A Low-Profile Pattern Reconfigurable MIMO Antenna

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ABSTRACT A low-profile pattern reconfigurable multiple-input multiple-output (MIMO) antenna is demonstrated in this paper. The antenna element is composed of a rectangular monopole and two sets of parasitic strips loaded with PIN diodes. The parasitic strips can operate as a reflector or a director by switching the PIN diodes on or off. As a result, the element provides a bidirectional mode and two directional modes. The MIMO antenna consists of two elements, which are arranged opposite to each other. Two decoupling strips are introduced to improve the isolation between the elements. The simulation and measurement results illustrate that the proposed antenna has nine pattern configurations. The overlapped bandwidth of the nine modes is 10.6%, and the isolation is greater than 16.5 dB. Also, a good diversity performance is obtained.

INDEX TERMS Low-profile, pattern reconfigurable, multiple-input multiple-output, PIN diode.

I. INTRODUCTION Due to its advantages of high data rate and link reliability, the multiple-input multiple-output (MIMO) technology has attracted lots of attention in modern wireless communications. By placing multiple antenna elements at the transmitter and receiver ends of the wireless communication system, MIMO can not only improve the capacity of channel, but also reduce the effects of multi-path fading [1]. It is well known that the channel capacity of a MIMO system increases with the uncorrelated channels [2]. To achieve the maximum channel capacity of MIMO systems, it is necessary to minimize the channel correlation related to the mutual coupling between antenna elements and the spatial correlation [3].

Usually, the mutual coupling between the elements is reduced by etching gaps or loading branches on the ground plane, placing the elements orthogonally, loading parasitic strips and using neutralization lines [4]–[8]. On the other hand, the spatial correlation of a MIMO channel is governed by the radiation pattern of the antenna. Therefore, one potential solution to increase the channel capacity is to adopt the pattern reconfigurable antenna to the MIMO system. In the last decades, several pattern reconfigurable MIMO antennas have been reported. The pattern reconfigurable property can be achieved by loading radio frequency (RF) switches on the radiating elements [9]–[12]. However, the overlapped bandwidth is narrow. Another solution to realize the pattern reconfigurable characteristic is to use the electrically steerable passive array radiator structure [13]. The parasitic element loaded with PIN diodes can operate in the director or reflector state by controlling the states of the diodes, and thus the antenna exhibits three reconfigurable patterns. The overlapped bandwidth of the antenna is significantly improved.

This paper presents a pattern reconfigurable MIMO antenna. It is composed of two elements arranged opposite to each other, and two decoupling strips are introduced to improve the isolation. The pattern reconfigurable characteristic is obtained by changing the bias voltages of the PIN diodes embedded in the parasitic strips of the elements. The antenna has nine pattern configurations. In comparison with the antennas reported in literatures [9]–[12], the overlapped bandwidth of the antenna in this work is largely enhanced. Moreover, the proposed antenna has a low profile compared to the antenna with similar overlapped bandwidth [13].

II. ANTENNA DESIGN

A. ANTENNA ELEMENT

Fig. 1 shows the geometry of the antenna element. It is composed of a rectangular monopole and two sets of parasitic meandering strips symmetrically placed on both sides of the
monopole. Four PIN diodes are inserted in the parasitic strips, and the complexity of the bias circuit is reduced through mounting two 12 nH inductors between the adjacent strips. By changing the bias voltages of the diodes, the set of parasitic strips operates as a director or a reflector, and thus the radiation pattern of the element can be reconfigured. The antenna element is designed to operate at 2.45 GHz and simulated with HFSS. The chosen substrate is inexpensive FR4 with dielectric constant of 4.4 and a thickness of 1.6 mm. The optimal parameters are as follows: $W = 80$ mm, $L = 45$ mm, $w_g = 25$ mm, $l_g = 11$ mm, $w_p = 11.5$ mm, $l_p = 30$ mm, $w_f = 2.98$ mm, $l_f = 12$ mm, $w_m = 10$ mm, $l_m = 2$ mm, $l_{n2} = 3$ mm, $p_1 = 13.26$ mm, $p_2 = 3$ mm and $g = 1$ mm, respectively. The diode used is BAR50-02V, which is modeled with a 3 kΩ resistor when it is forward biased and a 5 kΩ resistor in parallel with a 0.15 pF capacitor when it is reverse biased.

For the convenience of analysis, the diodes on the left strips are called the A-group diodes, and those on the right strips are called the B-group diodes. Table 1 lists the operation modes of element. In mode 1 (all diodes off), the length of all strips is less than $\lambda/2$ ($\lambda$ is the guided wavelength at 2.45 GHz), and then the left and right strips both operate as a director. Therefore, a bidirectional pattern is generated. In mode 2 (A-group diodes on and B-group diodes off), the length of the left strips is larger than $\lambda/2$, while that of the right strips is less than $\lambda/2$. The left and right strips work as a reflector and a director, respectively. As a result, the element produces a directional pattern with the maximum radiation along the positive $x$-axis. Similarly, a directional pattern with the maximum radiation along the negative $x$-axis is achieved in mode 3. In addition, when all diodes are simultaneously turned on, the left and right strips both act as a reflector, and then the electromagnetic energy cannot be effectively radiated. Thus, the last case is not discussed in this paper. Fig. 2 plots the reflection coefficient of the element. It is observed that the overlapped bandwidth in three modes is 2.3-2.6 GHz.

To demonstrate the working principle of the element, the surface current distributions and radiation patterns are studied. Fig. 3 depicts the simulated results at 2.45 GHz. In mode 1, the current is symmetrically distributed on the left and right strips acting as a director, and thus a bidirectional pattern is produced. In mode 2, the current is mainly concentrated on the right strips acting as a director, while that on the left strips working as a reflector is rather weak. Consequently, the element exhibits a directional pattern with the maximum radiation along the positive $x$-axis. Similarly, a directional pattern with the maximum radiation along the negative $x$-axis is achieved in mode 3. In addition, the number and length of the parasitic strips have a significant effect on the performance of the element. Without loss of generality, a numerical analysis of mode 2 is performed. Fig. 4 shows the reflection...
coefficient and normalized radiation pattern for different number of parasitic strips. It is observed that the bandwidth of antenna with one strip is wider while the front-to-back ratio (FBR) is smaller than that with two strips. To achieve a good directional characteristic, two strips are chosen in this work. Fig.5 plots the effect of the length of parasitic strips on the reflection coefficient and radiation pattern. It is clear that the impedance matching becomes better as the length of strips \( l_s = 6 \times w_m + 5 \times l_{m2} \) increases. Moreover, the maximum FBR is obtained when \( l_s \) selected to be 75 mm.

**B. MIMO ANTENNA**

Fig.6 shows the configuration of the pattern reconfigurable MIMO antenna. It consists of two antenna elements, which are arranged opposite to each other along the \( y \)-axis. Two decoupling strips are introduced between the ground planes to improve the isolation. The parameters of the elements are the same as those of the element in Fig.1. The distance between the patches of the elements is 12 mm. The optimal size of the decoupling strips is as follows: \( l_{d1} = 2 \) mm, \( l_{d2} = 6 \) mm and \( w_d = 28 \) mm, respectively.

The operation modes of the antenna are listed in Table 2. In mode 1, the elements operate in a bidirectional pattern, and thus the antenna exhibits a bidirectional behavior. In modes 2 and 3, the elements work in a directional pattern along the positive and negative \( x \)-axis, respectively. As a result, the antenna produces the same pattern as that of the elements. In modes 4 and 5, the bottom element operates in a bidirectional pattern, while the top one works in a directional pattern along the positive and negative \( x \)-axis, respectively.

| Mode | \( S_1 \) | \( S_2 \) | \( S_3 \) | \( S_4 \) | \( S_5 \) |
|------|------|------|------|------|------|
| Mode 1 | off | off | off | off | off |
| Mode 2 | on | off | on | off | off |
| Mode 3 | off | on | off | on | off |
| Mode 4 | off | off | on | on | on |
| Mode 5 | off | off | off | on | off |
| Mode 6 | on | off | off | off | off |
| Mode 7 | off | on | off | off | off |
| Mode 8 | on | off | off | on | on |
| Mode 9 | off | on | on | off | off |
Therefore, the antenna provides a bidirectional pattern at port 1 and a directional pattern along the positive and negative x-axis at port 2. Similarly, the pattern in modes 6 and 7 is directional at port 1 and bidirectional at port 2. In modes 8 and 9, two elements operate in a directional pattern along the positive and negative x-axis, respectively. Hence, a directional pattern along the positive and negative x-axis at ports 1 and 2 is generated in mode 8. The pattern in mode 9 is similar to that in mode 8, but in the opposite direction.

The effect of the decoupling strips on the performance of the antenna is also investigated. Without loss of generality, a numerical study of mode 1 is conducted. Fig. 7 shows the simulated surface current distributions of the antenna. The results are obtained when port 1 is excited. As depicted in Fig. 7 (a), it is observed that the current flowing from port 1 to port 2 is strong when there are no decoupling strips. Fig. 7 (b) illustrates that the coupled current is significantly reduced after the decoupling strips are introduced. Furthermore, the $S$-parameter of the antenna is plotted in Fig. 8. It is clear that the decoupling strips can improve the isolation between the elements.

### III. EXPERIMENTAL RESULTS

To validate the proposed pattern reconfigurable MIMO antenna, a prototype of the antenna is fabricated and tested. Fig. 9 shows the photograph of the fabricated antenna. The $S$-parameters are measured with an Agilent N5230A vector network analyzer, and the far field performance is measured with Lab-Volt 8092 antenna training test system.

#### TABLE 3. Measured bandwidth and isolation of antenna.

| Mode | BW @ Port 1 (GHz) | BW @ Port 2 (GHz) | $S_{11}$ (dB) |
|------|-------------------|-------------------|---------------|
| Mode 1 | 12.8% (2.27-2.58) | 21% (2.18-2.7) | 16.5 |
| Mode 2 | 10.6% (2.32-2.58) | 12.8% (2.27-2.58) | 22 |
| Mode 4 | 15% (2.34-2.72) | 20% (2.18-2.67) | 17.9 |
| Mode 8 | 12.8% (2.27-2.58) | 16.1% (2.19-2.58) | 17.4 |

#### TABLE 4. Measured peak gain, efficiency, FBR and ECC of antenna.

| Port | Mode 1 | Mode 2 | Mode 4 | Mode 8 |
|------|--------|--------|--------|--------|
| Peak gain (dBi) | 1.9 | 4.74 | 2.21 | 4.32 |
| Efficiency (%) | 82.3 | 81.1 | 82.2 | 81.4 |
| FBR (dB) | 2.07 | 10.98 | 0.91 | 10.36 |
| ECC | 0.002 | 0.003 | 0.011 | 0.009 |

ECC is defined as $\rho_c = \frac{|S_{11}|^2 + |S_{21}|^2}{|S_{11}|^2 + |S_{21}|^2}$.

Due to the symmetry of the structure, the $S$-parameters in the directional modes (2 and 3) are the same, so are those in the bidirectional / directional modes (4, 5 and 6) and the directional modes with opposite directions (8 and 9). Without loss of generality, the $S$-parameters in modes 1, 2, 4 and 8 are depicted in Fig. 10. It is obvious that the experiment results are basically consistent with the simulation ones. The measured impedance bandwidth and isolation are listed in Table 3. It is found that the overlapped bandwidth is 10.6% (2.34-2.58 GHz) and the isolation is larger than 16.5 dB. The differences between the simulation and experiment results are mainly caused by the accuracy of the dielectric constant of material used and the fabrication error.

Fig. 11 plots the normalized radiation patterns at 2.45 GHz. It is observed that a good agreement between the simulated and measured results is obtained. In modes 1-3, the same pattern is obtained at two ports. A bidirectional pattern in both...
E- and H-planes is generated in mode 1, while a directional pattern with the maximum radiation at $\varphi = 0^\circ$ in E-plane and $\theta = 90^\circ$ in H-plane is produced in mode 2. The pattern in mode 3 is similar to that in mode 2 except the maximum radiation at $\varphi = 180^\circ$ and $\theta = 270^\circ$. In mode 4, the antenna
exhibits a bidirectional pattern at port 1 and a directional pattern with the maximum radiation at $\phi = 0^\circ$ in E-plane and $\theta = 90^\circ$ in H-plane at port 2. A similar pattern in the opposite direction is generated in mode 5. Similarly, the pattern in modes 6 and 7 is directional at port 1 and bidirectional at port 2. In mode 8, the antenna provides a directional pattern with the maximum radiation at $\phi = 0^\circ$ and $\theta = 90^\circ$ at the port 1 and $\phi = 180^\circ$ and $\theta = 270^\circ$ at port 2. The pattern in mode 9 is also directional. The cross-polarization level is lower than $-25$ and $-15$ dB in E- and H-planes, which is not given in Fig.11. Table 4 lists the measured peak gain, radiation efficiency, FBR and envelope correlation coefficient (ECC) in modes 1, 2, 4 and 8. It is found that the peak gain and FBR for the directional pattern are larger than those for the bidirectional pattern. Also, the radiation efficiency is more than 80% at the frequency of 2.45 GHz and the ECC is less than 0.02.

IV. CONCLUSION

A low-profile planar MIMO antenna with the pattern reconfigurable characteristic is demonstrated in this paper. The antenna consists of two monopole elements arranged opposite to each other, and the isolation between the elements is improved through introducing two decoupling strips. The pattern reconfigurable property is achieved by controlling the states of the PIN diodes embedded in the parasitic strips of the elements. The experiment results demonstrate that the antenna can provide nine pattern configurations. The overlapped bandwidth of the nine modes is 10.6%, and the isolation is greater than 16.5 dB.

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