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Experiments of Orbital Angular Momentum Phase Properties for Long-Distance Transmission

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ABSTRACT In this paper, we propose a new method to effectively measure orbital angular momentum (OAM) properties for long-distance transmission. Properties of OAM wavefront in terms of phase and amplitude are measured by rotating the OAM wave antenna and fixing the plane wave antenna as a reference. To verify OAM phase properties for long-distance transmission, experiments are conducted in Tsingtao, China, with 3.7 km and 7.0 km across the Yellow Sea, which demonstrates that vortex phase properties of OAM keep well after long-distance transmission. Meanwhile, periodical properties of OAM waves' phase fronts are the same in different transmission distances.

INDEX TERMS Orbital angular momentum (OAM), rotation, long-distance transmission, vortex phase.

I. INTRODUCTION

During the last decade, electromagnetic (EM) waves carrying orbital angular momentum (OAM, l) has drawn considerable attentions at radio frequency due to infinitely orthogonal modes with OAM mode number $l \in \mathbf{Z}$. As a part of EM wave's angular momentum (AM), OAM is different from spin angular momentum (SAM, s), which is associated with electromagnetic wave's polarizations with only three modes ($s = 0, \pm 1$) [1]–[3]. OAM is related to helical phase front with vortex phase distribution $e^{-jl\phi}$, where ϕ is the transverse azimuth angle of the EM wave. Meanwhile, there is null zone in the center of helical phase front due to the phase singularity of OAM. Before OAM is firstly proposed at radio frequency utilizing antenna array in 2007 [4], OAM properties has been analyzed at optical regime for several years [5]–[9]. Then, as a potential candidate of mode division multiplexing (MDM) at radio frequency, OAM properties with orthogonal modes can be applied to enhance transmission capacity in the communication system [10]–[13]. Because of abundant phase information, EM waves carrying OAM can also be seen as a potential candidate of radar detection system [14], [15].

EM waves carrying OAM at radio frequency can be achieved using constructed circular electric or magnetic sources with vortex phase distribution, such as phase plates [16], crafted antennas [17], metasurface [18] and antenna arrays [19]–[21]. Using these generated OAM waves, experiments were conducted in laboratory environments or real environments to explore OAM properties applications [13], [22]–[24]. In existing published literatures, the longest OAM detection and application distance at radio frequency was conducted by Tamburini et al. in Venice with 442 meters distance [24]. On the other hand, due to null zones and vortex phase properties of OAM waves' helical phase fronts, EM waves carrying OAM are related to conical beams, whose beam peaks have divergence angles with respect to beam axes. The divergence effect can lead to the difficulty in receiving and utilizing OAM phase properties through a long-distance transmission. More seriously, how about OAM waves' vortex phase properties after long-distance transmission under the influence of divergence effect? Phase properties were only verified with short-distance transmission using the near field test system [25].

In this paper, phase and amplitude properties of OAM waves are analyzed and measured after long-distance transmission. The reminder of this paper is organized as follows. Section II presents the method and design of the experiment scheme exploring OAM wave front properties. Then, in Section III, the structure and performance of a multi-mode OAM antenna are presented, which is used as the transmitting OAM antenna. In Section IV, conducted experiments and corresponding experimental results in te real environment are presented. Finally, Section V gives conclusions.

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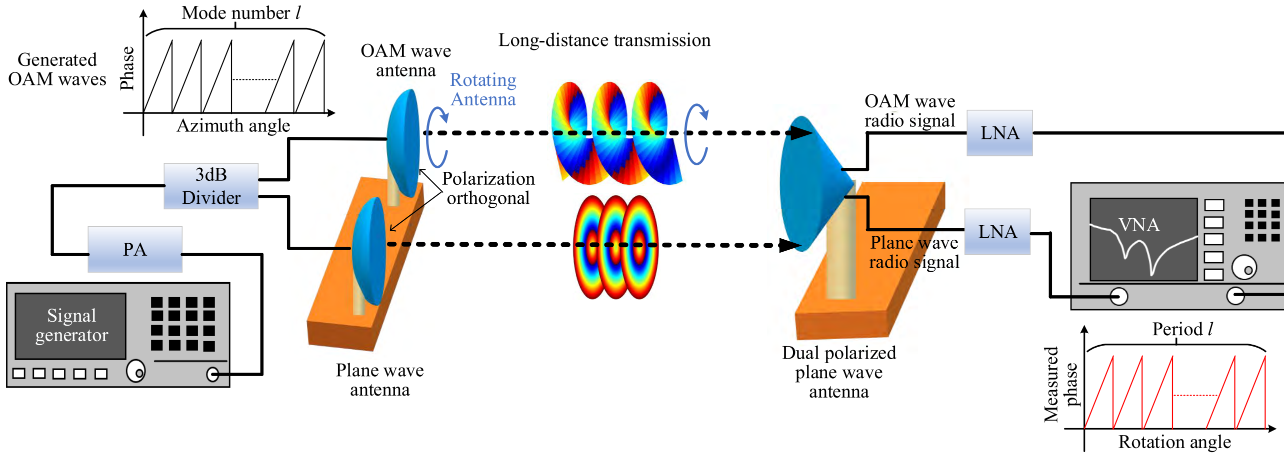

FIGURE 1. Scheme of the experiment exploring phase properties of EM waves carrying OAM for long-distance transmission.

II. DESIGN OF THE EXPERIMENT

Scheme of the experiment presented in Fig. 1 is to explore phase properties for long-distance transmission. A closed test system is constructed to measure OAM vortex wavefront properties in the receiving antenna. It is noted that the conventional linked cables between transmitting and receiving antennas is unacceptable for long-distance transmission. Thus, in this paper, the plane wave is proposed as a reference signal to construct the long-distance closed test system measuring OAM wave phase properties. In order to separate the OAM wave and the plane wave effectively, these two waves employ two orthogonal polarizations. As shown in Fig. 1, the radio signal is generated by the signal generator and amplified using power amplifier (PA). Using a 3db power divider, the radio signal is divided into two parts. One part is transmitted into the OAM antenna with mode number l and another one is transmitted to the plane wave antenna. Generated OAM waves (mode number l) have periodical properties with respect to the corresponding azimuth angle. After OAM wave propagating in the long distance, OAM wave and plane wave radio signals are both captured by the dual-polarized plane wave antenna with two low noise amplifiers (LNA). Utilizing receiver mode of vector network analyzer (VNA), phases and amplitudes of OAM waves can be measured and analyzed with respect to the plane wave radio signal.

Due to divergence effect of EM waves carrying OAM, cross section of complete vortex phase will get large along with transmission distance increasing. This divergence phenomenon leads to difficulty in capturing complete phase variation $2l\pi$ in a period of azimuth angle shown in Fig. 1. Here, instead of changing receiving antenna's position with all azimuth angle ϕ, rotating OAM wave antenna is applied. Correspondingly, phase fronts of OAM waves will rotate, complete phases and amplitudes properties of OAM wavefronts' cross sections can be recorded, then mode number l can be revealed in a period of OAM antenna's rotation angle.

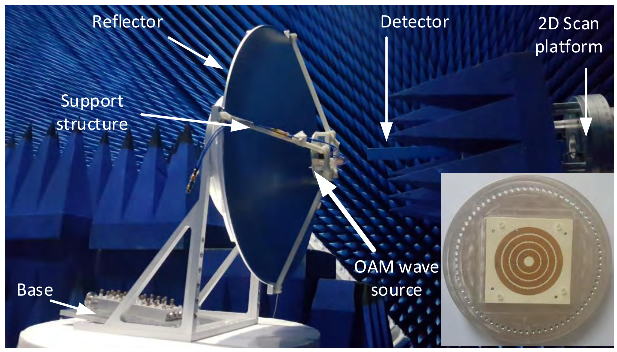

FIGURE 2. Structure of the OAM wave source on the parabolic reflector in the anechoic chamber.

III. ANTENNA GENERATING OAM WAVES

As described in [26], [27], high order cavity mode $TM_{(|l|+1)1}$ with 90° phase difference of the circular microstrip patch can be used to generate electromagnetic (EM) waves carrying OAM properties with mode number l and circular polarizations. Multi-concentric ring microstrip patches are applied to generate different OAM modes. Different ring microstrip patches are isolated from one another using metallic holes. Detailed parameters and analysis of the OAM wave source are shown in [28]. Utilizing external feeding networks, required orthogonal phases and same amplitudes of high order cavity mode $TM_{(|l|+1)1}$ can be excited. However, due to the small gain and divergent beam generated by the multi-concentric ring microstrip patches, transmission distance of generated OAM beams are short. To alleviate divergence effect of OAM beams and enhance gain, the parabolic reflector is used and the multi-concentric ring microstrip antenna is used as its source. The OAM wave source is fixed on the focal point of the reflector with the plastic support structure, which is fabricated using 3D printing technology, and the reflector and the base are manufactured by aluminium alloy. Applying propagation properties of OAM analyzed in [25], focused OAM waves still have vortex properties. Using optimization

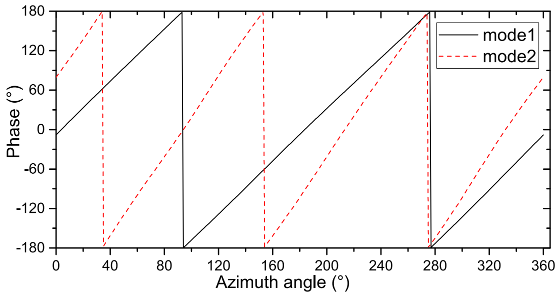

FIGURE 3. **Simulated phase of LHCP OAM waves with mode number $l = 1, 2$.**

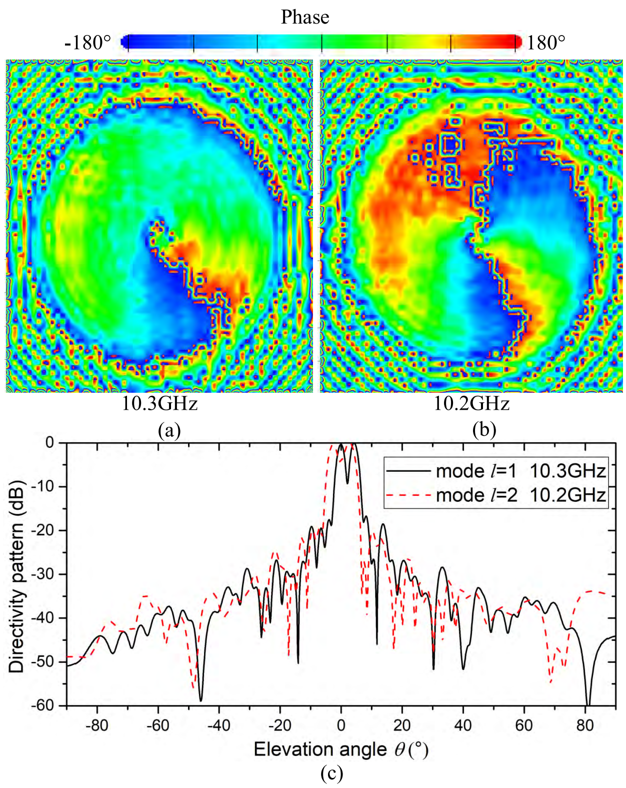

FIGURE 4. **Measured results of LHCP EM waves generated by the reflector OAM antenna with mode number $l = 1, 2$ at different frequencies: (a) x-polarized field's phase distribution of OAM mode number $l = 1$ at frequency 10.3GHz (b) x-polarized field's phase distribution of OAM mode number $l = 2$ at frequency 10.2GHz (c) cross sections of synthesized directivity pattern with mode number $l = 1, 2$ at different frequencies.**

of simulation software HFSS, optimized radius of the reflector is selected as 300mm and corresponding focal diameter ratio is chosen as 0.326 to focus energy of OAM wave as much as possible. Fig. 2 shows corresponding structure of the fabricated reflector OAM antenna. Simulated phase properties of generated left-hand circular polarization (LHCP) OAM waves with mode number $l = 1, 2$ are shown in Fig.3 at peaks of gain. Phase variations have extra 360° phase variation compared to mode number. Circular polarization, which is also spin angular momentum (SAM) part of emitted OAM waves, leads to the phenomenon.

The field distribution of the fabricated reflector OAM antenna is measured using the near field test detector and

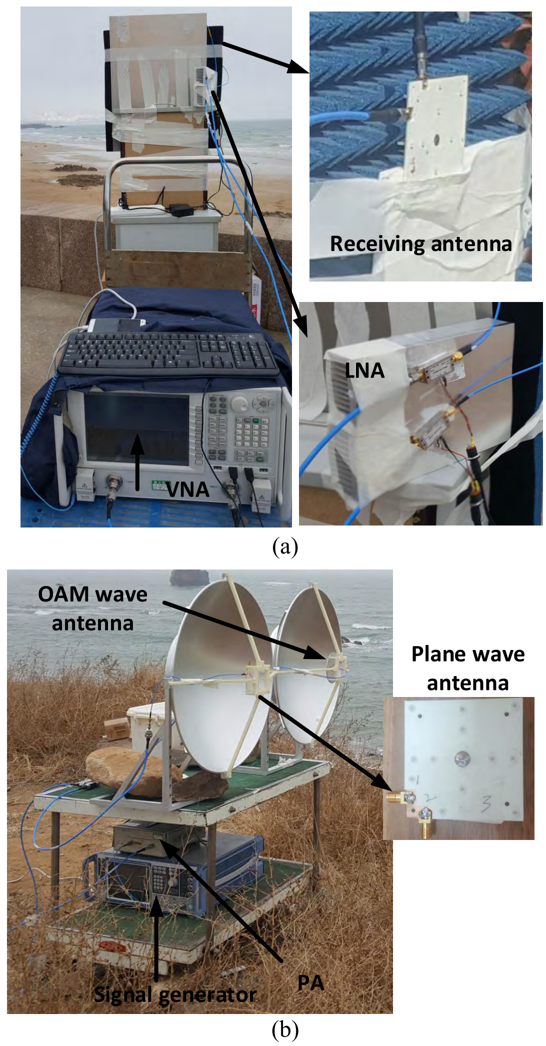

FIGURE 5. **Placements of the transmitting antenna and receiving antenna in the experiment. (a) receiving antenna with VNA and LNA (b) transmitting antenna with PA and signal generator.**

2D scan platform in the anechoic chamber. The near field test detector has linear polarization. Generated EM waves carrying OAM mode number $l = 1, 2$ of the reflector OAM antenna are measured at frequency 10.3GHz and 10.2GHz, respectively. The reflector OAM antenna is 100mm away from the scanning plane. Meanwhile, scanning range of emitted EM waves is set as 896mm × 896mm with 65 × 65 sampling points and the distance between adjacent sampling points is 14mm. All these distances are set to satisfy requirements of the near field scanning distance. Corresponding results of x-polarizarized fields' phase distributions and directivity patterns of OAM mode number $l = 1, 2$ are both shown in Fig. 4. Phase distributions still have vortex properties of mode number $l = 1, 2$, especially near the center of the scanning plane. Using the near field test system, directivity pattern can also be synthesized as depicted in Fig. 4(c). Divergence angles of mode number $l = 1, 2$ are respectively 2.2° and 2.9°, which are smaller than corresponding results of OAM wave source in [28]. Deviation angle of null zone

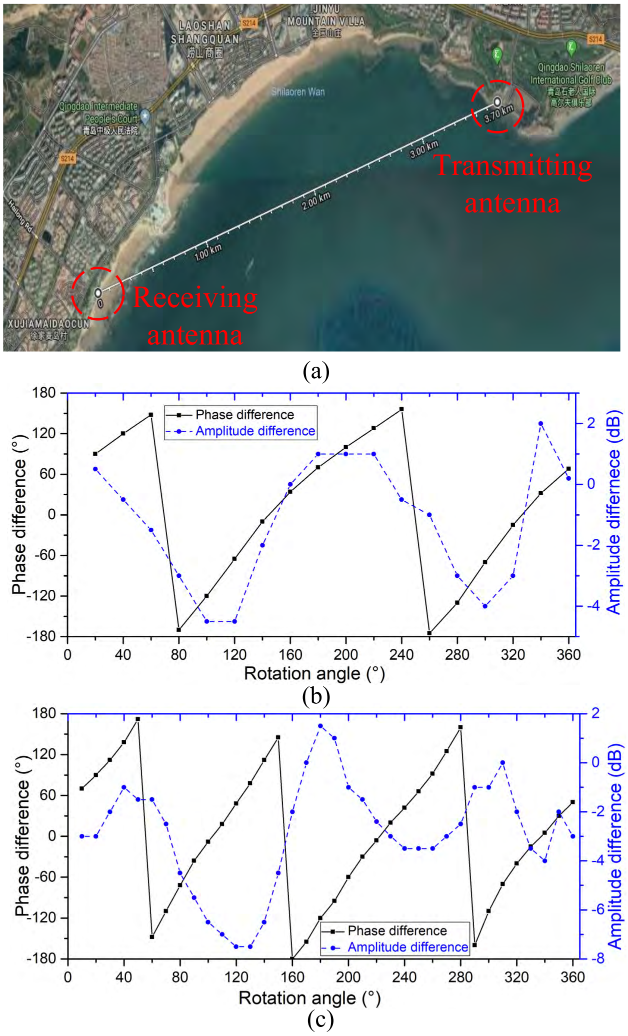

FIGURE 6. **Experiment with 3.7km distance shown in the Google Earth and corresponding measured results of the experiment. (a) 3.7km experiment shown in Google Earth (b) measured phase and amplitude difference between OAM wave and plane wave with OAM mode number $l = 1$ (c) measured phase and amplitude difference between OAM wave and plane wave with OAM mode number $l = 2$.**

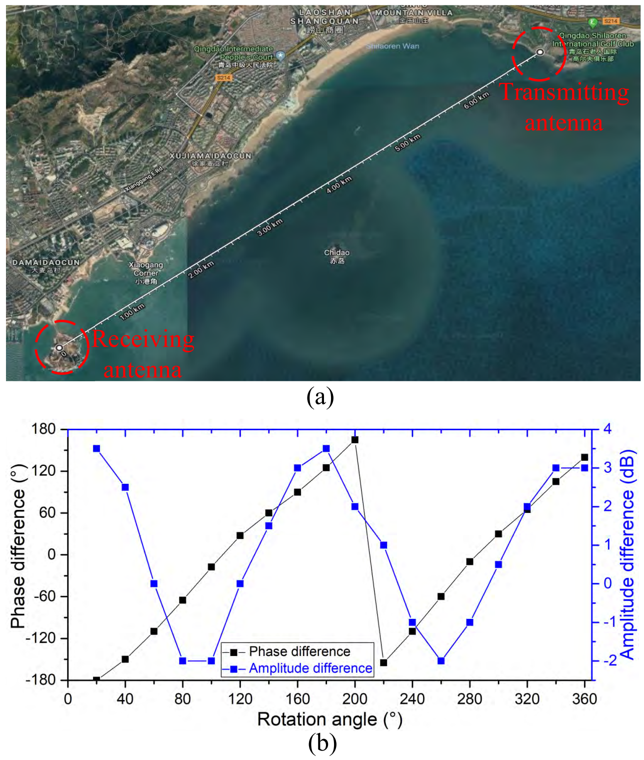

FIGURE 7. **Experiment with 7.0km distance shown in the Google Earth and corresponding measured results of the experiment. (a) 7.0km experiment shown in Google Earth (b) measured phase and amplitude difference between OAM wave and plane wave with OAM mode number $l = 1$.**

may be caused by misalignment of the near field test detector and the reflector OAM antenna. Overall, EM waves carrying OAM with mode number $l = 1, 2$ and small divergence angle can be generated by the reflector OAM antenna. These waves are suitable for verifying OAM phase properties for long-distance transmission.

IV. RESULTS AND DISCUSSIONS OF THE EXPERIMENT

Experiments of OAM phase transmission properties in the long distance are conducted in Tsingtao, China. Placements of the transmitting antenna and receiving antenna in the experiment are both shown in Fig. 5. Using coaxial cables, the Agilent PA is connected to the signal generator Rohde&Schwarz SMF100A, which generates radio wave signal, meanwhile, the PA has the gain equalling to 30dB. The reflector OAM antenna has the polarization of LHCP and fixed right-hand circular polarization (RHCP) microstrip patch antenna is used to emit plane wave as the reference radio signal in the experiment. Moreover, in order to guarantee the capability of distinguishing background noise and reference radio signal, plane wave is also focused using the same parabolic reflector. At the receiving end, a dual-circualr polarizations microstrip antenna is used to receive LHCP OAM wave's and RHCP plane wave's radio signals. In Fig.5(b), these orthogonal signals are separated into two coaxial cables and amplified using LNA. Gain of the LNA is 20dB. Using receiver mode of VNA, Agilent vector network analyzer E8361C is utilized to measure phase and amplitude differences between OAM wave radio signal and reference plane wave radio signal. After aligning both transmitting antenna and receiving antenna, rotating the OAM wave antenna around beam axis leads to the rotation of OAM wavefront at the receiving end. Utilizing the fixed RHCP plane wave signal as the reference radio signal, corresponding variation of phase and amplitude can be recorded, then OAM properties after long-distance transmission can be revealed.

As shown in Fig. 6(a), the experiment is conducted with 3.7km distance across the Yellow Sea. Signal generator's powers are 10dBm and 15dBm of mode number $l = 1, 2$ separately. Corresponding variation of phase and amplitude difference are also recorded in Fig. 6(b)(c) with OAM mode number $l = 1, 2$. Received power of $l = 1, 2$ reference plane waves are adjusted to -53dBm and -60dBm, which are close to received OAM waves' energies. With the increasing of OAM antenna's rotation angle, measured phases of OAM radio signal change through 2 and 3 periods of 360° about mode number $l = 1$ and 2, respectively. These phases' changes are caused by vortex phase properties of emitted OAM waves and corresponding results are accord with phase properties in Fig. 3. Compared to measured phase in Fig. 4(a,b), the phase variation has one extra 360° phase variation because of circular polarization. Mismachining tolerance, block of the support structure and the choppy sea may be the reason why amplitude difference in Fig. 6(b)(c) has fluctuation along with rotation angle increasing.

Furthermore, the distance of the experiment is increased to 7.0km, as depicted in Fig. 7. Generated power of signal generator is 15dBm and received power of plane wave is −57dBm. Position of receiving antenna is changed when position of transmitting antenna is fixed. In Fig. 7, corresponding phase still have periodical properties along with rotation angle increasing and these properties accord with vortex properties in Fig. 6(b). Thus, despite of the amplitude's fluctuation, vortex phase properties still exist after long-distance transmission and vortex phase fronts have same periodical phase transmission properties in different transmission distances.

V. CONCLUSION

In this letter, experiments of OAM phase properties for long-distance transmission are presented. Scheme of the experiment is designed and analyzed. To construct the closed test system, the plane wave radio signal is used as the reference, which can also avoid utilization of long and heavy linked cables. For the long distance transmission, rotation of the OAM wave source is proposed to avoid changing position of the receiving end. Meanwhile, EM waves carrying OAM with different OAM modes generated by the microstrip antenna is focused using parabolic reflector to alleviate divergence effect and enhance transmission distances. Finally, experiments are conducted and verified with different transmission distance in Tsingtao, China. The transmission distance is 3.7km and 7.0km across the Yellow Sea. Vortex phase properties of OAM still exist after long-distance transmission across the sea in spite of the amplitude's fluctuation. Periodical properties of phase front are the same in different distances. Our experiments and results may offer more options and possibilities to utilize OAM properties in the real environment, especially in long-distance transmission.

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