An OAM-Mode Reconfigurable Array Antenna With Polarization Agility

LE KANG1, HUI LI2, JINZHU ZHOU1, AND SHUFENG ZHENG3, (Member, IEEE)

1School of Mechano-Electronic Engineering, Xidian University, Xi’an 710071, China
2School of Automation and Information Engineering, Xi’an University of Technology, Xi’an 710048, China
3National Key Laboratory of Antennas and Microwave Technology, Xidian University, Xi’an 710071, China

Corresponding author: Jinzhu Zhou (xidian_jzzhou@126.com)

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ABSTRACT An Orbital angular momentum (OAM) antenna with both mode reconfigurability and polarization agility is proposed in this paper. The proposed antenna is designed based on a four-element uniform circular array with a phase-shifting reconfigurable feed network. To reduce its dimensions and complexity, the feed work is constructed with two stages of single-pole double-throw switches and a stage of 90° phase-shifting power dividers, partially of which can be shared among the chosen operating states. Moreover, the use of a small amount of p-i-n diodes as binary switches allows low insertion loss and low component cost. By varying the ON/OFF status of the diodes strategically, the resultant array can be reconfigured to horizontal polarization (HP) or vertical polarization (VP), along with OAM mode \( l = -1 \) or \(+1\) achieved for each polarization. The antenna performance is evaluated in terms of reflection coefficients, near-field distributions and far field radiation patterns. According to the measured results, the antenna exhibits an overlapped frequency band ranging from 2.29 to 2.59 GHz among the different operating states. Meanwhile, stable radiation patterns as well as high cross-polarization discrimination can be obtained. Benefiting from the above features, the antenna could help to improve the signal quality and increase the channel capacity in wireless communications.

INDEX TERMS Orbital angular momentum, mode reconfigurability, polarization agility, reconfigurable feed network.

I. INTRODUCTION

Owing to the merits of orthogonality among integer topological modes and rotational degree of freedom, orbital angular momentum (OAM) technology is considered a promising approach to achieving large transmission capacity and high spectral efficiency for wireless communications [1]–[3]. Besides, it may be applied for radar target imaging with the potential to acquire the cross-range profile of the target [4], [5]. To realize the generation of OAM carrying vortex beams, antennas have been designed using spiral phase modulation [6], [7] and spatial sampling of a continuous circular aperture [8]–[10]. Also, dielectric resonator antennas and travelling wave antennas can be employed to produce twisted radio beams with specific topological modes [11], [12]. To alleviate the mode mismatching problem and enable digital data coding, OAM-mode reconfigurable antennas have been developed to yield switchable beams with multiple independent modes via a single aperture [13]. Hitherto, various methods have been exploited for mode reconfigurability, such as reconfigurable feed network [14], mechanical rotation [15], active metasurface [16] and phased array [17]. However, most of the OAM antennas mentioned above suffer from some limitations, such as complex structure, slow tuning speed, large amount of tunable components and high cost.

Moreover, rapid growth in wireless communications requires versatile antennas that can be adjusted strategically to enhance the system performance. Polarization agile antennas have drawn considerable interest due to their desirable features including frequency reuse and mitigation of multi-path effects [18]. Therefore, combining mode reconfigurability with polarization agility becomes attractive for OAM antennas since more benefits could be brought to increase
TABLE 1. Properties of three-layer dielectric substrates.

| substrate | material | thickness (mm) | relative permittivity | dielectric loss tangent |
|-----------|----------|----------------|-----------------------|------------------------|
| top       | FR4      | 1.0            | 4.4                   | 0.02                   |
| middle    | PTFE     | 1.0            | 3.5                   | 0.003                  |
| bottom    | FR4      | 0.8            | 4.4                   | 0.02                   |

the functionality of communication systems or applications. Although some solutions have been reported in literature to provide different OAM-modes and polarizations [19], [20], they cannot alter the mode and polarization characteristics independently. The antenna array [21] enables OAM-mode and polarization manipulation by switching the excitation ports, while its feed structure is relative bulky and complex. Thus, the design of antennas with reconfigurabilities in both OAM-mode and polarization still poses challenges in terms of realization complexity, fabrication cost, power loss, and tuning speed.

To deal with the aforementioned challenges, an OAM-mode and polarization tunable array antenna for generating vortex beams is presented in this paper. The antenna is constructed based on a four-element uniform circular array (UCA). Low-cost stacked microstrip antennas are selected as the array elements, which can be fed though either of two orthogonal excitation ports. Moreover, a phase-shifting scheme with successive 90° or −90° phase delays is obtained by adopting both a mirror arrangement of the elements and a reconfigurable feed network. Compared to those in the dual-polarized dual-mode antennas [20], [21], the designed feed network are integrated and shared for both polarizations. It also avoids using complicated impedance matching or phase delaying schemes, which helps to reduce the size and complexity of the feed structure. For realizing electrical control of the available states, low-loss p-i-n diodes are introduced in the feed network as radio frequency (RF) switches, and their status can be altered with a bias circuit for mode and polarization switching. As a consequence, the antenna can produce four operating states corresponding to OAM mode \( l = \pm 1 \) along with horizontal polarization (HP) or vertical polarization (VP). The antenna performance for all chosen states is further investigated on basis of reflection coefficients, near-field intensity and phase distributions, as well as far field radiation characteristics.

II. ANTENNA DESIGN AND ANALYSIS

A. ARRAY CONFIGURATION

The configuration of the proposed array antenna is shown in Fig. 1, which is implemented on three-layer substrates. The top layer substrates are placed 5 mm above the middle one, and supported by plastic holders. Both the middle and bottom layer substrates are stacked together and separated by a common ground plane. Table 1 lists the properties of the dielectric substrates.

The antenna is composed of a four-element UCA, a reconfigurable feed network and a direct current (dc) bias circuit. The four elements are equidistantly arranged along a circle with a radius of 0.5\( \lambda_0 \) at 2.45 GHz, which makes a tradeoff between inter-element mutual coupling and radiation side-lobe level. Each element is a stacked microstrip antenna with two patch radiators, with its upper circular and lower ring patches printed on the top surfaces of the top and middle layer substrates, respectively. It is fed by two orthogonal ports, either of which is excited at each time, resulting in switchable polarizations. The lower patch can be regarded as a microstrip ring resonator, while the upper patch functions as a parasitic radiator to enhance the impedance bandwidth and radiation performance of the antenna element.

The feed network has a symmetric structure with respect to both \( x \)-axis and \( y \)-axis. Its single input is attached to a 50-Ω SMA connector at the central feed point, and eight outputs to the ring patches. P-i-n diodes are mounted in the gaps between the transmission lines (TLs) of the feed network. To provide the bias voltages for these tunable components, a dc bias circuit is designed on the bottom surface of the bottom layer substrate.

B. FEED NETWORK

The details of the reconfigurable feed network, which plays a vital role in the realization of reconfigurabilities, is sketched in Fig. 2(a). To allocate excitations for the antenna element, the feed network have an input port (denoted as \( P_0 \)), and four pairs of output ports (denoted as \( P_1 \) and \( P_2 \), \( P_3 \) and \( P_4 \), \( P_5 \) and \( P_6 \), and \( P_7 \) and \( P_8 \)), each of which is excited by a p-i-n diode.
and $P_5$, $P_7$ and $P_8$, respectively). Its overall structure can be divided into three single-pole double-throw (SPDT) switches and a stage of phase-shifting power dividers.

Fig. 2(b) plots the schematics of two SPDT switches and phase-shifting power divider (denoted as SW1, SW2, and PD). It can be seen that SW1 and SW2 are both made up of three microstrip TLs, two p-i-n diodes in a back-to-back arrangement and dc bias circuit. For SW1, the characteristic impedance of all three TLs is $Z_{01} = 50 \Omega$. For SW2, the TL with a characteristic impedance of $Z_{02} = 70.7 \Omega$ also performs as a $\lambda_g/4$ ($\lambda_g$ is the guided wavelength at 2.45 GHz) transformer. The commercial p-i-n diodes SMP1345-040LF from Skyworks are used as binary switches. When either of the diodes is set ON status while the other is set OFF, each SPDT switch can be regarded as an L-shaped transmission path with two switchable orientations. To supply the required bias voltages, the anodes of the diodes are separately linked to the bias pads via 33-nH RF choke inductors, and their cathodes are all shorted to the ground. The two cascaded SPDT switches are bridged by a 10-pF dc block capacitor for the purpose of dc isolation.

In addition, PD is employed for 2-way power dividing and it utilizes two T-shaped power splitters, which share two output ports and a TL with a characteristic impedance $Z_{03} = 100 \Omega$. A quarter-wavelength delay line is introduced in the shared TL as a 90° phase shifter. In this manner, a phase shift of 90° or −90° is obtained between the output ports when either of the T-shaped power splitters becomes active by controlling the ON/OFF status of the p-i-n diodes. Hence, the resultant feed network have two pairs of output ports with equal amplitude and switchable phase shifts, and the other unused ports blocked.

In the feed network, a total number of 20 p-i-n diodes are used, which are controlled by 12 dc bias voltages (defined as $V_1$ to $V_{12}$). For brevity, these voltages of 1.5 V and 0 V are expressed in digital forms of “1” and “0”, allowing the diodes operate at the ON and OFF status, respectively. The performance of the feed network are investigated through simulation, which is implemented in CST Microwave Studio. In the simulation, the diodes serve as a 3.5-Ω resistance for ON status and a 0.18-pF capacitance for OFF status, both of which are in series with a 0.45-nH inductor.

Fig. 3 displays the surface currents on the feed network with different bias configurations. When the bias voltages $V_1$ to $V_{12}$ are set as ‘1001011000100’ or ‘011000010001’, strong currents are observed along two individual paths from the central port to the four ports in horizontal orientation. The different current paths are exploited to generate different phase shifts for the horizontal output ports. Otherwise, the surface currents mainly flow toward the four output ports in vertical orientation for the other two cases. The results also validate that the SPDT switches (SW2) and phase-shifting power dividers (PD) can be shared for different cases.

To further examine its performance, the corresponding S-parameters of the feed network are shown in Fig. 4. Due to the structure symmetry, the results are shown only for four output ports. It is found that for all cases, the reflection coefficients ($|S_{00}|$) are better than −24 dB over the band of 2.3-2.6 GHz. Meanwhile, magnitudes of the transmission coefficient ($|S_{10}|$) from the central input port to the output ports are about -6.9 dB with variations of less than 0.4 dB. Otherwise, $|S_{01}|$ decreases to lower than -28 dB, which implies little energy is delivered to the unused ports. It also can be calculated that the phase differences ($\arg(S_{10})$ - $\arg(S_{20})$) between the horizontal ports reach 90° and −90° when the bias voltages are set as ‘1001011000100’ and ‘011000010001’, respectively. Similarly, the phase differences ($\arg(S_{30})$ - $\arg(S_{40})$) between the vertical ports are 90° and −90° with bias voltages set as ‘011000010001’ and ‘100110001000’, respectively.
C. WORKING PRINCIPLE

In order to realize both polarization agility and OAM mode reconfigurability, the antenna elements with switchable polarizations are combined with the reconfigurable feed network. With proper dc bias states, the feed network can be tuned to deliver the excited signals to two pairs of output ports, which are horizontally or vertically oriented. And a 90° or −90° phase shift are generated between the two ports in each pair. Also, an additional 180° phase shift is yield by mirroring four antenna elements with respect to horizontal or vertical directions. As a result, a phase-shifting scheme with successive 90° or −90° phase delays is obtained by a superposition of the two types of phase shifts. Simultaneously, the antenna elements are fed though the four horizontal or vertical ports connected with the feed network each time, and hence the polarization of the array antenna is determined without extra control. In this way, the required working states can be obtained by adjusting the dc bias voltages of the p-i-n diodes strategically, as summarized in Table II.

For all four states, the reflection coefficients of the array antenna are better than -10 dB over the band of 2.29-2.58 GHz, as indicated in Fig. 5. It is noted that with the symmetric feed structure and radiators, the antenna exhibits good consistency among different states. The simulated antenna gains within the operating band are about 7.0-8.9 dBi for all chosen states. Besides, only 6 diodes are set ON status while the others are set OFF for each state, and the radiation efficiencies range from 65.4% to 75.6%.

Further simulated verification is obtained by studying the E-field distributions of the array antenna in the near-field, as described in Fig. 6. For states 1 and 2, it shows that the E-field vectors mainly flow along the horizontal direction (x-axis). And the E-field vectors are distributed along the vertical direction (y-axis) for states 3 and 4. On the other hand, the E-field rotates in a clockwise manner for states 1 and 3, while rotates anticlockwise for states 2 and 4. For both rotation manners, the phase of the vectors varies by 2π radians with azimuth during a circular path around the z-axis. The clockwise and anticlockwise rotating E-fields suggest the intrinsic spiral wavefronts of OAM beams with modes \( l = +1 \) and \( l = -1 \), respectively.

III. EXPERIMENTAL RESULTS AND DISCUSSIONS

A. ANTENNA FABRICATION

Fig. 7 shows the proposed antenna prototype, in which two types of printed circuit boards (PCBs) are fabricated individually and assembled together. More specifically, each circular patch is realized on a single-sided PCB. The ring patches together with the feed network, the common ground plane, and the dc bias circuit separately are printed on the top,
middle, and bottom surfaces of a multilayer PCB. The bias pads in the feed network are connected to the ground plane and bias circuit through metallic vias. To conveniently control the positive bias voltages provided a dc power supply, a 12-bit switch is utilized in the bias circuit. The entire array with dimensions of $170 \times 170 \times 7.8$ mm$^3$ is assembled with plastic screws and holders. It is center-fed though a 50-Ω SMA connector, with the inner conductor attached to the feed network and outer flange to ground soldering. To enable mounting of the connector, a square hole is machined at the lower layer of the multilayer PCB.

**B. REFLECTION COEFFICIENTS**

As shown in Fig. 7(d), the reflection coefficients of the fabricated antenna are measured with a Rohde & Schwarz ZNB20 Vector Network Analyzer (VNA). In the measurement, an ITECH IT6302 dc power supply is utilized to provide the positive bias voltages. For brevity, only the performance for four selected bias states (tabulated in Table II) is discussed in Fig. 8. The measured $-10$ dB impedance bandwidths are about 300 MHz, 309 MHz, 311 MHz and 305 MHz for states 1, 2, 3, and 4, respectively. Thus, an overlapped bandwidth of 300 MHz is obtained to cover the range of 2.29–2.59 GHz. It is indicated that the measured and simulated results agree well at all operating modes. The slight deviations are primarily caused by the fabrication tolerance and manual welding.
FIGURE 10. Measured near-field intensity distributions at 2.45 GHz. (a) state 1. (b) state 2. (c) state 3. (d) state 4.

FIGURE 11. Measured near-field phase distributions at 2.45 GHz. (a) state 1. (b) state 2. (c) state 3. (d) state 4.

C. NEAR-FIELD DISTRIBUTIONS

The near-field intensity and phase distributions of the antenna are measured using a planar scanning system, as shown in Fig. 9. A dipole antenna works as the near-field probe, which has a small size of 52.5 × 60 × 60 mm³, a wide bandwidth of more than 25%, and a moderate gain of 5.2 dBi at 2.45 GHz. The scanning plane, which has a range of 1000 mm × 1000 mm with an increment of 5 mm, is located 480 mm far from the antenna under test (AUT). $E_x$- and $E_y$-field distributions are separately recorded for the former and latter two states defined in Table II. According to the results illustrated in Fig. 10, doughnut-shaped intensity distributions are observed with a singularity at the center for all states.

There also exist some discontinuities on the main lobe, which is due to the fact that UCA with finite elements is recognized as the spatial sampling of a circular aperture. Besides, it is seen from Fig. 11 that spiral phase profiles of the OAM carrying vortex beams can be achieved. Along a circular path around the $z$-axis, the phase changes $2\pi$ radians in a clockwise or counterclockwise direction, which corresponds to OAM mode $l = +1$ or $-1$. The measured results are consistent with the analysis and simulation in Section II.

D. FAR-FIELD RADIATION CHARACTERISTICS

The radiation characteristics measurements of the proposed antenna are conducted in a far-field anechoic chamber.
TABLE 3. Comparison between proposed and reported OAM array antennas.

| Ref. | No. of elements | No. of states | OAM mode | Polarization | Ports |
|------|-----------------|---------------|----------|--------------|------|
| [13] | 4               | 2             | +1/-1    | LP           | 1    |
| [14] | 8               | 5             | -2/-4/0  | LP           | 1    |
| [19] | 4               | 2             | +1/-1    | LHCP/RHCP   | 1    |
| [20] | 4               | 2             | +1/-1    | HP/VP        | 2    |
| [21] | 4               | 4             | +1/-1    | HP/VP        | 2    |
| Prop. | 4              | 4             | +1/-1    | HP/VP        | 1    |

Fig. 12 depicts the normalized radiation patterns for different working states at 2.45 GHz. It can be found central dips at the broadside direction in both $xoz$ and $yoz$ planes. The intensity dips with depths of lower than $-21.5$ dB for all states further reveals the generation of twisted radio beams. Meanwhile, the measured main lobes are all directed at about $\pm 29^\circ$. Moreover, the co-polarized components are much dominant compared to the cross-polarized counterparts. In the main lobe directions, the measured cross polarization discriminations are better than 19.8 dB for all states.

A performance comparison between the proposed and other reported OAM array antennas is summarized in Table III. It is found that the proposed antenna takes the advantage of independent control of both OAM mode and polarization across a single port. Furthermore, the designed reconfigurable feed network is presented without complex impedance matching or phase delaying methods, which allows a more compact and simpler feed structure.

IV. CONCLUSION

In this paper, an OAM-mode and polarization tunable antenna has been proposed and investigated. The antenna consists of four identical radiating elements, a reconfigurable feed network and a dc bias circuit. An orthogonally-fed microstrip antenna acts as the radiating element, in which stacked patch radiators are implemented to improve the impedance matching and radiation performance. The feed network is developed with partially shared SPDT switches and phase-shifting power dividers for different working states, which leads to a simple and symmetric configuration. Both simulated and experimental result show that for the designed antenna, OAM mode with $l = +1$ or $-1$ as well as polarization with HP or VP can be switched simultaneously. It is capable of maintaining relatively consistent reflection coefficient and radiation patterns among different states. Also, low cross polarization characterized with cross polarization discrimination of greater than about 20 dB are obtained for all operating states. The proposed design could be suitable for OAM-based applications that require integration of multiple functions within a single antenna aperture.

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**LE KANG** received the B.S. and M.S. degrees from Xidian University, China, in 2008 and 2011, respectively, and the Ph.D. degree in electromagnetic field and microwave technology from the National Key Laboratory of Antennas and Microwave Technology, Xidian University, in 2017. From 2011 to 2012, he was an RF Engineer with Huawei Company, China. He is currently a Lecturer with the School of Mechano-Electronic Engineering, Xidian University. His current research interests include reconfigurable antennas and phased arrays.

**HUI LI** received the Ph.D. degree in electromagnetic field and microwave technology from the National Key Laboratory of Antennas and Microwave Technology, Xidian University, Xi’an, China, in 2018. She is currently a Lecturer with the School of Automation and Information Engineering, Xi’an University of Technology. Her main research interests include wideband antennas, reconfigurable antennas, and antenna with orbital angular momentum waves.

**JINZHU ZHOU** received the B.S. and M.S. degrees in electromechanical engineering from Northwest A&F University, in 2002 and 2005, respectively, and the Ph.D. degree in mechanical engineering from Xidian University, in 2011. He is currently a Professor with the Key Laboratory of Electronic Equipment Structure Design, Ministry of Education, Xidian University. He has published over 36 articles. He holds 12 patents issued and 13 patents pending. His research interest is in the field of highly integrated phased array antenna. He was a recipient of the Best Paper Award for microwave filters tuning and smart skin antennas at the International Symposium. He has received the 2014 Shaanxi Province Science and Technology Award (First Class).

**SHUFENG ZHENG** (Member, IEEE) received the Ph.D. degree in electromagnetic field and microwave technology from Xidian University, Xi’an, China, in 2012. Since 2012, he has been with the National Key Laboratory of Antennas and Microwave Technology, Collaborative Innovation Center of Information Sensing and Understanding, Xidian University, where he is currently a Lecturer. His current research interests include wideband antennas, circularly polarized antennas, reconfigurable antennas, frequency selective surfaces, and metamaterials.

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