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A Simple Dual-Band Circularly Polarized Rectangular Dielectric Resonator Antenna

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Abstract—A simple slot coupled dual-band circularly polarized (CP) rectangular dielectric resonator antenna (DRA) is presented. The TE_{111} and TE_{113} modes of the rectangular DRA are excited by a modified annular slot. Working principle of the proposed antenna is explained in this paper. Design guideline of the proposed antenna is also devised based on the parameter study. The simple feeding and radiating structures of the proposed antenna make it easy to be designed and fabricated. A prototype antenna was designed, fabricated and measured. The simulated and measured results confirm the dual-band CP performance of the proposed antenna.

1. INTRODUCTION

Dielectric resonator antenna (DRA) has been widely investigated in the last two decades because of its advantages such as small size, low cost, ease of excitation and high radiation efficiency [1–9]. Rectangular DRA is the most versatile because it has more degrees of freedom than the cylindrical and hemispherical ones [10, 11].

The rapid development of modern wireless communication systems has stimulated the investigation of dual-band DRA. Several methods have been proposed to realize a dual-band DRA. A dual-band design can be achieved by combining the DRA with another radiating resonator, such as a second DR [12, 13] or a slot resonator [14]. However, the introduction of the second resonator leads to a significant increase of antenna complexity. The resonance of the feed structure can also be utilized to attain a dual-band DRA [15]. Recently, it is demonstrated that taking advantage of the higher-order DRA modes is an alternate way to achieve a dual-band DRA [16–21]. The dielectric waveguide model (DWM) [10, 11] and the design formulas in [16, 17] can be used to calculate the fundamental and higher-order frequencies of the rectangular DRA. Based on the existing formulas, it is simple to design a dual-band rectangular DRA.

The research of dual-band DRA using higher-order modes was mainly focused on linearly polarized (LP) designs [16–18]. Only a few CP DRAs making use of higher-order modes have been reported [19–22]. TE_{111}, TE_{121} and TE_{131} modes of a rectangular DRA with large aspect ratio can be used to realize a dual-band CP DRA when the aspect ratio is properly chosen [19]. However, the antenna proposed in [19] has a low broadside gain of 2.3 dBi at the lower band, because the radiation pattern of TE_{121} mode is null in the boresight direction [23]. In [20], dual-/wide-band CP cylindrical DRA has been obtained by using vertical strips with quadrature in phase to excite the fundamental and higher order broadside modes in the cylindrical DRA. However, this feed structure is complicated to implement because a dual-band 90° coupler is necessary. A singly-fed dual-band CP DRA has been presented in [22] with its broadside TE_{111} and TE_{113} modes excited. Although feed network of the proposed antenna is simple, the structure of the dielectric resonator (DR) is complicated. Because two corners

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of the DR are truncated and a diagonal groove at the top face of the DR is introduced. A dual-band CP DRA can also be achieved by taking advantages of the resonances of dielectric resonator (DR) and feeding structure [24]. However, as described in [25], making use of the radiation of feeding structure to obtain a dual-band antenna may do harm to the DRA matching.

In this paper, a simple slot fed dual-band CP rectangular DRA is proposed based on the dual-mode approach. A modified annular slot is used to excite the fundamental TE_{111} and the higher order TE_{113} modes of the rectangular DRA for dual-band CP operation. The feeding and radiating structures of the proposed antenna are simple, which make it easy to be designed and fabricated. The design concept and parametric study of the proposed antenna are covered by this paper. Based on the parametric study, the design guideline is devised. A prototype antenna is implemented, and good agreement between the simulated and measured results is obtained.

2. ANTENNA STRUCTURE AND DESIGN PRINCIPLES

The configuration of the proposed dual-band CP DRA is shown in Figure 1. The DRA is made from a ceramic material with permittivity of ε_r. The rectangular DRA, which has dimensions of $a \times b \times c$ ($a = b$), is located at the center of a FR4 substrate. The FR4 substrate has a thickness of t and a side length of l_g. The DRA is excited by a modified annular slot fabricated on the dielectric substrate. The modified annular slot consists of an annular slot and two linear slot arms. The annular slot has a radius of r and a width of w. The two linear slot arms with lengths of l_1 and l_2 are located at 135° and 45° from the y-axis, respectively, and their widths are equal to that of the annular slot. The microstrip line, which is composed of a 50 Ω microstrip line and a tuning stub, is etched on the other side of the substrate. The lengths and widths of the 50 Ω microstrip line are l_{m1} and w_{m1}, respectively. And those of the tuning stub are l_{m2} and w_{m2}, respectively. For convenience, some parameters of the DRAs in this paper are selected as $\varepsilon_r = 12$, $a = b = 37$ mm, $c = 30$ mm, $t = 1.6$ mm and $l_g = 100$ mm. The theoretical resonant frequencies of the TE_{111} and TE_{113} modes are 1.55 GHz and 2.59 GHz, respectively [10].

A linear slot can be used to excite a linear polarized (LP) or a CP DRA. A LP DRA is obtained when the slot is parallel to the DRA [11]. And a CP design can be achieved by exciting two nearly degenerate modes with 90° phase difference, when the DRA is inclined by about 45° with respect to the slot [26–28]. However, when frequency ratio of the TE_{111} and TE_{113} modes is large, a single linear slot cannot be used to excite the two pairs of modes for dual-band CP operation.

The proposed antenna can be regarded as a modified linear slot fed CP DRA at the lower frequency band. To demonstrate the working principles of the proposed antenna at the lower band, the lowest two resonant modes of the DRA are studied. Figure 2 shows the H-fields and resonant frequencies of the

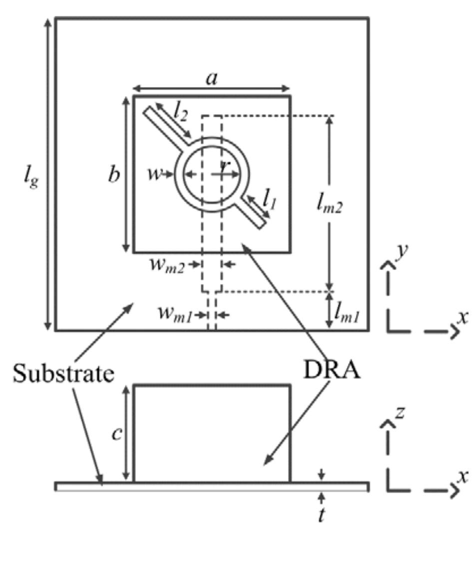

Figure 1. Geometry of the modified annular slot excited dual-band CP rectangular DRA.

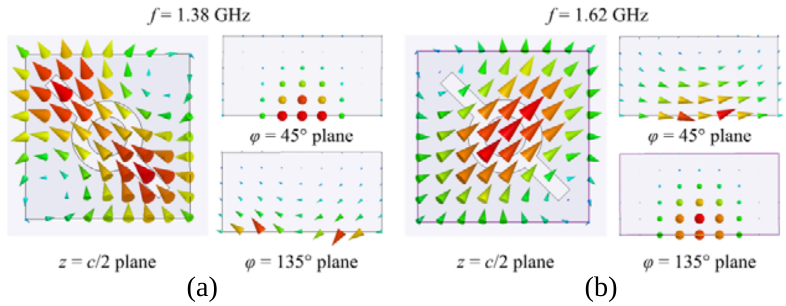

Figure 2. H-fields and resonant frequencies of the TE_{111} modes of the DR placed on a ground plane with a modified annular slot ($r = 4.5\,\mathrm{mm}$, $w = 3.5\,\mathrm{mm}$ and $l_1 = l_2 = 10\,\mathrm{mm}$). (a) TE_{111}^{Par} mode. (b) TE_{111}^{Per} mode.

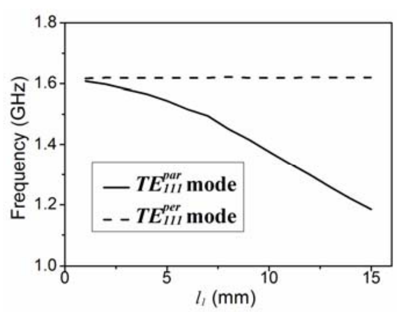

Figure 3. Resonant frequencies of the TE_{111}^{Par} and TE_{111}^{Per} modes as functions of l_1 ($l_1 = l_2$).

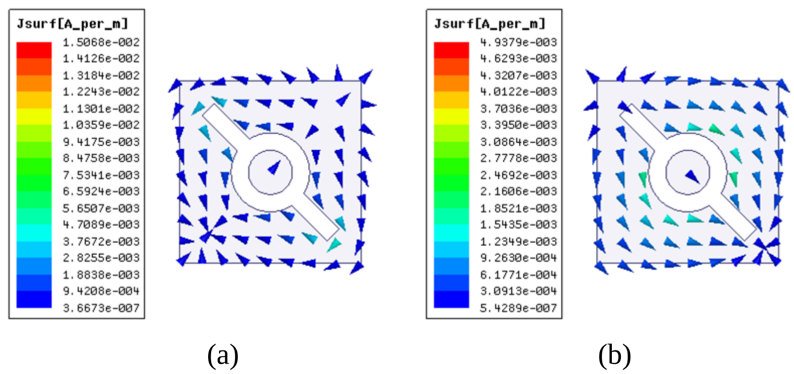

Figure 4. Current distributions on ground plane of the TE_{111}^{Par} and TE_{111}^{Per} modes. (a) TE_{111}^{Par} mode. (b) TE_{111}^{Per} mode.

TE_{111} modes of the DRA, when the dimensions of modified annular slot are $r = 4.5\,\mathrm{mm}$, $w = 3.5\,\mathrm{mm}$ and $l_1 = l_2 = 10\,\mathrm{mm}$. The introduction of the modified annular slot on the ground plane changes the fields and resonant frequencies of the TE_{111} modes. H-fields of the two degenerate modes are parallel and perpendicular to the two linear slot arms, respectively. Thus, the lowest and second lowest modes of the DRA are named as TE_{111}^{Par} and TE_{111}^{Per} modes, respectively. Resonant frequencies of the TE_{111}^{Par} and TE_{111}^{Per} modes as functions of l_1, when $l_2 = l_1$, are shown in Figure 3. The resonant frequency of the TE_{111}^{Per} mode remains nearly unchanged while that of the TE_{111}^{Par} mode decreases with the increase of l. Current distributions on ground plane of the TE_{111}^{Par} and TE_{111}^{Per} modes are shown in Figure 4. Form Figure 4(a), current path of the TE_{111}^{Par} mode is lengthened when l_1 or l_2 increased, which lowers its resonant frequency. As shown in Figure 4(b), l_1 and l_2 have minor effects on current path of the TE_{111}^{Per} mode, so they have small effects on resonant frequency of the TE_{111}^{Per} mode. Thus the frequency ratio of the two modes can be adjusted by changing the lengths of the two linear slot arms. The same technique, tuning the frequency ratio of the two nearly degenerate modes, is used in [26–28] by changing the length-width ratio of the rectangular DRA. Thus, good CP performance at the lower frequency band can be realized by optimizing the dimensions of the two linear slot arms.

As proposed in [29], CP operation can be obtained by using a perturbed annular slot to feed the DRA. In [29], the annular slot is perturbed by two slot arms toward the center of it, which makes it inconvenient to be combined with a linear slot. CP radiation can also be realized when the two arms are outside of the annular slot. The proposed antenna can be regarded as a perturbed annular slot excited CP DRA at the upper frequency band. The TE_{113} modes of the proposed DRA are excited with 90° phase difference for CP radiation by the perturbed annular slot. Radius r of the annular slot is the main parameter which affects the CP performance at the upper band. Small AR value at upper band can be achieved by tuning r and other parameters of the modified annular slot.

3. PARAMETRIC STUDY AND DESIGN GUIDELINE

For the proposed modified annular slot fed dual-band CP DRA, r, l_1 and l_2 are the key structural parameters. To investigate their effects on the antenna performances, a parametric study was carried out.

Figure 5 shows the simulated AR at the upper band for different values of r, where $l_1 = l_2 = 8\,\text{mm}$ and $w = 3.5\,\text{mm}$. It is observed that the CP performance of the upper band shows heavy dependence on the radius of annular slot. The reason is that TE_{113} modes in the DRA is excited by the perturbed annular slot with a radius of r.

Figure 6 shows the effects of the parameters l_1 and l_2 on the AR performances at both the two bands. It can be observed that the lengths of the two slot arms have a major effect on the AR performance at the lower band and a minor effect on the AR performance at the upper band. Thus, the values of l_1 and l_2 can be optimized to realize a good AR at the lower band, while it does not do much harm to the CP performance at the upper band.

The reflection coefficient of the proposed antenna for different values of l_{m2} and w_{m2} is shown in Figure 7. It is clear that good impedance matching at both of the two bands can be obtained by tuning l_{m2} and w_{m2}.

For a dual-band CP antenna, it is important to investigate the maximum frequency ratio that can be achieved. Simulated results show that the maximum frequency ratio of the proposed DRA is about 1.93.

Based on the above parametric studies with respect to the AR and reflection coefficient

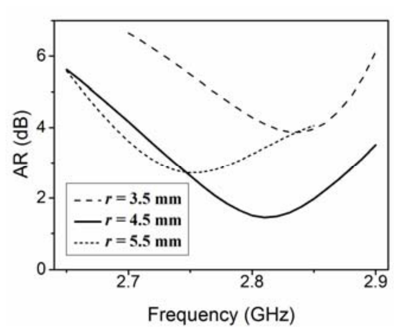

Figure 5. Simulated axial ratio at the upper band for different values of r. (Geometry parameters: $w = 3.5\,\text{mm}$, $l_1 = 8\,\text{mm}$ and $l_2 = 8\,\text{mm}$).

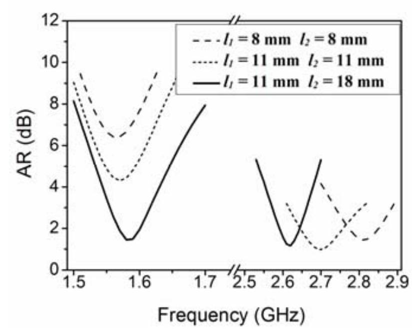

Figure 6. Simulated axial ratio of the two bands for different values of l_1 and l_2. (Geometry parameters: $r = 4.5\,\text{mm}$, $w = 3.5\,\text{mm}$).

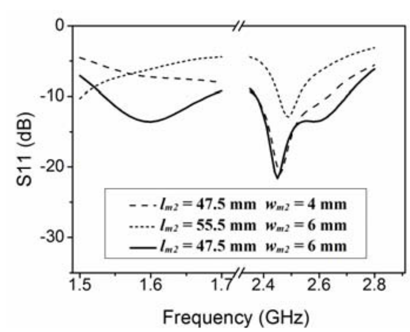

Figure 7. Simulated reflection coefficient for different values of l_{m2} and w_{m2}. (Geometry parameters: $r = 4.5\,\text{mm}$, $w = 3.5\,\text{mm}$, $l_1 = 11\,\text{mm}$ and $l_2 = 18\,\text{mm}$).

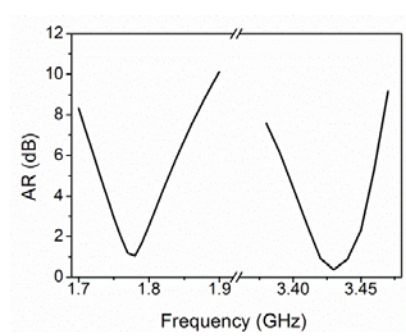

Figure 8. Simulated AR of the prototype with parameters of $\varepsilon_r = 12$, $a = b = 37\,\text{mm}$, $c = 20\,\text{mm}$, $r = 4\,\text{mm}$, $w = 3\,\text{mm}$, $l_1 = 15\,\text{mm}$ and $l_2 = 7\,\text{mm}$.

performances at the two bands, the design procedure of the proposed antenna is concluded as follows. Firstly, the dimensions of the rectangular DRA are decided by the desired operating frequencies and the permittivity of the DRA. The existing formulas in [2, 16, 17] can be utilized to design the dimensions of the rectangular DRA. Secondly, the radius r of the annular slot is designed to obtain a good AR at the upper band. Thirdly, good CP performance at the lower band can be achieved by adjusting the lengths of the two linear slot arms. And then retune the values of r, l_1 and l_2 to realized good CP operation at both the frequency bands. Finally, l_{m2} and w_{m2} are designed to obtain a good impedance matching.

4. MEASURED RESULTS

To verify the proposed design, a prototype antenna with optimized design parameters of $r = 4.5$ mm, $w = 3.5$ mm, $l_1 = 11$ mm, $l_2 = 18$ mm, $l_{m1} = 12$ mm, $w_{m1} = 3$ mm, $l_{m2} = 47.5$ mm and $w_{m2} = 6$ mm was fabricated and measured. The photos of the prototype antenna are shown in Figure 9.

Figure 10 shows the simulated and measured ARs of the proposed antenna. The measured 3-dB AR bandwidths are 3.7% (1.61–1.67 GHz) and 3.7% (2.65–2.75 GHz) for the lower and upper bands, respectively. The simulated minimum ARs for the lower and upper bands occur at 1.58 GHz and 2.62 GHz, respectively. The measured ones occur at 1.64 GHz and 2.70 GHz, which are near the resonant frequencies of the TE_{111} and TE_{113} modes, respectively. The simulated and measured reflection coefficients of the proposed antenna are shown in Figure 11. The measured impedance bandwidths ($S_{11} < -10$ dB) are 9.1% (1.58–1.73 GHz) and 14.4% (2.39–2.76 GHz), which cover the lower and upper CP bands, respectively.

The simulated and measured radiation patterns of the proposed antenna at the center frequencies of the lower and upper CP bands are shown in Figure 12. The radiation patterns are broadside as expected, because the TE_{111} and TE_{113} modes are broadside modes. Figure 13 shows the simulated and measured LHCP gains of the proposed antenna. From Figure 13 measured LHCP gain is about 5.4 dBi at 1.64 GHz and 5.8 dBi at 2.70 GHz, respectively.

(a) (b)

Figure 9. Photos of the prototype antenna. (a) Top view. (b) Bottom view.

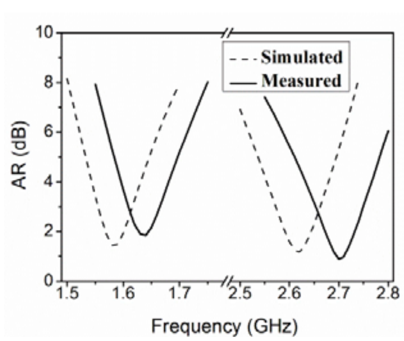

Figure 10. Simulated and measured axial ratios of the proposed antenna.

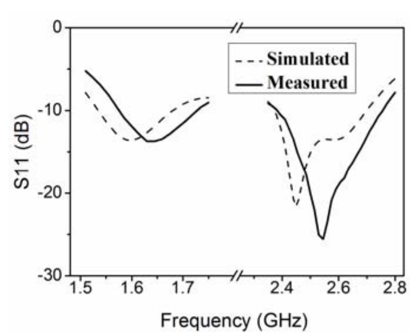

Figure 11. Simulated and measured reflection coefficients of the proposed antenna.

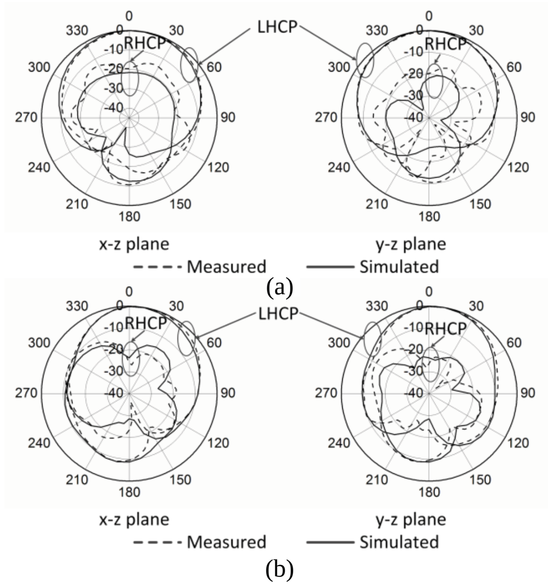

Figure 12. Simulated and measured radiation patterns of the proposed antenna. (a) Measured at $f = 1.64\,\text{GHz}$ and simulated at $f = 1.58\,\text{GHz}$; (b) measured at $f = 2.70\,\text{GHz}$ and simulated at $f = 2.62\,\text{GHz}$.

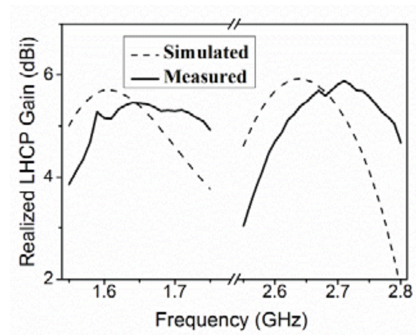

Figure 13. Simulated and measured LHCP gain of the proposed antenna.

5. CONCLUSION

A dual-band CP DRA has been proposed in this paper by utilizing the TE_{111} and TE_{113} modes of a rectangular DRA. In this design, a modified annular slot has been used to excite the two couples of degenerate modes simultaneously for dual-band CP radiation. Both of the feeding and radiating structures of the proposed antenna are simple. The design concept of the proposed antenna has been introduced and certified, and the design guideline of the proposed antenna has been devised based on the parametric study.

A prototype was designed and fabricated, the measured 3-dB AR bandwidths and impedance bandwidths ($S_{11} < -10\,\text{dB}$) are 3.7%, 9.1% for the lower band and 3.7%, 14.4% for the upper band, respectively.

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