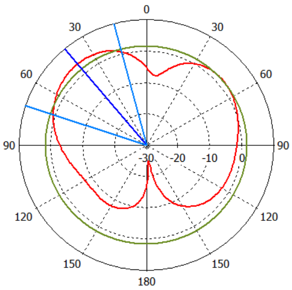
(a) LHCP & φ=0°



(b) RHCP & φ=0°



(c) LHCP & φ=90°



(a) RHCP & φ=90°

Fig. 8. The antenna radiation pattern at 4.9GHz

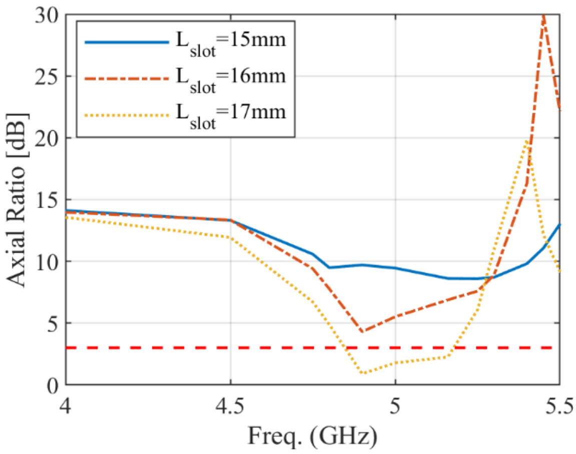


Fig. 9. The axial ratio of the antenna at various lengths of cross-shaped slot

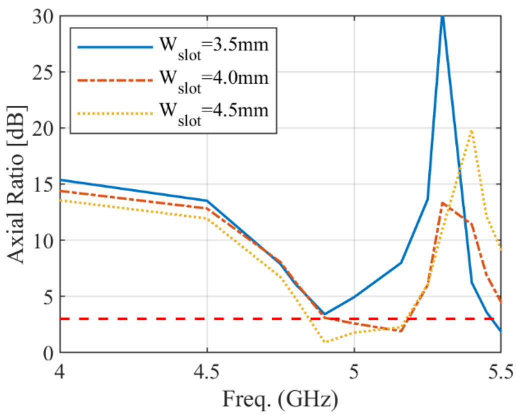


Fig. 10. The axial ratio of the antenna at various widths of cross-shaped slot

Table 2. Comparison of the Proposed Antenna with Other Existing Structures

Ref. No	IB	ARB	G	TE
[19]	500	100	3.84	-
[20]	230	120	3.57	89.2
[21]	420	303	5	-
This work	600	320	7.3	94

IV. CONCLUSION

In this paper, a sandglass-shaped DR antenna has been designed and studied. To obtain the gain, reflection coefficient, efficiency, radiation pattern and axial ratio of the designed antenna, two numerical methods (MoM and FEM) have been used. To obtain the circular polarization, the cross-shaped slot is applied on the antenna ground plane. Also, the effect of different physical parameters of the designed antenna on the axial ratio bandwidth has been investigated. The proposed antenna resonates at 4.9 GHz with 10 dB impedance bandwidth of 600 MHz from 4.6-5.2 GHz. In addition, the 3dB axial ratio bandwidth is equal to 400MHz at the first passband. The designed antenna has a peak gain of 7.3 dB. The proposed circularly polarized DR antenna is suitable for different wireless systems such as Wi-Fi and WiMax.

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