Single-feed circularly polarized rectangular dielectric resonator antenna coupled with dual mode slot-line square ring resonator

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Abstract A novel single-feed circularly polarized (CP) rectangular dielectric resonator antenna (RDRA) based on dual mode slot-line square ring resonator (SSRR) is proposed. The dual mode SSRR loaded with a perturbation is used to excite the \(TE_{111}\) mode and \(TE_{111}\) mode of rectangular dielectric resonator (RDR) simultaneously. By selecting a suitable size of the perturbation, the orthogonal degenerate modes of the SSRR are obtained. Accordingly, the CP radiation pattern of the proposed RDRA is generated from the orthogonal degenerate modes of the SSRR. A prototype is designed and measured. The RDRA has a wide impedance bandwidth of 14.28\% (3.16-3.66GHz). The achieved 3 dB Axial Ratio (AR) bandwidth of the RDRA is about 100MHz at 3.5GHz. With the advantages of compact structure, CP performance and easy fabrication, this structure can be a good candidate for 5G communication system in the future.

key words: Circularly polarization, dielectric resonator antenna, dual mode, slot-line ring resonator

Classification: Microwave and millimeter wave devices, circuits, and hardware

1. Introduction

In the past two decades, dielectric resonator antennas (DRAs) have drawn more attention due to their attractive characteristics such as light weight, high radiation efficiency, low conductor loss, and no excitation of surface waves [1]. Circularly polarized (CP) DRAs have a wide range of application in wireless communication systems since they can avoid the loss of polarization mismatch. Basically, feed networks of broadside CP DRAs can be divided into two categories, namely single and dual feeds [2]. The simplicity of the single-feed circularly polarized antenna makes it an interesting choice for antenna engineers [3]. Various configurations using single-feeds have been proposed to design CP DRAs. The first configuration of designing a single-feed CP DRA is to stack or splicing several DRs [4-6]. The second configuration is to change the shape of DRs [7-8]. The third is to merge the radiation fields of the DRA and other antennas [9-10]. The fourth is to add metallic strips onto DRAs’ side walls [11-12]. And the last is to modify the coupling aperture embedded on the ground plane [13-37]. The aperture-coupling excitation method with a microstrip feed-line has the advantage of having the feed network located below the ground plane, thus avoiding spurious radiation and the advantage of integrating DRAs with printed feed structures [38]. Therefore, this excitation method has usually been used to excite the DRAs [13-37] [39] and the last method of designing a single-feed CP DRA (modifying the coupling aperture embedded on the ground plane) is the most popular one by designers. There are many kinds of modified coupling apertures used to design single-feed CP DRAs. The simplest one is to incline the rectangular coupling slot at an angle or off-center it relative to the DRA [13-16]. The unequal cross slots [17-23], the open annular slots [24-31] and the ring slots [32-37] are the other tree simple coupling apertures to design single-feed CP DRAs. When ring slots are used as the coupling structures, the feeding microstrip line printed on the bottom surface of the substrate usually needs to pass through the ring to form a quasi-dual feeding structure [32-36]. In addition to forming a quasi-dual feeding structure, in [37] a simpler way called perturbed ring slot has been used to design CP DRA. But in [37], the slot just served as a coupling structure rather than a resonator near the operating frequency and the electrical operation at the proposed structure has not been demonstrated. In this paper, a CP rectangular dielectric resonator antenna (RDRA) coupled with a dual mode SSRR is presented. The dual mode SSRR etched on the ground plane acts as a feeding structure. The \(TE_{111}\) mode and \(TE_{111}\) mode of rectangular dielectric resonator (RDR) with the same amplitude and quadrature phase difference are excited simultaneously by this structure for CP radiation. The electrical operation at the SSRR is demon-
2. Antenna configuration

As shown in Fig. 1, the antenna consists of two parts: a rectangular substrate and a rectangular DR. The substrate has dimensions of \( w_s \times l_s \times h \) and a relative permittivity \( \varepsilon_{r1} \). The rectangular DR with a relative permittivity \( \varepsilon_{r2} \) has dimensions of \( a \times b \times d \). The microstrip feed line with width \( w_f \) is printed on the bottom surface of the substrate. At the end of the feed line, there is an open matching stub with length \( l_f \). The dual mode SSRR etched on the ground plane is made up of two parts: a slot-line square ring resonator and a capacitive perturbation stub. The stub with dimensions \( l_p \times w_p \) is located at the lower right corner. The side length of SSRR and the slot-line width are \( l_s \) and \( w_s \) respectively.

The parameters of the prototype are shown in Table 1.

Table 1 Design Parameters (mm) of the prototype.

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3. Operating principles

3.1 Dual mode SSRR

Fig. 2 shows the geometry of the SSRR and the SSRR with perturbation. Fig. 3 shows the return losses corresponding to the geometries in Fig. 2. It can be clearly seen that, with introduction of a perturbation, the fundamental mode of the square ring resonator is divided into two resonant modes which are called Split Mode1 and Split Mode2. It can also be seen that the coupling strength of the two split modes decreases as \( l_p \) increased. It should be noted that the dual-port excitation configuration is used here to explain the principle more conveniently. Fig. 4 shows the E-field magnitudes distributed in the slot at resonate frequency (a) Fundamental Mode (b) Split Mode1 (c) Split Mode2.

It is interesting to find that the electric fields of Split Mode1 and Split Mode2 are naturally orthogonal to each other. By adjusting the length of the perturbation, the coupling strength of the two orthogonal modes can be adjusted and then the phase difference between the two.
modes will be changed. The two orthogonal modes of slot can be used to exit the TE_{x111} mode and TE_{y111} mode of RDR for CP radiation.

3.2 Dual mode RDR

Fig. 5 shows the return losses for without perturbation and \( l_p = 2, 4, 6\) mm, where \( l_p \) is the perturbation length defined in Fig. 1. As can be observed from Fig. 5, with introduction a perturbation to the SSRR, the TE_{111} mode of the DR is divided into two resonant modes, which are called DR Mode1 and DR Mode2, respectively. The coupling strength between DR Mode1 and DR Mode2 decreases as \( l_p \) increased. It should be noted that by changing the height of DR as described in [40], the DR mode can be easily distinguished from the slot mode. For saving space, detailed description is omitted here.
3.3 CP RDRA
As mentioned in the previous paragraph, the coupling strength of the two resonant modes of DR can be adjusted by changing the length of the perturbation, which means the phase difference between the two modes of DR will be changed. When the two resonant modes of DR have the equal amplitude with a quadrature phase difference, a CP radiation will be obtained. Fig. 6 shows the ARs of the proposed antenna for different $l_p$. As previous discussing, $l_p$ plays a significant role on the CP performance of the proposed antenna. The E-field vector at 3.5GHz distributed on top surface (a, c, e, g) of DR and their corresponding E-field magnitude distributed in the slot (b, d, f, h) are plotted in Fig.7 according to time phase. From Fig7, a clockwise rotated E-field is moving along the slot, and the $\text{TE}_{2111}$ mode and $\text{TE}_{3111}$ mode of RDR with a quadrature phase difference are then excited, which will generate a left hand CP (LHCP) radiation. It should be mentioned that the electric fields distributed in the slot at 0 and T/2 (or at T/4 and 3T/4) have the same amplitude but opposite phase. Of note: the new coupling method of dual mode SSRR shows a great designing flexibility. By changing the position of perturbation simply, the new coupling method can also be used to design a RHCP DRA, which will be discussed in detail in the next section.

3.4 LHCP and RHCP RDRA
The electric field vectors of Antenna I and Antenna II are shown in Fig. 8, respectively. From Fig. 8, it can be seen that when the perturbation located at the corner B, the electric field vector distributed on top surface of DR travels in a clockwise direction, which contributes to a LHCP wave. However, when the perturbation located at the corner A, the electric field travels in a counter-clockwise direction, leading to a RHCP wave. Comparison of simulated return loss between antenna I and II are shown in Fig. 9. The AR of Antenna I, II are plotted in Fig. 11 is fabricated and measured. The antenna is fabricated on a Rogers TMM4 substrate with $\varepsilon_r=4.5$ and the RDR is fabricated from ceramic with $\varepsilon_r=9.9 \pm 0.2$. The RDR and the substrate are bound together by a thin layer of strong adhesive. It should be noted that, in this paper, only a LHCP RDRA is fabricated. Fig. 12 shows the simulated and measured return loss of the proposed CP RDRA. Both the Simulated and measured ARs and gains of the proposed structure in the broadsight direction are presented in Fig. 13. The antenna exhibits a simulated 3-dB AR bandwidth of 3.14%.

4. Experimental results and discuss
To validate the design, a prototype of the CP RDRA as shown in fig. 11 is fabricated and measured. The antenna is fabricated on a Rogers TMM4 substrate with $\varepsilon_r=4.5$ and the RDR is fabricated from ceramic with $\varepsilon_r=9.9 \pm 0.2$. The RDR and the substrate are bound together by a thin layer of strong adhesive. It should be noted that, in this paper, only a LHCP RDRA is fabricated. Fig. 12 shows the simulated and measured return loss of the proposed CP RDRA. Both the Simulated and measured ARs and gains of the proposed structure in the broadsight direction are presented in Fig. 13. The antenna exhibits a simulated 3-dB AR bandwidth of 3.14%.
(3.45-3.56GHz) and a measured 3-dB AR bandwidth of 2.8% (3.49-3.59GHz), which are close to a typical AR bandwidth of single-feed DRA for $\sigma=10$ [2]. Since the impedance pass-band completely covers AR pass-band, the overlapping bandwidth of simulated and measured are also 3.14% and 2.8%. The simulated and measured antenna gains in the overlapping bandwidth are ranged from 3.37dBi to 3.84dBi and 2.81 dBi to 3.83 dBi respectively. Due to the fabricated tolerance and the inevitable air gap between the ground plane and DR, small difference between the simulated and measured results is observed. Fig.14 shows the LHCP radiation patterns of the proposed antenna at 3.5GHz on the x-o-z and y-o-z plane. The measured and simulated results exhibit a great coincidence. However, according to Fig.14, the simulated maximum gain direction is slightly inclined, and the inclination angles are $-3^\circ$ and $7^\circ$ on the x-o-z and y-o-z plane respectively. For the measured results, the inclination angles are $4^\circ$ and $6^\circ$ respectively. As expected, the slight inclination is due to the asymmetric feeding structure.

6. Conclusion

In this paper, a single-feed CP RDRA using the new coupling method of dual mode SSRR has been designed and investigated. The properties of dual mode SSRR is studied by observing its electric field distribution and resonant modes. After that, the influence of perturbation on RDR modes is analyzed. With introduction of a perturbation, the TE_x11 and TE_y11 mode of RDR are excited simultaneously. By adjusting the size of perturbation, a CP radiation pattern of RDR is achieved. AR, return loss, gain and radiation pattern of the proposed antenna have been simulated and measured. A reasonable agreement between measured and simulated results was obtained. The measured 3-dB AR bandwidth and -10dB impedance bandwidth are 2.8% (3.49-3.59GHz) and 14.28% (3.16-3.66GHz), respectively. The maximum measured antenna gain is 3.83 dBi. The proposed antenna with compact structure, CP performance and easy fabrication can be a good candidate for 5G communication system.

References


Circularly polarized dielectric resonator antennas have been extensively studied for their unique properties and potential applications. Various designs have been proposed to enhance their performance and functionality. Several key references that contribute to the understanding of these antennas include:


