A Mode Reconfigurable Orbital Angular Momentum Water Antenna

JIE MING AND YAN SHI, (Senior Member, IEEE)
School of Electronic Engineering, Xidian University, Xi’an 710071, China
Corresponding author: Yan Shi (shiyan@mail.xidian.edu.cn)

This work was supported in part by the Natural National Science Foundation of China under Grant 61771359, and in part by the Natural Science Basic Research Plan in Shaanxi Province under Grant 2018JM6006.

ABSTRACT

In this paper, a water antenna has been designed to generate tunable orbital angular momentum (OAM) vortex wave. With a revisiting theoretical analysis about radiation characteristic of the shorted ring patch fed by two probes, a frequency dependent single shorted ring water antenna is designed. With the increase of the operating frequency, the single-ring water antenna can radiate the OAM waves with the changeable modes. Furthermore, a dual shorted ring water antenna is proposed. With a tunable feeding network, the OAM waves with the reconfigurable modes including the \( l = 1 \), \( l = 2 \) and mixed modes can be radiated by adjusting ON/OFF states of the PIN diode. The prototype of the dual-ring water antenna is fabricated and measured. Good agreement between the simulation and the measurement demonstrates that the overlapped bandwidth for three states covers 2.35–2.55 GHz with a good mode purity.

INDEX TERMS

Water antenna, frequency dependent, single shorted ring, dual shorted ring, tunable feeding network, reconfigurable modes.

I. INTRODUCTION

With rapid development of wireless communication system, improvement of spectral efficiency and system capacity has been facing serious challenges owing to the limited frequency spectrum. In recent years, orbital angular momentum (OAM) has attracted much attentions due to its twisted wave front. Theoretically, the OAM contains unlimited range of orthogonal eigenstates, which provide a promising method to enlarge the channel capacity [1].

Various approaches have been developed to generate the OAM wave in the optics and at RF. The spiral phase plate (SPP) is one of the common devices to generate the OAM vortex wave [2]. The thickness of the SPP along the azimuthal direction increases such that a plane wave front of an incoming wave is converted into a helix wave front. However, the dielectric loss of the SPP degrades the performance of OAM wave. Circularly distributed antenna array first proposed by Thidé et al. in 2007 [3] is an another popular way to radiate the vortex beam carrying the OAM.

When the antenna element in the array has a phase variation along the azimuthal direction, the OAM wave with the mode of \(|l| < N/2\) is generated, in which \( N \) is the number of the elements. But the use of the feeding network greatly increases complexity and cost of the whole array. In order to improve this problem, some metasurface inspired reflectarrays and transmitarrays have been developed to achieve the OAM wave. By designing the OAM dependent phase distribution, the reflection/transmission wave carrying the OAM is generated when a single horn illuminates the reflectarray/transmitarray [4]–[8]. However, these arrays are still space consuming. Recently, some antenna elements have been proposed to radiate the OAM wave including waveguide ring resonator [9], dielectric resonator antenna [10], microstrip patch antenna [11], etc. In [12], a multimode concentric microstrip antenna was developed to generate the OAM waves by exciting multiple TM\(_{lm}\) modes. But the above antenna designs only operate in a narrow frequency band.

On the other hand, water antenna has attracted increasingly interests due to its transparency, reconfiguration, and low cost [13]–[16]. At room temperature, the pure water is a dielectric with high permittivity at microwave frequencies. Hence when the water is employed to design the antenna, the resultant antennas have some advantages including compact size [17] and good radiation efficiency [18], etc.
In this paper, a water antenna has been proposed to generate the OAM vortex wave with the reconfigurable modes in a frequency band. The theoretical analysis about the OAM wave radiated by the shorted ring antenna is revisited. A single shorted ring water antenna is first proposed, and the OAM vortex wave with the frequency dependent modes is radiated. Furthermore, a dual shorted ring water antenna is designed and fabricated to generate the OAM wave with the tunable modes in a frequency band from 2.35 GHz to 2.55 GHz.

II. THE PROPOSED OAM WATER ANTENNA

A. OPERATION MECHANISM OF OAM VORTEX WAVE

In order to demonstrate the operation mechanism of the proposed water antenna, we first studied the radiation performance of a shorted circular ring patch antenna with an inner radius \(a\) and an outer radius \(b\), which is fed by a coaxial probe at \((\rho_0, 0)\) and fabricated on a substrate with permittivity of \(\varepsilon_1\) and thickness of \(h\). At the periphery of \(r = a\), the ring patch is shorted. Hence the ring patch antenna can be theoretically analyzed by using a cavity model with a finite admittance wall at the periphery of \(r = b\), and three PEC walls at the top, the bottom and the periphery of \(r = a\). The radiated TM\(_{nm}\) far field can be expressed as [19], [20]

\[
E_{\theta n} = -\frac{j^n e^{-jk_0 r}}{2r} k_0 V_0 F_{nm}(\rho_0) \cos n\varphi \\
\cdot \left[ bF_{nm}(b) \left( J_{n-1}(k_0 b \sin \theta) - J_{n+1}(k_0 b \sin \theta) \right) \\
- aF_{nm}(a) \left( J_{n-1}(k_0 a \sin \theta) - J_{n+1}(k_0 a \sin \theta) \right) \right],
\]

\[
E_{\varphi n} = -\frac{j^n e^{-jk_0 r}}{2r} k_0 V_0 F_{nm}(\rho_0) \cos \varphi \sin n\varphi \\
\cdot \left[ bF_{nm}(b) \left( J_{n-1}(k_0 b \sin \theta) + J_{n+1}(k_0 b \sin \theta) \right) \\
- aF_{nm}(a) \left( J_{n-1}(k_0 a \sin \theta) + J_{n+1}(k_0 a \sin \theta) \right) \right],
\]

where \(J_n\) and \(Y_n\) are the \(n\)-order Bessel functions of the first and the second kinds, respectively, and

\[
F_{nm}(\rho) = Y_n'(k_n a) J_n(k_n \rho) - J_n'(k_n a) Y_n(k_n \rho),
\]

in which prime denotes the derivative. The value of \(k_{nm}\) can be solved by the following characteristic equation

\[
Y_n'(k_n a) J_n(k_n b) - J_n'(k_n a) Y_n(k_n b) = 0.
\]

When two probes with the same magnitude and a phase difference of 90° located at \((\rho_0, 0)\) and \((\rho_0, \varphi_0)\), respectively, are used to excite the ring antenna, the total radiation fields are given by

\[
E_{\theta n, total} = -\frac{j^{n+1} e^{-jk_0 r}}{2r} k_0 V_0 F_{nm}(\rho_0) \cos \theta \\
\cdot \left( 1 + e^{i(\pi/2 - n\varphi_0)} \right) e^{jn\varphi} \\
\cdot \left[ bF_{nm}(b) \left( J_{n-1}(k_0 b \sin \theta) - J_{n+1}(k_0 b \sin \theta) \right) \\
- aF_{nm}(a) \left( J_{n-1}(k_0 a \sin \theta) - J_{n+1}(k_0 a \sin \theta) \right) \right].
\]

As shown in (4) and (5), there are two terms related to the Bessel functions \(J_{n-1}\) and \(J_{n+1}\), respectively. For small values of the argument, the low-order Bessel functions are larger than higher-order ones [11]. Hence in a small region of \(\theta\), the \(J_{n+1}\) can be approximately ignored. Furthermore, we convert the electric field components in spherical coordinate to those in Cartesian coordinate, i.e.,

\[
E_{\theta n, total} \approx C_{nm} \frac{J_{n-1}(k_0 b \sin \theta)}{2} e^{(\pi/2 - n\varphi_0)\eta} + \frac{1 + e^{i(\pi/2 + n\varphi_0)} e^{-jn\varphi}}{2}.
\]

\[
E_{\varphi n, total} \approx jC_{nm} \frac{J_{n+1}(k_0 b \sin \theta)}{2} e^{(\pi/2 - n\varphi_0)\eta} - \frac{1 + e^{i(\pi/2 + n\varphi_0)} e^{-jn\varphi}}{2},
\]

where

\[
C_{nm} = -\frac{j^n e^{-jk_0 r}}{2r} k_0 V_0 F_{nm}(\rho_0) \cos \theta \\
\cdot \left[ bF_{nm}(b) J_{n-1}(k_0 b \sin \theta) \\
- aF_{nm}(a) J_{n-1}(k_0 a \sin \theta) \right].
\]

When \(\varphi_0\) is chosen as \(\pi/2n\), we have \(1 + \exp(\pi/2 - n\varphi_0) = 2\) and \(1 + \exp(\pi/2 + n\varphi_0) = 0\), and accordingly (6) and (7) can be reduced as

\[
E_{\theta n, total} \approx C_{nm} e^{(n-1)\varphi},
\]

\[
E_{\varphi n, total} \approx jC_{nm} e^{(n-1)\varphi}.
\]

It can be found that the OAM vortex wave with the mode of \(l = n-1\) can be excited for \(\varphi_0 = \pi/2n\).

On the other hand, when \(\varphi_0\) is chosen as \(\pi - \pi/2n\), (6) and (7) can be rewritten as

\[
E_{\theta n, total} \approx \left\{ \begin{array}{ll}
C_{nm} e^{-j(n-1)\varphi} & n = even \\
C_{nm} e^{(n-1)\varphi} & n = odd,
\end{array} \right.
\]

\[
E_{\varphi n, total} \approx \left\{ \begin{array}{ll}
jC_{nm} e^{-j(n-1)\varphi} & n = even \\
jC_{nm} e^{(n-1)\varphi} & n = odd.
\end{array} \right.
\]

According to (11) and (12), we can know that in the case of \(\varphi_0 = \pi - \pi/2n\), the OAM waves with the modes of \(l = -(n-1)\) and \(l = (n-1)\) can be generated, respectively, when \(n\) is an either even or odd number.

If \(\varphi_0\) is neither \(\pi/2n\) nor \(\pi - \pi/2n\), the OAM wave can still be radiated, depending on the magnitudes of the coefficients \(1 + \exp(\pi/2 - n\varphi_0)\) and \(1 + \exp(\pi/2 + n\varphi_0)\). Fig. 1 depicts the variation of the magnitudes of two coefficients with the \(\varphi_0\) in the cases of \(n = 1, 2\) and 3. For \(n = 2\),
the magnitude of the coefficient $1 + \exp(\pi/2 - n\phi_0)$ is far larger than that of the coefficient $1 + \exp(\pi/2 + n\phi_0)$ when $\phi_0$ is in the range from 30° to 60°. Therefore, the OAM wave with $l = 1$ is radiated. For $n = 3$, the magnitude of the coefficient $1 + \exp(\pi/2 - 3\phi_0)$ is far smaller than that of the coefficient $1 + \exp(\pi/2 + 3\phi_0)$ when $\phi_0$ belongs to [20°, 40°] or [140°, 160°]. In this case, the OAM wave with $l = -2$ is radiated. It is worthwhile pointing out that for $140° \leq \phi_0 \leq 160°$, the OAM waves with $l = -1$ and $l = 0$ can be generated in the cases of $n = 2$ and $n = 1$, respectively. With these discussions, we can design the antenna for the generation of the OAM wave with the reconfigurable mode in a frequency band.

**B. SINGLE ANNULAR WATER ANTENNA DESIGN FOR FREQUENCY DEPENDENT OAM WAVE**

A single shorted ring water antenna is developed to radiate the frequency dependent OAM wave, as shown in Fig. 1. An annular groove with a depth of $H_7$ is etched on a transparent Acrylic substrate with relative permittivity of 2.65 and loss tangent of 0.01 and thickness of $H_8$. A metallic ring is fabricated in the groove and a metallic ground plate is fabricated on the bottom of the Acrylic substrate. The pure water with relative permittivity of 81 and loss tangent of 0.04 is placed at the top of the ring in the groove, and an Acrylic substrate with the thickness of $H_6$ is located on the top of the water. A shorted wall with a thickness of 0.2 mm is used to connect the metallic ring with the ground. A feeding network is fabricated on a FR4 substrate with the thickness of $H_{10}$ on the reverse side of the ground. Two probes connected with the feeding network are used to excite the annular patch. The dimensions of the designed water antenna are given in Table 1. The feeding network is a Wilkinson power divider with an isolation resistor of 100 $\Omega$. The length difference between two microstrip lines $L_2$ and $L_3$ results in a 90° phase difference.

**TABLE 1. Parameters of single-ring water antenna (Unit: mm).**

| Parameters | Value | Parameters | Value | Parameters | Value |
|------------|-------|------------|-------|------------|-------|
| $a_1$      | 61.3  | $a_4$      | 79    | $H_8$      | 3.2   |
| $d_1$      | 71    | $H_6$      | 1     | $H_{10}$   | 0.8   |
| $\theta_3$ | 45°   | $H_7$      | 1     | $k_1$      | 92    |
| $w_1$      | 1.6   | $w_2$      | 0.8   | $L_1$      | 17.9  |
| $L_2$      | 131.5 | $L_3$      | 147.3 |            |       |

**FIGURE 2. The proposed single-ring water antenna. (a) The 3D structure. (b) Top view. (c) Side view. (d) Feeding network.**

The $S_{11}$ of the single-ring water antenna, the current distributions on the ring, and the phase distributions of the $E_z$ on the observation at $z = 500$ mm are shown in Fig. 3. It can be seen from Fig. 3(a) that there are multiple operating bands for $S_{11} \leq -10$ dB, i.e., 2.04~2.21 GHz, 2.31~2.42 GHz, 2.48~2.66 GHz, and 2.81~2.98 GHz. According to Fig. 3(b), it can be observed that in each band, the water antenna operates in different modes, i.e., TM$_{21}$, TM$_{31}$, TM$_{41}$, and TM$_{51}$. According to the above discussion, we can know that when the center angle $\theta_3$ between two probes is set as 45°, the annular patch operating in the TM$_{21}$ mode can radiate the
OAM wave with the mode of \( l = 1 \). With the same probe excitations, when the annular patch operates in the TM\(_{31}\), TM\(_{41}\), and TM\(_{51}\) modes, respectively, the OAM wave with the modes of \( l = 2 \), \( l = 3 \), and \( l = 4 \) are achieved. As shown in Fig. 3(c), the phase distributions of the \( E_x \) at 2.2 GHz, 2.4 GHz, 2.6 GHz, and 2.9 GHz, corresponding to the OAM wave of the modes of \( l = 1 \), \( l = 2 \), \( l = 3 \), and \( l = 4 \), respectively, are observed.

C. DUAL ANNULAR WATER ANTENNA DESIGN FOR RECONFIGURABLE OAM WAVE
According to the above design, we can know that the single-ring water antenna can radiate the frequency dependent OAM wave. In order to achieve the OAM wave with the reconfigurable mode, a dual shorted ring water antenna is proposed, as shown in Fig. 4. In the dual-ring water antenna there are two annular grooves and two shorted ring patches, each of which is covered by the pure water and excited by two feeding probes, as shown in Fig. 4(a). The thickness of two shorted walls is set as 1 mm. Four feeding probes are connected with a reconfigurable network shown in Fig. 4(d). The feeding network consists of a T-junction power divider, two Wilkinson power dividers, two 90° phase shifters, and two PIN diodes from Infineon (BAR50-02L). The DC bias circuits for the PIN diodes involves RF choking inductor of 33 nH and DC blocking capacitor of 30 pF. The resistors with 100 \( \Omega \) are used in the Wilkinson power dividers for isolations between the output ports. The detailed dimensions of the proposed dual-ring water antenna are given in Table 2.

In the reconfigurable feeding network, two Wilkinson dividers are combined by a T-junction power divider. By adjusting the ON/OFF states of two PIN diodes in the feeding network, the four probes connected to two Wilkinson

---

**FIGURE 3.** Performance of the single shorted ring water antenna. (a) \( S_{11} \). (b) Surface current distribution. (c) Phase distribution.

**FIGURE 4.** The dual shorted ring water antenna. (a) The whole structure. (b) Top view. (c) Side view. (d) Feeding network.
TABLE 2. Detailed dimensions of the proposed dual-ring water antenna (Unit: mm).

| Parameters | Value | Parameters | Value | Parameters | Value |
|------------|-------|------------|-------|------------|-------|
| $d_1$      | 22    | $b_1$      | 30    | $H_1$      | 10    |
| $d_2$      | 49    | $b_2$      | 57    | $H_2$      | 3     |
| $\theta_1$| 45°   | $a_1$      | 6     | $\ell$     | 0.8   |
| $\theta_2$| 150°  | $a_2$      | 41    | $L_4$      | 10    |
| $k$        | 79    | $H_1$      | 1     | $W_6$      | 1.52  |

dividers selectively excite two ring patches. In each Wilkinson divider, a $90^\circ$ phase shifter is introduced to achieve a $90^\circ$ phase difference between two output signals of the Wilkinson divider. The lithium battery is used to provide a 3.3 V voltage for each PIN diode. When the PIN diode 1 is in ON state and the PIN diode 2 is in OFF state, the inner ring patch is excited by two probes with the center angle $\theta_1$ of $45^\circ$. When the inner ring operates in TM$_{21}$ mode, the OAM wave with the mode $l = 1$ is generated. With the PIN diode 1 in OFF state and PIN diode 2 in ON state, two probes with the center angle $\theta_2$ of $150^\circ$ are selected to excite the outer ring patch. With the outer ring operating in TM$_{31}$ mode, the OAM wave with the mode of $l = -2$ is radiated. If the two PIN diodes are in ON state, the OAM wave with the mixed mode is radiated. The different operating states of the proposed dual-ring water antenna are illustrated in Table 3. Here the equivalent circuit models of the PIN diode in the ON and OFF states from its data sheet are shown in Fig. 5.

TABLE 3. Reconfigurable OAM mode in different states.

| PIN 1 | PIN 2 | OAM |
|-------|-------|-----|
| State 1 | ON   | OFF | $l=1$ |
| State 2 | OFF  | ON  | $l=2$ |
| State 3 | ON   | ON  | $l=1$ and $l=2$ |

FIGURE 5. Equivalent circuits of the PIN diode in ON and OFF states.

In order to demonstrate the effect of the pure water on the performance of the dual-ring antenna, Fig. 6 gives the far field comparison between the dual-ring antenna with and without the pure water in the State 1. It can be seen that with the pure water, the gain of the conical pattern (null at broadside) at 2.45 GHz in XOZ plane increases from 2.5 dB to 4.1 dB, which reduces the degree of divergence of the OAM wave in the propagation process. This is because the pure water as a high permittivity superstrate eliminates the surface wave excitation, thus resulting in a higher radiation efficiency and gain [21].

TABLE 4. Performance comparison between the references and this work.

| Ref. | OAM | Effective BW (%) | Transparency | Size (mm) |
|------|-----|------------------|--------------|-----------|
| [9]  | $l=3$ | 3.33             | No           | 10        |
| [10] | $l=\pm1$ | 5.22             | No           | 1.856     |
| [11] | $l=1$ | 1.24             | No           | 0.8       |
| [12] | $l=1,-2$ | 0.9              | No           | 2.32      |
| Work | $l=1$-2,mixed mode | 8.16             | Yes         | 1.29      |

III. SIMULATION AND MEASUREMENT RESULTS

The proposed dual-ring water antenna is fabricated and measured, as shown in Fig. 7. Fig. 8 gives the simulated and measured $S_{11}$. It can be seen that the measured operation bands for $S_{11} \leq -10$ dB in the States I and II are from 2 to 3 GHz. By contrast, the simulated impedance bandwidths are from 1.7 to 2.7 GHz and from 1.99 to 2.96 GHz, respectively, in the States I and II. In the State III, the measured impedance bandwidth is from 2.17 to 3 GHz, and the simulated impedance bandwidth is from 2.12 to 3 GHz. The measured resonant
frequencies slightly move towards higher frequencies compared with the simulated ones. These discrepancies are due to the fabrication errors including inaccuracy of the acrylic substrate and the pure water and the welding and installing errors of the ring patches and feeding probes. The overlapped measurement band for three states is 2.35 to 3 GHz, and thus the proposed water antenna well operates in WIFI band.

The normalized total electric field patterns in three states are measured at 2.45 GHz and compared with the simulated ones, as shown in Fig. 9. A good agreement between each other can be observed. A slight discrepancy occurs in the endfire direction, because the battery and the DC bias circuit are placed at the behind of the water antenna. It can be found that there is a null amplitude at the broadside direction owing to the generation of the OAM vortex wave.

Fig. 10 shows the simulated and measured phase distributions of the $E_x$ on the observation plane of $z = 0.5$ m in three states at different frequencies. Good agreement between the simulation and the measurement can be obtained. Phase distributions of the OAM waves with the $l = 1$ and $l = -2$ and the mixed modes can be observed in the States 1, 2 and 3,
respectively. Fig. 11 depicts the variation of the mode purities with frequencies in the three states. In order to evaluate the purity of the OAM modes, the $E_x$ is sampled on the circle with a radius of 420 mm on the observation plane and a spectral analysis of Fourier transform is implemented [7], [8]. It can be found that in the State I, the OAM wave with the mode $l = 1$ can be generated in a frequency band from 2.15 GHz to 2.7 GHz. At the frequencies lower than 2.15 GHz, the plane wave, i.e., the OAM wave with the mode of $l = 0$, is radiated. This is because the proposed antenna operates in the TM$_{11}$ mode below 2.15 GHz. In the State II, the OAM wave with the mode of $l = -2$ can be achieved in a frequency band of 2.3~3 GHz. In the bands of 2.15~2.3 GHz and 2~2.15 GHz, the OAM waves with the modes of $l = 1$ and $l = 0$ are radiated due to the TM$_{21}$ and TM$_{11}$ modes of the antenna, respectively. It is worth while pointing out that at the frequencies higher than 2.55 GHz, the purity of the OAM wave with the mode of $l = 2$ decreases. This is
because the OAM wave with the higher order mode is generated, as shown in Fig. 12. In the State III, the OAM wave with the mixed mode is achieved in the frequency band of 2.35–2.55 GHz. Therefore, the overlapped band for the three states in terms of the mode purity and impedance matching is 2.35–2.55 GHz. Table 4 shows the performance comparison between the published works and the proposed design. It can be seen that the proposed design can radiate the OAM vortex waves with more modes in a wider band and has a compact size and transparent characteristic.

IV. CONCLUSION

In this paper, a water antenna has been designed to generate the OAM wave with the tunable modes in a frequency band. With the theoretical analysis about the shorted ring patch, a dual shorted ring water antenna fed by the four probes is designed to radiate the OAM wave with the \( l = 1, l = 2 \) and mixed modes. The use of the water as a superstrate reduces the degree of divergence of the OAM wave. The measurement results demonstrate that the proposed water antenna can achieve the OAM wave with the reconfigurable modes in the band of 2.35–2.55 GHz, which provides a feasible way for the OAM based wireless communication applications.

REFERENCES

[1] Y. Yan, G. Xie, M. P. J. Lavery, H. Huang, N. Ahmed, C. Bao, Y. Ren, Y. Cao, L. Li, Z. Zhao, A. F. Molisch, M. Tur, M. J. Padgett, and A. E. Willner, “High-capacity millimetre-wave communications with orbital angular momentum multiplexing,” Nature Commun., vol. 5, no. 1, p. 4876, Dec. 2014.

[2] M. Uchida and A. Tonomura, “Generation of electron beams carrying orbital angular momentum,” Nature, vol. 464, no. 7289, pp. 737–739, Apr. 2010.

[3] B. Thidé, H. Then, J. Sjöholm, K. Palmer, J. Bergman, T. D. Carozzi, Y. N. Istomin, N. H. Ibragimov, and R. Khamitova, “Utilization of photon orbital angular momentum in the low-frequency radio domain,” Phys. Rev. Lett., vol. 99, no. 8, Aug. 2007, Art. no. 087701.

[4] S. Yu, L. Li, G. Shi, C. Zhu, X. Zhou, and Y. Shi, “Design, fabrication, and measurement of reflective metasurface for orbital angular momentum vortex wave in radio frequency domain,” Appl. Phys. Lett., vol. 108, no. 12, Mar. 2016, Art. no. 121903.

[5] S. Yu, L. Li, G. Shi, C. Zhu, and Y. Shi, “Generating multiple orbital angular momentum vortex beams using a metasurface in radio frequency domain,” Appl. Phys. Lett., vol. 108, no. 24, Jun. 2016, Art. no. 241901.

[6] M. Veysi, C. Guclu, F. Capolino, and Y. Rahmat-Samii, “Revisiting orbital angular momentum beams: Fundamentals, reflectarray generation, and novel antenna applications,” IEEE Antennas Propag. Mag., vol. 60, no. 2, pp. 68–81, Apr. 2018.

[7] Y. Shi and Y. Zhang, “Generation of wideband tunable orbital angular momentum vortex waves using graphene metamaterial reflectarray,” IEEE Access, vol. 6, pp. 5341–5347, 2018.

[8] Z. K. Meng, Y. Shi, W. Y. Wei, Y. Zhang, and L. Li, “Graphene-based metamaterial transmittarray antenna design for the generation of tunable orbital angular momentum vortex electromagnetic waves,” Opt. Mater. Express, vol. 9, no. 9, pp. 3709–3716, Sep. 2019.

[9] X. Hui, S. Zheng, Y. Chen, Y. Hu, X. Jin, H. Chi, and X. Zhang, “Multiplexed millimeter wave communication with dual orbital angular momentum (OAM) mode antennas,” Sci. Rep., vol. 5, no. 1, Sep. 2015, Art. no. 10148.
[10] J. Ren and K. W. Leung, “Generation of microwave orbital angular momentum states using hemispherical dielectric resonator antenna,” *Appl. Phys. Lett.*, vol. 112, no. 13, Mar. 2018, Art. no. 131103.

[11] M. Barbuto, F. Trotta, F. Bilotti, and A. Toscano, “Circular polarized patch antenna generating orbital angular momentum,” *Prog. Electromagn. Res.*, vol. 148, pp. 23–30, Jan. 2014.

[12] Z. Zhang, S. Xiao, Y. Li, and B.-Z. Wang, “A circularly polarized multimode patch antenna for the generation of multiple orbital angular momentum modes,” *IEEE Antennas Wireless Propag. Lett.*, vol. 16, pp. 521–524, 2017.

[13] C. Hua, Z. Shen, and J. Lu, “High-efficiency sea-water monopole antenna for maritime wireless communications,” *IEEE Trans. Antennas Propag.*, vol. 62, no. 12, pp. 5968–5973, Dec. 2014.

[14] Y. Li and K.-M. Luk, “A water dense dielectric patch antenna,” *IEEE Access*, vol. 3, pp. 274–280, 2015.

[15] Y.-H. Qian and Q.-X. Chu, “A broadband hybrid monopole-dielectric resonator water antenna,” *IEEE Antennas Wireless Propag. Lett.*, vol. 16, pp. 360–363, 2017.

[16] C. Song, E. L. Bennett, J. Xiao, T. Jia, R. Pei, K.-M. Luk, and Y. Huang, “Passive beam-steering gravitational liquid antennas,” *IEEE Trans. Antennas Propag.*, vol. 68, no. 4, pp. 3207–3212, Apr. 2020.

[17] J. Sun and K.-M. Luk, “A wideband low cost and optically transparent water patch antenna with omnidirectional conical beam radiation patterns,” *IEEE Trans. Antennas Propag.*, vol. 65, no. 9, pp. 4478–4485, Sep. 2017.

[18] M. Zou, Z. Shen, and J. Pan, “Frequency-reconfigurable water antenna of circular polarization,” *Appl. Phys. Lett.*, vol. 108, no. 1, Jan. 2016, Art. no. 014102.

[19] S. E. El-Khamy, R. M. El-Awadi, and E.-B. A. El-Sharrawy, “Simple analysis and design of annular ring microstrip antennas,” *IEE Proc. H, Microw., Antennas Propag.*, vol. 133, no. 3, pp. 198–202, 1986.

[20] Y. Lin and L. Shafai, “Characteristics of concentrically shorted circular patch microstrip antennas,” *IEE Proc. H, Microw., Antennas Propag.*, vol. 137, pp. 18–24, Feb. 1990.

[21] C.-Y. Huang and J.-Y. Wu, “Compact microstrip antenna loaded with very high permittivity superstrate,” *IEEE Antennas Propag. Soc. Int. Symp.*, vol. 2, Jun. 1998, pp. 680–683.

**JIE MING** received the B.E. degree in electronic information engineering from Hubei Normal University, Hubei, China, in 2018. He is currently pursuing the master’s degree in electromagnetics and microwave technology at Xidian University, Xi’an, China. His research interests include antenna design and orbital angular momentum wave.

**YAN SHI** (Senior Member, IEEE) received the B.Eng. and Ph.D. degrees in electromagnetic fields and microwave technology from Xidian University, Xi’an, China, in 2001 and 2005, respectively.

He joined the School of Electronic Engineering, Xidian University, in 2005, where he was promoted to a Full Professor, in 2011. From July 2007 to July 2008, he worked as a Senior Research Associate with the City University of Hong Kong, Hong Kong. From September 2009 to September 2010, he was a Visiting Postdoctoral Research Associate with the University of Illinois at Urbana-Champaign. From June 2017 to July 2017, he was a Visiting Professor with the State Key Laboratory of Millimeter Wave, City University of Hong Kong. He has authored or coauthored over 100 articles in refereed journal, a book, and a chapter. His research interests include computational electromagnetics, metamaterial, antenna, and wireless power transfer.

Dr. Shi is a Senior Member of the Chinese Institute of Electronics (CIE). He received the Program for New Century Excellent Talents in University awarded by the Ministry of Education of China, in 2011, the New Scientific and Technological Star of Shaanxi Province awarded by the Education Department of Shaanxi Provincial Government, in 2013, the First Prize of Awards for Scientific Research Results of High Education of Shaanxi Province awarded by the Education Department of Shaanxi Provincial Government, in 2013, and the Second Prize of Awards of Science and Technology awarded by the Shaanxi Province Government, in 2015.