Characteristic Mode Analysis of Circular Microstrip Patch Antenna and Its Application to Pattern Diversity Design

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ABSTRACT In this paper, a highly-isolated microstrip patch antenna (MPA) is presented for pattern diversity applications. The physical insight of MPA is investigated without the influence of external exciter by using the theory of characteristic modes (TCMs). Shorting pins are added to manipulate the resonant frequencies of eigenmodes. TM_{11}, TM_{01}, and TM_{02} modes are clearly tracked and identified. For the first time, all the three modes are simultaneously utilized to enhance the performances of MPA. To be specific, TM_{01} and TM_{02} modes have conical pattern, thus are combined to increase the bandwidth, while TM_{11} mode has broadside pattern, and is used to provide pattern diversity. A two-port feed network, consisting of probe feed and aperture coupling, is designed to excite the three modes. The measured −10 dB bandwidth of the two ports is 720 MHz and 130 MHz. The simulated port isolation reaches 42 dB, and the measured value is higher than 27 dB. The proposed MPA has the advantages of clear operating principle, flexible mode tuning and high port isolation, thus is attractive in MIMO systems.

INDEX TERMS Microstrip antenna, theory of characteristic mode, pattern diversity, wideband antenna.

I. INTRODUCTION
Microstrip patch antennas (MPAs) are popular in various wireless applications due to the merits of low profile, low cost, and planar structure [1]. There are rich resonating modes available in this kind of antennas. It is easy to excite the TM modes of MPA to produce broadside or conical (or omnidirectional) radiation patterns. For example, the TM_{10} mode of rectangular patch and the TM_{01} mode of circular patch are often used to generate broadside and conical radiation patterns [2], [3]. Apart from single mode, two or more modes are merged to achieve multiple functions, such as dual-band [4], wideband [5], circular polarization [6], dual polarization [7], and pattern diversity [8]. The combination of multiple modes is very cost-effective to improve the performances of MPA.

Adding shorting pins between the microstrip radiator and the ground plane attracts great interest, since it introduces additional degree of freedom to tune the modes of MPA. One widely used application is shifting the resonant frequencies of modes, so that two modes with similar radiation patterns can be combined to increase the bandwidth [9]–[12]. For instance, in [9], both the TM_{01} and TM_{02} modes of circular patch are used to produce conical radiation patterns. The resonant frequencies of the two modes are pulled close by introducing shorting pins. Other applications of the shorting pins include enhancing the peak gain [13], [14], reducing the cross-polarization [15], [16], increasing the beamwidth [17], suppressing the harmonic radiation [18], steering the null [19], and achieving pattern diversity [20]. For example, in [20], broadside and conical patterns are generated by the TM_{11} and TM_{01} modes. Shorting pins are introduced to make sure the two modes have the same frequency band.

Cavity model is widely adopted to analyze the modes of MPA [21], [22]. In this model, the open boundary is assumed to be perfect magnetic conductor (PMC). So the electric field in the cavity is perpendicular with the cavity. This method provides a simple way to observe the mode behavior of MPA, but has difficulty in analyzing shorting pins, because the number of shorting pins in practical model is discrete. In [14], the equivalent circuit of shorting pins in circular patch cavity is studied, and the mechanism for gain enhancement is revealed. However, it uses continuous annular
metallic wall to represent the shorting pins. Thin-wire short-circuited wall is used in [23] to increase the accuracy, but the shorting pins still need to be densely arranged. The calculation error will be large when the number of shorting pins is small.

The theory of characteristic mode (TCM) provides another straightforward way to observe the modes of MPA. This theory is based on the Method of Moments (MoM), thus is universal for all kinds of antennas [24]. One big advantage of this method is that the internal eigenmode of the radiator can be analyzed without the influence of external exciter. The physical insight of mode behavior is clear. In addition, the orthogonality of eigenmodes is useful to achieve multi-input-multi-output (MIMO) function. In the last decade, TCM has been widely used in smartphone antenna designs. Multiple chassis modes of the smartphone are excited to broaden the bandwidth or provide MIMO operation [25]–[27]. Recently, TCM has been used in microstrip antenna designs [28]–[35]. For example, the eigenmodes of E-shaped patch and U-slot patch are depicted in [28]–[31]. The influence of the exciter on eigenmodes is analyzed in detail. What’s more, discrete number of shorting pins can also be evaluated. For instance, in [33], the effect of shorting pins on reducing out-of-band mutual coupling is presented. In [35], a dual-polarized patch antenna is proposed with eigenmode analysis. Finite number of shorting pins is used to enhance the bandwidth of higher order modes. However, to the best of the authors’ knowledge, the effect of shorting pins on circular patch model has not been analyzed with TCM.

Pattern diversity, also known as angle diversity, is widely used in MIMO communications, which is usually achieved by generating broadside and conical patterns at the same time. High port isolation is preferred to provide unrelated wireless channels. In this paper, multiple eigenmodes of circular patch are used to design wideband highly-isolated pattern diversity antenna. Based on TCM, the resonances of TM$_{01}$, TM$_{02}$, and TM$_{11}$ modes are tracked in a wide frequency range without the influence of external exciter. Here, the concept of mode merging refers to the fact that multiple modes are utilized simultaneously to improve the performances of antenna. To be specific, TM$_{01}$ and TM$_{02}$ modes are merged to produce conical radiation patterns, while TM$_{11}$ mode is utilized to produce broadside radiation patterns. Hybrid feed technique, including probe feed and aperture coupling, is designed to excite the two radiation patterns. The port isolation can achieve 40 dB. The rest of the contents are organized as follow. In Section II, the eigenmodes of the circular MPA with shorting pins are identified. The effect of the shorting pins on TM$_{01}$, TM$_{02}$, and TM$_{11}$ modes is analyzed in detail. In Section III, a compact two-port MPA is designed for pattern diversity. TM$_{01}$, TM$_{02}$, and TM$_{11}$ modes are simultaneously excited to generate broadside and conical radiation patterns. Two feed schemes are compared to achieve high port isolation. In Section IV, a practical prototype is fabricated and measured. Finally, the conclusion is drawn in Section V.

### II. EIGENMODES OF MPA WITH SHORING PINS

In order to analyze the internal modes of MPA, microstrip radiator without external exciter is discussed. Fig. 1 shows the geometry of the MPA. It consists of a circular patch, an annular column of shorting pins, a ground plane, and a single layer of substrate. The substrate is made of RO4003C ($\varepsilon_r = 3.55$, $\tan\delta = 0.002$), with thickness of 1.524 mm. The circular patch and the ground plane are printed on the top and bottom sides of the substrate, respectively. There are 9 shorting pins that are uniformly placed with respect to the center. The fabrication of the model is easy, since standard PCB technique is adopted. Table 1 lists the parameters of the model. The radius of the circular patch, the offset distance between the shorting pins and the center of the circular patch, the diameter of the shorting pins, and the number of the shorting pins are four key parameters that determine the mode performance of the MPA.

| Parameter                  | Symbol | Value  |
|----------------------------|--------|--------|
| Radius of the patch        | $r_a$  | 18 mm  |
| Offset distance of the shorting pins | $r_s$ | 12.5 mm |
| Diameter of the shorting pins | $D$   | 0.5 mm |
| Number of the shorting pins | $N$   | 9      |

### A. EQUIVALENT CIRCUIT MODEL

The equivalent circuit model (ECM) of the proposed circular MPA is analyzed firstly. According to the transmission line theory, the ECM of circular MPA without shorting pins has been derived in [36]. However, the ECM becomes complex when discrete shorting pins are annularly placed. In order to evaluate the effect of the shorting pins, the ECM of the MPA model has been modified, as shown in Fig. 2. Considering that the shorting pins are located between the center and the edge of the circular patch, an additional $RLC$ circuit is added to represent the loading effect of the shorting pins [14]. Then, the resonant frequency of the circular MPA with $n$ shorting pins can be calculated using equation (1).

$$ f_m = \frac{1}{2\pi \sqrt{|L_u||L_p/n + L_c/n||C_u + nC_p + nC_m|}} \quad (1) $$
FIGURE 2. Equivalent circuit model of the proposed microstrip antenna.

where $L_a$ and $C_a$ are obtained from $L_1 || L_2$ and $C_1 || C_2$. $L_p$, $L_c$, $C_p$, and $C_m$ are determined by the physical parameters of the shorting pins.

ECM provides a straightforward way to analyze the effect of the shorting pins on MPA. However, the calculation of the parameters is difficult, especially for multiple modes, since the shorting pins are discretely distributed.

B. EIGENMODE IDENTIFICATION

Comparing with ECM, TCM is simpler and more accurate to analyze the loading effect of finite number of shorting pins. The theory of this method has been presented in many literatures [37], thus is not shown in this paper for brevity. Here, only one quantity, namely the modal significance (MS), is considered to evaluate the mode performance. The definition of MS is as follows:

$$\text{MS} = \left| \lambda_n \right|$$

where $\lambda_n$ is the eigenvalue of the $n$-th mode. $\lambda_n$ represents the ratio of stored energy to radiated energy of the $n$-th mode. $\lambda_n$ will be zero when all the energy is radiated.

As is shown in Equation (1), MS maps the $[-\infty, +\infty]$ value range of $\lambda_n$ into the normalized range of $[0, 1]$. MS equals to 1 when all the energy is radiated, and equals to 0 when all the energy is stored. The maximal value of MS determines the resonant frequency of the mode. It provides a convenient way to evaluate the eigenmode performance. The more the value approaches to 1, the stronger the radiating ability is. In practical engineering applications, we usually use $\text{MS} \geq 1/\sqrt{2}$ to define the available bandwidth. Therefore, MS represents not only the radiating ability, but also the bandwidth potential of the mode.

Full wave simulation software CST ver. 2019 is applied to calculate the eigenmodes of the circular patch model, where CM analysis has been integrated in the Multilayer Solver. The size of the ground plane is assumed to be infinite in the calculation. The MS of the microstrip circular patch model with shorting pins is analyzed in wide frequency band. Fig. 3 shows the first three eigenmodes that can be resonant in the concerned frequency band. According to the peak value of MS, the resonant frequencies of the three modes are at 3.42 GHz, 4.44 GHz, 5.25 GHz, respectively. The bandwidth of the mode increases, as frequency increases. It is noted that there is a degenerate mode at the second resonance.

This mode has orthogonal polarization with mode 2, and is not discussed for brevity.

The eigencurrents are observed to identify the eigenmodes of the radiator. Fig. 4 shows the currents distribution on the circular patch at the three resonances. In Fig. 4(a), it is seen that the currents are along the radial axis, and the directions of the currents at the inner side and outside of the shorting pins are opposite. This distribution indicates that mode 1 is the TM$_{01}$ mode. In Fig. 4(b), the currents are mainly along the horizontal direction, and the currents at the left edge and right edge have the same direction. It implies that mode 2 is the TM$_{11}$ mode. In Fig. 4(c), the currents are along the radial axis, which is similar with mode 1. However, the directions at the inner and outer sides of the shorting pins are the same, rather than opposite. It indicates that mode 3 is the TM$_{02}$ mode. By observing the eigencurrents distribution, all the three eigenmodes are clearly identified.

The far fields of the three modes are analyzed to further verify the mode identification. Fig. 5 shows the 3-D radiation
patterns of the three modes at their resonant frequencies. It is shown that TM$_{01}$ and TM$_{02}$ modes have conical radiation patterns, while TM$_{11}$ mode has broadside radiation patterns. The peak gains of the three modes are 5.0 dBi, 9.8 dBi, and 4.8 dBi, respectively. These observations also verify the identification of the three modes.

C. PARAMETER ANALYSIS

The unit cell of the proposed MPA is analyzed by sweeping the key parameters. As listed in Table 1, there are four parameters that affect the structure of the model. The effect of these parameters on MS is studied to tune the resonant frequencies of TM$_{01}$, TM$_{02}$ and TM$_{11}$ modes.

Fig. 6 shows the effect of the radius of the circular patch ($r_o$) on the MS of the three modes. It is seen that increasing $r_o$ can effectively decrease the resonant frequencies of all the three modes. Figs. 7-9 analyzed the influence of the shorting pins in detail. As shown in Fig. 7, when the shorting pins move towards the center of the circular patch, the resonant frequencies of TM$_{11}$ mode and TM$_{02}$ mode shift downward, while the resonant frequency of TM$_{01}$ mode stays stable. In Fig. 8, the influence of the diameter of the shorting pins ($D$) is studied. It is shown that decreasing $D$ can effectively decrease the resonant frequencies of TM$_{11}$ mode and TM$_{01}$ mode, while has little effect on TM$_{02}$ mode. Fig. 9 discusses the number of shorting pins ($N$). As $N$ increases, the resonant frequencies of both the TM$_{11}$ mode and TM$_{01}$ mode shift upward, while the resonant frequencies of TM$_{02}$ mode stays stable.

From the parameter analysis above, it is concluded that the resonant frequencies of the three modes can be
effectively shifted by changing the parameters of the shorting pins. Although each mode cannot be tuned independently, the multiple parameters provide sufficient degrees of freedom to control the resonant frequencies of the modes. For example, \( r_s \) only affects \( \text{TM}_{11} \) and \( \text{TM}_{02} \) modes, \( N \) only affects \( \text{TM}_{01} \) and \( \text{TM}_{11} \) modes. In the following sub-section, the multiple modes will be manipulated so that they can enhance the antenna performance.

D. COOPERATION OF MULTIPLE EIGENMODES

Considering that \( \text{TM}_{01} \) and \( \text{TM}_{02} \) modes have conical pattern, and \( \text{TM}_{11} \) mode has broadside pattern, the possible idea of mode cooperation can be: (i) Wideband by merging \( \text{TM}_{01} \) and \( \text{TM}_{02} \) modes; (ii) Pattern diversity by merging \( \text{TM}_{11} \) and \( \text{TM}_{01} \) (or \( \text{TM}_{02} \)) modes; (iii) Wideband and pattern diversity by merging \( \text{TM}_{01} \), \( \text{TM}_{02} \) and \( \text{TM}_{11} \) modes. Obviously, the third type has the best performances.

It is necessary to move the resonating frequencies of the multiple modes so that they will be close to each other. Based on the parameter analysis, the number of the shorting pins is further investigated. Fig. 10 shows the resonant frequencies of \( \text{TM}_{11} \), \( \text{TM}_{01} \), \( \text{TM}_{02} \) modes with different number of shorting pins. As \( N \) increases, the resonant frequencies of \( \text{TM}_{11} \) mode and \( \text{TM}_{01} \) mode increases rapidly, while the frequency increase of \( \text{TM}_{02} \) mode is insignificant. The resonant frequencies of \( \text{TM}_{11} \) mode and \( \text{TM}_{01} \) mode are close to each other, when the number is near 18. The frequencies of all the modes become stable when the number is higher than 21. Because the dense arrangement of shorting pins resembles continuous metallic wall. It is also shown that the resonant frequency of \( \text{TM}_{01} \) mode is always lower than that of \( \text{TM}_{11} \) mode. Thus, it is impossible to utilize the two modes to achieve pattern diversity at the same frequency.

After loading proper number of shorting pins, the \( \text{TM}_{01} \), \( \text{TM}_{02} \) and \( \text{TM}_{11} \) modes can be utilized simultaneously. Fig. 11 depicts the cooperation process of the three modes. On the one hand, the bandwidths of \( \text{TM}_{01} \) and \( \text{TM}_{02} \) modes are merged to obtain wideband operation. Both modes can generate conical radiation patterns. On the other hand, the resonant frequency of the \( \text{TM}_{11} \) mode is designated to be the same as that of the \( \text{TM}_{02} \) mode. Considering that \( \text{TM}_{11} \) mode can generate broadside radiation patterns, pattern diversity function can be achieved when the two patterns are excited independently. Such kinds of pattern diversity can provide signals in half hemisphere. The wide angle coverage ability is promising for indoor WLAN applications.

Fig. 12 illustrates the algorithm for the proposed antenna design. In the beginning, conventional MPA without shorting pins is studied. The eigenmodes of the model are calculated based on CM analysis. If the resonant frequencies of \( \text{TM}_{01} \), \( \text{TM}_{02} \), and \( \text{TM}_{11} \) modes are not close to each other, it will increase the number of shorting pins and carry out iteration. If the three modes can be merged, it will design a two-port feed network for the three modes to achieve pattern diversity.

III. PATTERN DIVERSITY ANTENNA DESIGN

As shown in Fig. 4, the eigcurrents of \( \text{TM}_{01} \) and \( \text{TM}_{02} \) modes are along the radial axis. To obtain conical radiation pattern, the proper feed location for the two modes should be at the center of the circular patch. The eigcurrents of \( \text{TM}_{11} \) mode are along the horizontal direction. To obtain broadside radiation pattern, the proper feed location for this mode should have some offset distance from the center point. With this scheme, a two-port feed network can be designed to excite the three modes simultaneously.

Probe feed is a simple way to excite the modes of microstrip antenna. In the beginning, two probe feeders are
The influence of this feeder on antenna symmetry might be low, since the feed line does not contact with the circular patch directly. Fig. 13(b) shows the modified geometry of the microstrip antenna. The probe feeder of Port 2 is replaced by aperture coupling feeder. The two feeders consist of a probe-aperture hybrid feed scheme. The H-shaped aperture is etched on the ground plane. A small piece of substrate is added below the ground plane, where an L-shaped microstrip line is printed on the bottom of the substrate. The substrate is made of 0.508-mm-thick RO4003C. The characteristic impedance of the feed line is 50 \( \Omega \). The optimized parameters are as follows: \( p = 11 \) mm, \( l_1 = 8.4 \) mm, \( l_2 = 5 \) mm, \( l_3 = 1.6 \) mm, \( w = 0.8 \) mm. The other parameters are the same as those of the antenna with two probe feeders.

As shown in Fig. 14, the port isolation is quite different, when aperture coupling feeder is used. The value is above 40 dB in the overlapping bandwidth, which is greatly larger than the 11 dB in two-probe feed scheme. The comparison implies that using aperture coupling to replace the probe for Port 2 is effective to improve the port isolation. The hybrid feed scheme will be adopted in the final design.

The merging process of TM\(_{01}\) and TM\(_{02}\) modes is shown in Fig. 15. The resonant frequency of TM\(_{01}\) mode increases, while that of TM\(_{02}\) mode stays stable, when the number of shorting pins (\( N \)) increases. The resonant depth of both modes also becomes deeper. Using the −10 dB criterion, the bandwidths provided by the two modes can be merged, thus achieving wide bandwidth.
significantly advantages over the traditional microstrip antenna in utilizing the number of modes and port isolation.

IV. EXPERIMENTAL RESULTS

The prototype of the two-port MPA is fabricated and measured. Fig. 17 shows the photograph of the prototype. It has two layers of RO4003C substrate, with sizes of $56 \times 56$ mm$^2$ and $20 \times 20$ mm$^2$, respectively. Four plastic screws are used to assemble the two layers together. Two SMA connectors are soldered at the bottom and edge of the board.

Fig. 18 shows the simulated and measured $S$ parameters of the two-port MPA prototype. The simulated and measured reflection coefficients show reasonable agreement. There are two resonances for Port 1 excitation, and one resonance for Port 2 excitation. The measured $-10$ dB bandwidth of the two ports is $720$ MHz ($4.53-5.25$ GHz) and $130$ MHz ($5.09-5.21$ GHz) respectively. The measured port isolation is worse than the simulated value. It may be caused by fabrication error and assembling error. However, the measured port isolation is still higher than $27$ dB, which is sufficiently high.

The radiation patterns of the antenna are measured in a far field chamber. During the measurement, when one port is connected with the VNA, the other port is terminated with $50\Omega$ load. The simulated and measured normalized radiation patterns with Port 1 and Port 2 excitations are shown in Fig. 19. Good agreement can be observed from the simulated and measured results. The radiation patterns have conical shape, when Port 1 is excited. The main beam is up tilted due to the influence of the ground plane. On the other hand, broadside radiation patterns are observed in the two principal planes when Port 2 is excited. It is also shown that the measured cross polarizations are worse than the simulated ones, but are still below $-18$ dB in both planes.

Fig. 20 shows the simulated and measured peak gains with frequency variation. For Port 1 excitation, the beam direction is at about $40^\circ$. It is seen that the peak gain is $4.8$ dBi, and the gain variation is within $1$ dB across the bandwidth. For Port 2 excitation, the gain at the broadside direction is $9.5$ dBi.
This value is larger than that of conventional patch antenna without shorting pins. It implies that the shorting pins can also increase the gain of MPA, since the radiating aperture is enlarged. Fig. 21 shows the simulated radiation efficiency of the two ports. In the −10 dB impedance bandwidth, the radiation efficiency of Port 1 and Port 2 is higher than 81% and 77%, respectively. The different values of radiation efficiency with the two port excitations are caused by the fact that different modes have different radiating ability.

Table 2 compares the proposed antenna with other circular MPAs that have annular column of shorting pins. Comparing with the referenced designs, the proposed antenna can excite the maximal number of modes simultaneously, and multiple functions of wideband and pattern diversity. Although [18] can also excite 3 modes, it needs 3 radiators, thus the antenna structure is bulky.

**V. CONCLUSION**

In this paper, multiple eigenmodes of circular MPA with shorting pins are analyzed based on characteristic mode analysis. Key parameters of the shorting pins are studied in detail. Three modes, namely TM_{11}, TM_{01}, TM_{02} modes, are simultaneously utilized to enhance the performances of the MPA. The bandwidth of TM_{01} and TM_{02} modes are merged to provide wide bandwidth with conical radiation patterns, while TM_{11} mode is used to generate broadside radiation patterns, thus achieving pattern diversity. A simple two-port feed network is designed to excite the three modes simultaneously. High port isolation is achieved by using probe-aperture hybrid feed. The measured bandwidth is 720 MHz for conical pattern, and is 130 MHz for broadside pattern. The measured port isolation is above 27 dB. With the advantages of flexible mode tuning, wide bandwidth, high port isolation, and pattern diversity, the proposed MPA has great potential in MIMO communications.

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