Generating and Detecting Broad-Band Underwater Multiple OAMs Based on Water-Immersed Array

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ABSTRACT In this paper, we focus on the generation of broadband underwater vortex waves carrying multiple OAMs. Based on a wideband underwater antenna, a water-immersed horn antenna array is designed and tested. The experimental results, which are in agreement with the simulation ones, validate that the proposed antenna array can readily generate high-quality vortex waves. To further validate the performance of the proposed underwater antenna array, experimental verifications of 2-D underwater imaging for the targets of two corner reflectors have been carried out, and the result shows that the targets can be distinguished efficiently. Meanwhile, two generation methods and one detection method of the multiplexed OAMs are also presented, from which the multiplexed OAMs can be generated and detected efficiently. And the performances of two generation methods have also been compared and discussed, from which we can know that the first generation method with a smaller structure costs lower and is more efficient.

INDEX TERMS Broadband, orbital angular momentum (OAM), antenna array, underwater, multiplexing and demultiplexing.

I. INTRODUCTION

From 1992, the beams carrying orbital angular momentum (OAM) [1] have attracted lots of interests, and they have a rotating phase factor $e^{i l \theta}$, where $\theta$ is the azimuth angle and $l$ is an integer number called “topological charge” corresponding to the order of the OAM mode. In addition, the fact that OAM can provide a new rotational degree of freedom to electromagnetic (EM) waves has been demonstrated by lots of researches, which would be advantageous for manipulating particles [2], quantum information processing [3], communication systems [4], [5], and imaging systems [6]–[8].

As well known, the generation of vortex waves carrying OAM is the first and the most important step for its applications. OAM was first discovered in optical domain, after which in 2007, it was firstly introduced to the radio frequency (RF) domain [9], and then it became a hot spot in microwave region [10], [11]. Lots of methods [12] have been proposed to generate OAM in RF domain: spiral phase plate (SPP) [13], horn lens antenna [14], circular patch antenna [15], slot antenna [16], cylinder dielectric resonator antennas [17], antenna array [18], [19], spiral antennas [20]–[22], metasurface [23], [24] and so on. However, these above mentioned structures all cannot generate underwater vortex waves due to the impedance mismatching between the antenna and the coaxial line of 50 $\Omega$, which hinders the underwater applications of OAM, such as underwater short range communication and underwater short range high resolution imaging.

Recently, two types of double-ridge horn antennas [25], [26] have been reported to generate broad-band electromagnetic (EM) waves in water or high dielectric constant medium. A water-immersed antenna array [27] has been proposed to generate underwater vortex waves.
Firstly, the feed impedance of these antennas was kept constant at 50 Ω while the wave impedances in water was changed significantly to 42.6 Ω (120π/√78.4). The above value is virtually identical to the feed impedance of 50Ω, which influences the wideband properties of the antenna [26]. In order to keep the radiation properties unchanged, it is essential to scale not only the size of the antenna but also its input impedance. Secondly, due to the narrow-band property of the array element [27], the reported array can only generate narrow-band underwater vortex waves carrying multiple OAMs. Thirdly, there are also two acoustic vortices-based underwater communication systems [28], [29], which can realize the high-speed long-range underwater communication, but the frequency is too lower, and not suitable for the underwater short range high resolution imaging. Finally, the broad-band and multiple OAMs are both necessary to increase the channel capacity and improve imaging resolution. Therefore, it is necessary to explore an alternative approach with low input impedance for generating broad-band underwater vortex waves carrying multiple OAMs.

In this paper, in order to generate the broad-band underwater vortex waves carrying multiple OAMs, a broadband antenna array has been designed, simulated and fabricated. The measurement experiments are conducted in an anechoic environment (water) and comparisons between the measured fields and the simulated ones are performed, which demonstrates that it can generate high-quality OAM waves. And the generated vortex waves can transmit far enough (about 90 mm) in water to meet the OAM’s application requirement. The 2-D underwater imaging for two corner reflectors have been carried out, in which the targets can be distinguished efficiently. Meanwhile, we have proposed two methods for generating multiplexed OAMs mode and one method to detect multiplexed OAMs mode. As for the performance comparisons, the first method is more efficient, in which the antenna structure is smaller and the cost is lower. Finally, some useful conclusions are given out.

II. BROADBAND UNDERWATER ANTENNA ARRAY
A. ANTENNA ARRAY CONFIGURATION

Since the approach based on the phased uniform circular array (UCA) is much flexible and easily controlled [18], it is suitable for the generation of underwater vortex waves. And the array element comes from the reference [24], from which the geometry of the single wideband antenna and some results of it are given out, as shown in Fig.1. It can be seen that the single antenna can generate wideband underwater EM wave with high quality, which lays a foundation for OAM-generating antenna array. Meanwhile, eight elements are located equidistantly around the perimeter of the concentric circle, as shown in Fig. 2. The radius a of the concentric circle is 56 mm (about 4λg) while the center frequency is 2.45 GHz. Since the phase difference between each two adjacent elements is δ = 2πl/N, the phase difference between the first array element and the last array element equals 2πl. On the condition that the antenna is linearly polarized, the feed coaxial lines of the antenna array should all be positioned in the same direction to generate the linearly polarized vortex waves.

The antenna array is also simulated by CST software [29]. In order to calculate the transmission loss of EM wave in water, the box in simulations is fully filled with the deionized water, in which all the components of this antenna are
FIGURE 3. (a) Simulated and (b) experimental $S_{11}$ of the antennas.

B. INTENSITY AND PHASE DISTRIBUTIONS

The simulated and measured $S_{11}$ of the antenna elements are shown in Figs. 3(a-b), respectively. It can be seen that the water-immersed rectangular horn antenna array performs very well in the frequency range of 2.1~3.8 GHz and each of them is almost the same as the others. However, there are some differences in the center frequency, which could be concluded as the relative dielectric constant value differences of water from 1.5 GHz to 4 GHz between simulations and experiments [30]. In addition, because of the small scales of antenna in water (corresponding to scales of antenna in the frequency range of 18.4~35.1 GHz in air), the consistency and accuracy of the antenna array elements’ scales cannot be totally enhanced, which also results in the differences of the experimental $S_{11}$ among the antenna array elements, but it should be noticed that each of the experimental $S_{11}$ is less than −10 dB from 2.1 ~4 GHz and the difference among the eight elements is less than 6 dB at 2.45 GHz. Since the influence of the amplitude error on the imaging performance can almost be ignored [18], the performances of this antenna can meet the requirements of the concrete applications of OAM.

Since the imaging performance is considerably affected by the phase errors [18], more attentions should be paid to controlling the phase errors of the elements. The designed and measured normalized phase distributions of the combined power divider and phase shifter are presented in Table 1, respectively. The maximum phase errors of OAM modes $l = 0$, $l = -1$, $l = -2$ and $l = -3$ are 4.7 degree, 2.5 degree, 3.83 degree and 5.2 degree, respectively, which are still acceptable for the concrete application of OAM.

TABLE 1. The designed and measured with normalization phase shift of the combined power divider and phase shifter.

| channel | $l = 0$ | $l = -1$ | $l = -2$ | $l = -3$ |
|---------|---------|---------|---------|---------|
| 1       | 0       | 0       | 0       | 0       |
| 2       | 0       | -55     | -89     | -135    |
| 3       | 0       | -90     | -180    | -270    |
| 4       | 0       | -135    | -270    | -45     |
| 5       | 0       | -180    | 0       | -180    |
| 6       | 0       | -225    | -90     | -315    |
| 7       | 0       | -270    | -180    | -90     |
| 8       | 0       | -315    | -270    | -225    |

It is well known that the OAM mode number satisfies $|l| < N/2$ [10], where $N$ is the number of elements on one circle. Therefore, OAM modes of this proposed antenna array vary from −3 to +3. Since the OAM beams for a pair of topological charges have similar field distributions, the phase and intensity distributions of the negative topological charges are only provided and analyzed.

The results of normalized phase distributions and intensity distributions with different OAM modes at 2.45 GHz are presented in Figs. 4 and 5, respectively. It can be seen that the generated OAM waves have a spiral phase front and a singularity in the center, which are quite similar to the theoretical results [9], [10]. In addition, the experimental phase distributions are almost the same as the simulated ones to some extents. The reasons for the small differences between measured intensity distributions and the simulated ones could be summarized as follows: a) these differences mainly come from the influences of the amplitude error and the position error of the measurement plane; b) the transmission loss of EM wave in water in experiment may be larger than that in simulation. Since the radiation signals may have not coupled totally to generate vortex waves on the plane of 30 mm away from antenna array, the performance of that of 90 mm may be better. Meanwhile, the singularity is going to be larger with the increase of $l$, which is exactly the characteristic of vortex waves. And the distortion of the measured phase and intensity distributions near the rim of the figures 4 and 5 may stem from
the spatial aliasing effect caused by the finite size of receiving antenna in experiments.

In order to take account into the influence of frequency, the results of normalized phase and intensity distributions of different frequency with distance of 90 mm between antenna array and receiving antenna have been shown in Fig. 6, respectively. It can be seen that the spiral wave front and the singularity of the OAM wave keep stable roughly when the frequency changes. However, the area of the spiral wave front and the singularity becomes smaller with the increase of frequency. The reason is that the larger the frequency is, the smaller divergence angle the vortex wave has, leading to the smaller spiral wave front.

C. RADIATION PATTERN

The asymmetrical shape of the main lobe may lead to a performance decline for the OAM’s applications [18]. In order to measure the radiation patterns, a set of measurements were taken, as shown in Fig. 7. Compared with the OAM-generating system in Fig. 2, the beam control network, and the PC for data storage and control program are replaced by a microwave power source, an Agilent N1913A power meter and a rotating displacement table which can control the elevation angle of the receiving antenna. The input power is 0dBm while the loss of the coaxial line is about 3.5dB.

The radiation patterns as a function of the elevation angle at 2.45 GHz are shown in Fig. 8, where the azimuth angle is set as zero. The experimental results with the 46.72 dB (0.1223058 × 382) transmission loss of EM wave in water, the 3.5dB loss of coaxial, the combined 13dB loss of power dividers and phase shifters, and the 23dB gain of amplifier were measured, shown as the black lines. Meantime, the red lines are the corresponding simulated ones which have included the above losses and the gain of amplifier.
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**FIGURE 8.** Radiation patterns for different OAM modes at 2.45GHz. (a) l = 0. (b) l = −1. (c) l = −2. (d) l = −3.

Although the simulated curves are a little bit different from the measured ones, the change trends of them with the elevation angle are still consistent with each other. And the differences between the two curves may come from the different loss of water in the simulation and experiment, the weak signal detection errors, the reflection of some measuring devices, the measured errors and the spatial averaging effect of measured data caused by the finite size of receiving antenna. The distance 90mm between the transmitting and receiving antennas is shorter than the minimum value $8a^2/\lambda_g$ (17.92cm) in theory, which may also influence the experimental radiation patterns. Due to the loss of vortex waves in water, the distance cannot be far than 9mm under our current experimental condition.

D. PURITY ANALYSIS

In order to derive the factor of the antenna array and calculate the purity of the vortex waves, the far-field distributions should be calculated firstly. For a detection point $P(r, \theta, \phi)$ in the far field, the electric field $E(r)$ can be given from [6], [18] and the normalized array factor can be given by [19]:

$$f(\theta, \phi) = m_r e^{i\theta} J_l(k_g a \sin \theta)$$  \hspace{1cm} (1)

where $m_r$ is a constant related with the constant $r$, $l$ indicates the OAM mode number, $\phi$ is the azimuthal angle, $J_l$ represents the $l$th order Bessel function of the first kind, $k_g$ is the wave vector in water, $a$ is the radius of the array and $\theta$ is the angle between $k_g$ and propagation direction $z$.

Since all OAM modes are orthogonal with each other, the array factor of an arbitrary scalar beam can be expressed as the superposition of OAM states:

$$f = \sum l \omega_l \cdot e^{il\phi}$$  \hspace{1cm} (2)

where $\omega_l$ represents the weight of the $l$th OAM mode and can be obtained by integrating $f$ with $e^{il\phi}$ around $\phi$:

$$\omega_l = \frac{1}{2\pi} \int_0^{2\pi} f \cdot e^{-il\phi} d\phi$$  \hspace{1cm} (3)

Based on the above formulas (1) ~ (3), the OAM modes decomposition of the vortex waves at 2.45GHz has been performed by means of Fourier Transform of the field distributions on a circle corresponding to the magnitude maximum [31], and the results for both the experimental and the simulated data are presented in Fig. 9. The proportions of the main mode in simulation and experiment are all above 85%, which indicates a good performance of the antenna array.

**FIGURE 9.** Histograms of OAM spectrum weight of the different modes at 2.45 GHz. (a) $l = 0$. (b) $l = −1$. (c) $l = −2$. (d) $l = −3$.

E. EXPERIMENTAL VERIFICATION OF 2-D IMAGING

To further validate the performance of the proposed underwater antenna array, the 2-D underwater imaging experiments have been carried out. The experimental scenario is shown in Fig. 10(a), which is similar to that of radiation pattern experimental facilities. However, the receiving antenna is placed almost at the center of the antenna array to receive the echo signals from the targets of two corner reflectors, and the two corner reflectors are located in the scenario with the positions of $P_1$ (9.5cm, 12.5°, 0.2π) and $P_2$ (9.5cm, 12.5°, 1.2π), respectively.

**FIGURE 10.** (a) 2-D underwater imaging experimental scenario. (b) The experimental 2-D image for the underwater targets of two corner reflectors.

In experiments, in order to eliminate the effects of background noise, we have measured the data without the targets and with the targets. Subsequently, the echo signals are...
just the differences between two sets of data. Meanwhile, to enhance the SNR, the sampling frequency range has been greatly decreased to 0.75∼1.25GHz, and the step is 100MHz. The topological charge is from −3 to 3. At our selected operating band, the average SNR is about 5dB.

Based on the FFT method, we obtain the image in the scale of 24 cm × 2π rad, which is discretized to 64 × 64 imaging cells, as shown in Fig. 10(b). It can be seen that the targets of two corner reflectors (red circle) can be distinguished efficiently. Due to the small SNR and other influences on our experiments, there are few noise signals (as indicated in black circle). Fortunately, the positions of two targets are about $P_1(10cm, 0.205πr)$ and $P_2(10cm, 1.22πr)$ respectively, which are consistent with the true locations. Note that the range locations are obtained by taking one half of the values in image (double path). Meanwhile, the range and azimuth resolutions in image are about 4cm and 0.32π respectively, which are close to the resolutions (3.4cm and 0.3πr) in theory. The formula of the range resolution in theory is defined as $c/2B_τ / \sqrt{ε_r} = 3.4cm$, where $c$ is light speed, $B_τ$ is transmitting signal bandwidth, and $ε_r$ is the relative dielectric constant (78.4) of water. The corresponding azimuth resolution is $2π / Δl = 0.3π$, where $Δl$ is number of OAM modes.

**III. THE MULTIPLEXING AND DEMULTIPLEXING OF OAM**

As well known, in order to increase communication capacity and improve imaging resolution based on vortex waves, the OAM multiplexing and demultiplexing technologies are necessary. Thus, the generation and detection of the multiplexed OAM are of great importance. In this section, two generation methods and one detection method are taken into account.

**A. THE GENERATION OF MULTIPLEXED OAM WAVES**

The first generation method is based on the multiplexing phase holograms [4]. Through feeding the satisfactory intensity and phase configurations to the array elements, the multiplexed OAM waves can be generated. The multiplexed field with a set of target OAM modes of $\{l_1, l_2, \ldots, l_m\}$ can be expressed as

$$B \exp [iφ(φ)] = \sum_{m=1}^{n} A_{lm} \exp (i l_m φ)$$

where $B$ is a constant modulus of amplitude, $φ(φ)$ is the complex phase of multiplexed vortex waves, and $A_{lm}$ is the weight coefficient of single vortex wave carrying OAM mode $l_m$. Thus, $|A_{lm}|^2$ is the normalized power distribution of multiplexed vortex waves for different OAM modes and satisfy the formula (5):

$$\sum_{l}^{n} |A_{lm}|^2 = 1$$

Here, using the antenna array of 16 elements, we chose the vortex waves with OAM modes $l = 1$ and 3 ($A_1 = A_3 = 0.707$) to produce the multiplexed vortex waves, and there is 22.5 degree difference between the initial phase of the two OAM mode. Based on the formula (4)～(5), the normalized feeding intensities to the 16 elements are 1.387, 1.387, 1.176, 0.786, 0.276, 0.276, 0.276, 0.276, 1.176, 1.387, 1.387, 1.176, 0.786, 0.276, 0.276, 0.276; and 1.176, respectively. The corresponding phases are 11.25, 56.25, 101.25, 146.25, 191.25, 56.25, 281.25, 146.25, 191.25, 236.25, 281.25, 326.25, 191.25, 236.25, 101.25 and 326.25 degree respectively. The radius of array antenna is set as 66mm, and the generated intensity distributions of the vortex waves carrying OAM modes $l = 1$, 3 and multiplexed OAM modes of $l = 1$ and 3 are presented in Figs. 11(a-c), respectively. The observation plane with the scales of 252mm × 252mm is 70mm away from the array antenna. Therefore, only the intensity distributions in center area in Figs. 11(a-b) are still the “doughnut shape” in theory, which fits the characteristics of the vortex waves. And the distributions in other area are of lower quality. Meanwhile, the intensity distribution in Fig. 11(c) seems messy and we cannot distinguish it. Therefore, the conclusion that the detection of the multiplexed OAM waves is of great importance is emphasized again.

**FIGURE 11.** The generated intensities of the vortex waves carrying OAM modes (a) $l = 1$, (b) $l = 3$ and (c) multiplexed OAM modes.
B. THE DETECTION OF MULTIPLEXED OAM WAVES

Based on the theory in [32], the OAM mode \( l \) of vortex wave via Archimedean slot antenna depends on the number \( N \) of the Archimedean slot arm, which can be expressed as

\[
l = \pm N.
\]

Thus, we used two Archimedean slot antennas carrying OAM modes \( l = 1 \) or \( 3 \) to detect the generated multiplexed vortex waves, and the geometry of the whole models including the two structures for detecting the generated intensity distributions are displayed in Figs. 13(a-d), respectively. The Figs. 13(a-b) are the detection models for the generated intensity distributions based on the first generation method, and the Figs. 13(c-d) are the detection models for the generated intensity distributions based on the second generation method. The Archimedean slot antennas in Figs. 13(a-d) can generate the OAM modes \( l = -1, -3, -1 \) and \( -3 \), respectively, and are all placed 80mm away from the array antenna.

Based on the four detection models in Figs. 13(a-d), the corresponding detected intensity distributions are presented in Figs. 14(a-d), respectively. The observation plane with the same scales of 252mm \( \times \) 252mm is 50mm away from the Archimedean slot antenna in Figs. 14(a-b) and 100mm away from the Archimedean slot antenna in Figs. 14(c-d). The reason for the different observation distance is that the inner and outer array in second method influences each other, and the purities of the generated OAM modes are not high. With fewer array elements, the structure in first method is smaller, so the cost is lower, which both demonstrates a better performance of the first method.

IV. CONCLUSION

Based on a broadband underwater antenna, an OAM-generating antenna array is constructed to generate broadband underwater vortex waves in this paper. The simulation results of the intensity and phase-front distributions are consistent with the measured ones. In addition, the far-field patterns are obtained from the radiation fields while the purities of OAM waves are calculated by means of OAM spectrum decomposition. These results all demonstrate that the antenna array can generate broadband underwater vortex waves of high quality. The experimental verifications of 2-D underwater imaging for the targets of two corner reflectors have been carried out, from which the image shows that the targets can be distinguished efficiently. The range and azimuth resolutions in image are about 4cm and 0.32\( \pi \).
respectively, which are close to the resolutions (3.4 cm and 0.37 cm) in theory, further validating the performance of the proposed underwater antenna array. Meanwhile, two methods for generating multiplexed OAMs mode and one method to detect multiplexed OAMs mode have been proposed in this paper. Although the first generation method is more efficient, whose antenna structure is smaller and the cost is lower, both the two generation methods and one detection method are efficient and acceptable.

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