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# A Pattern Reconfigurable Antenna With Four Switchable Directional Beams Using Characteristic Mode Analysis

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***Abstract*—In this paper, a pattern reconfigurable antenna with four switchable directional beams operating at 2.1 GHz is proposed. Specifically, the proposed antenna consists of a square annular patch and a circular patch placed at the center of the square slot. Based on the characteristic mode analysis (CMA), the desired modes can be excited selectively by placing the feeding ports in suitable positions to form a directional beam at a certain angle. Through switching the on/off states of the feeding ports, four directional beams towards different angles can be realized. Simulation results verify that the proposed antenna can generate four switchable beams with the front-to-back ratio larger than 20 dB.**

***Index Terms*—Characteristic mode analysis (CMA), directional antenna, reconfigurable antenna.**

## I. Introduction

The pattern reconfigurable antennas with switchable beams can improve the signal-to-noise ratio (SNR) and system capacity of wireless systems [1]. Hence, it is widely applied in the wireless communication systems. Generally, directional antennas are necessary for the beam-switching systems, as they can form the radiation beam at a certain angle, enabling high radiation power for small angle coverage. In the past decades, numerous designs to realize directional antennas have been presented. For instance, by the combination of an electric dipole and a magnetic dipole, the complementary antenna was proposed to form a cardiac shaped directional radiation pattern [2], [3]. Nevertheless, this kind of antenna is of complex configuration. With the development of wireless communications, it is highly desirable to achieve a pattern reconfigurable antenna with low design difficulty and complexity.

To simplify the structure of such an antenna, the characteristic mode analysis (CMA) is utilized in this work. Based on the geometry of the antennas, the CMA provides the information of current distribution and radiation characteristics of various modes. Therefore, the antennas operating mechanism can be well understood. By placing inductive or capacitive excitation elements in predefined positions, the expected modes can be excited [4]–[9]. Through the superposition and cancellation of electric fields of different modes, it is possible to tailor the radiation patterns of antennas. As an example, a squint beam was achieved by the joint excitation of a fundamental mode of the patch and the mode of the parasitic strip [10].

In this paper, a square annular patch and a circular patch are used to achieve a pattern reconfigurable antenna. With the help of the CMA, the modes of the proposed antenna are observed intuitively. By the proper feeding structures, the desired modes are excited separately to obtain the directional radiation pattern. Moreover, by simply changing the on/off states of the feeding ports in the circular patch, a reconfigurable antenna with four switchable directional beams is achieved.

## II. Antenna Configuration and Operating Principle

### A. Antenna Configuration

The geometry of the proposed antenna is given in Fig. 1. As shown, a square annular patch with four slots and a circular patch with four slots are etched on the top layer of the substrate. Rogers RO4003 is used as the substrate, which has a relative dielectric constant of 3.55 and a thickness of 0.4 mm. Table I lists the dimensions of the proposed antenna.

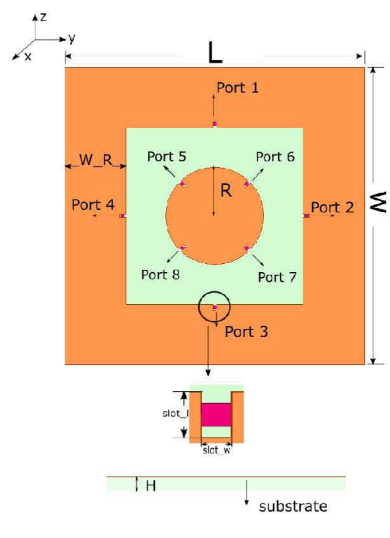


Fig. 1. Geometry of the proposed antenna

TABLE I
DIMENSIONS OF THE PROPOSED ANTENNA (UNIT: MM)

| L | W | R | H | W_R | slot_l | slot_w |
|---|---|---|---|---|---|---|
| 44 | 44 | 7.2 | 0.4 | 9.4 | 1 | 0.5 |

### B. Operating Principle

The CMA of the proposed antenna without slots is simulated by Feko. Fig. 2 shows the current distribution and radiation patterns of Mode 2 and Mode 3 at 2.4 GHz. It is clear that the radiation pattern of Mode 2 is analogous to that of an electric dipole with the current polarized along x-axis, as shown in Fig. 2(a). Apparently, based on the ring current and omnidirectional pattern given in Fig. 2(b), the radiation characteristic of Mode 3 is similar to that of a magnetic dipole.

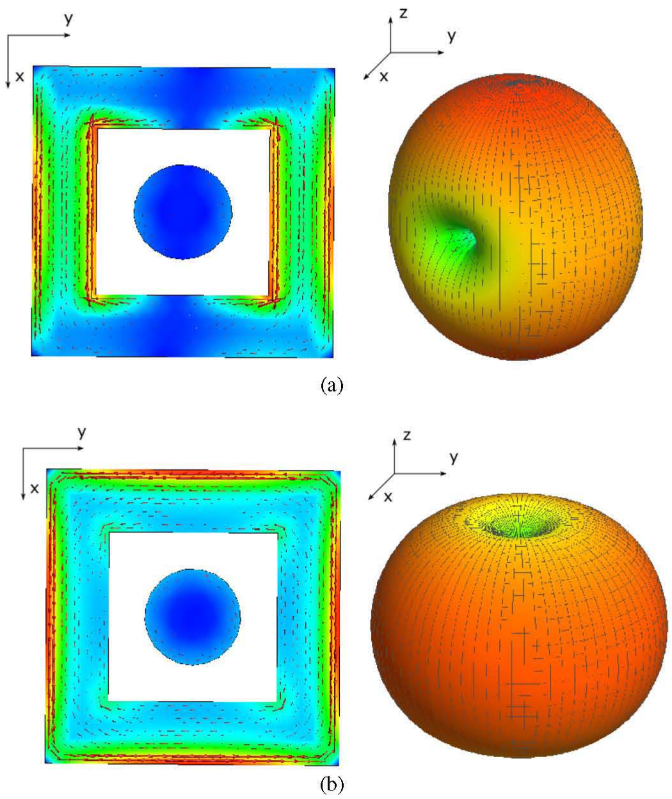


Fig. 2. Current distribution and the corresponding radiation pattern of the proposed antenna without slots at 2.4 GHz. (a) Mode 2; (b) Mode 3.

Four slots etched in the circular patch and four slots etched in the square annular patch at the proper positions are adopted as inductive couplers elements (ICE). The feeding excitation is realized by the ideal wire ports. To excite Mode 2 and Mode 3, two feeding methods are adopted and illustrated below.

*State 1)*: Feeding only one of the four ports in the circular patch can excite Mode 2 as an electric dipole. As shown by the normalized modal weighting coefficient (MWC) in Fig. 3(a), it can be observed that Mode 2 is excited.

*State 2)*: Feeding four ports in the square annular patch with identical power and phase, Mode 3 as a magnetic dipole can be excited. The normalized modal weighting coefficient shown in Fig. 3(b) confirms that Mode 3 is excited efficiently.

When feeding four ports in the square annular patch and one port in the circular patch in equal power and phase, Mode 2 and Mode 3 can be excited simultaneously. It can be verified by the normalized modal weighting coefficient (MWC) illustrated in Fig. 4. As shown, Mode 2 and Mode 3 can be excited selectively. Although there are other unexpected modes excited at the same time, they have little influence on the prospective design. Thus, it is not necessary to use extra feeding structures for suppressing these unwanted modes.

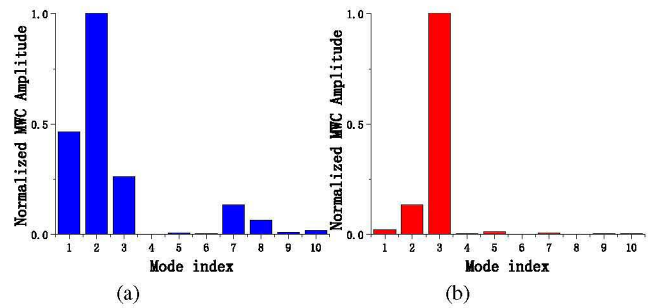


Fig. 3. Normalized MWC Amplitude of (a) State 1 and (b) State 2 at 2.4 GHz.

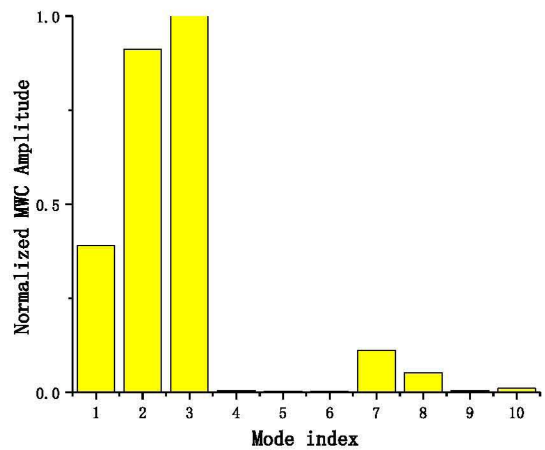


Fig. 4. Normalized MWC Amplitude of the proposed antenna at 2.4 GHz.

## III. RESULTS AND DISCUSSION

To verify the above design idea, the proposed antenna with feeding is analyzed by the full-wave simulation tool HFSS. Fig. 5 and Fig. 6 show the radiation patterns of the proposed antenna in the two main planes. With the existence of the substrate, the central operating frequency point of the proposed antenna is shifted to 2.1 GHz. As shown, four directional radiation patterns with a peak gain of 3.27~3.60 dBi and the front-to-back ratio of 22~34 dB are realized. When feeding Port 1-4 in the square patch and changing the feeding port of 5-8 in the circular patch, the four directional patterns towards different angles can be obtained respectively.

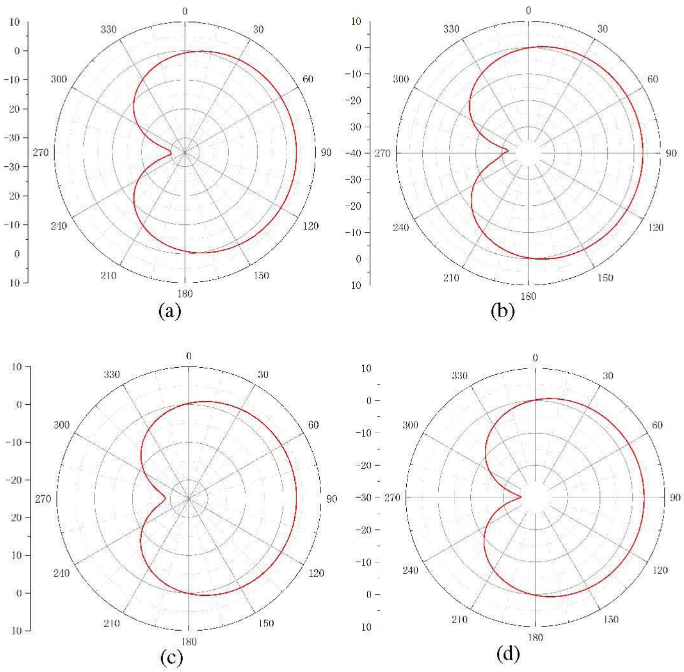

Fig. 5. Full-wave simulation pattern of the proposed antenna with feeding Port 1-4 and (a) Port 5 or (b) Port 6 or (c) Port 7 or (d) Port 8 at 2.1 GHz in xoz-plane.

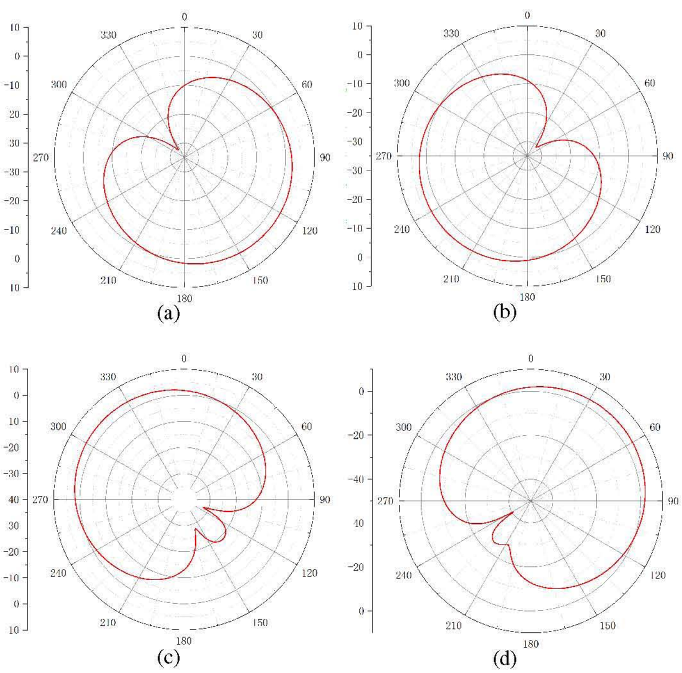

Fig. 6. Full-wave simulation pattern of the proposed antenna with feeding Port 1-4 and (a) Port 5 or (b) Port 6 or (c) Port 7 or (d) Port 8 at 2.1 GHz in xoy-plane.

From the above simulation results, it can be concluded that joint excitation of the modes of the square annular patch and the circular patch can achieve a directional beam. Moreover, the switchable function of the four directional beams can be manipulated by simply changing feeding ports in the proposed antenna.

## IV. Conclusion

This paper presents a pattern reconfigurable antenna, which consists of a square annular patch and a circular patch. It can generate four switchable directional beams towards different directions. Utilizing the CMA, the characteristic currents and fields of different modes of the proposed antenna can be investigated quantitatively. According to the CMA, the desired modes can be excited effectively by feeding the proposed antenna properly. A directional pattern with a large front-to-back ratio can be obtained by constructively combing the suitable modes of the proposed antenna. In addition, by changing the on/off states of the feeding ports, four switchable directional patterns can be implemented simply. With the flexible beam agility and simple structure, the proposed antenna can be very appealing for various applications.

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