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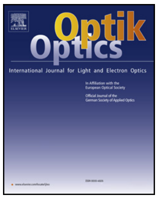

Original research article

Influence of oceanic turbulence on propagation of Airy vortex beam carrying orbital angular momentum

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ABSTRACT

With Rytov approximation theory, we derive the analytic expression of detection probability of Airy vortex beam carrying orbital angular momentum (OAM) through an anisotropic weak oceanic turbulence. We investigate the influences of turbulence parameters and beam parameters on the propagation properties of Airy-OAM beam. The numerical simulation results show that the anisotropic oceanic turbulence with a lower dissipation rate of temperature variance, smaller ratio of temperature and salinity contributions to the refractive index spectrum, larger dissipation rate of kinetic energy per unit mass of fluid, bigger inner scale factor, higher anisotropic coefficient causes the larger detection probability of Airy-OAM beam. Moreover, the Airy-OAM beam with a smaller topological charge, larger main ring radius and longer wavelength, has strong resistance to oceanic turbulent interference. Additionally, the detection probability decreases with the increase of receiving aperture size. In comparison with Laguerre-Gaussian-OAM beam, Airy-OAM beam has more anti-interference to turbulence when its topological charge is larger than 5 due to its non-diffraction and self-healing characteristics. The results are useful for underwater optical communication link using Airy-OAM beam.

1. Introduction

With the growing demand of underwater optical communication (UOC), as well as the increasing needs of underwater imaging systems and sensor networks, the propagation properties of vortex beams carrying orbital angular momentum (OAM) has attracted a wider attention in an underwater environment [1–16]. The OAM modes with different topological charges are orthogonal to each other, which make it possible for OAM modes used as a new degree of freedom for information multiplexing, where the capacity, as well as the bandwidth efficiency, can be greatly enhanced. Baghdady et al. realized 3Gbit/s UOC system with two OAM modes multiplexing for link distance 2.96 m by taking advantage of this characteristics of OAM modes [17]. Similarly, Ren et al. achieved a higher transmission rate, 40 Gbit/s, for a UOC system by using four OAM multiplexed modes [18].

However, OAM mode is a spatial distribution [19–21], its wavefront is susceptible to the spatial aberrations caused by underwater or atmosphere turbulence [22–26]. That is, as optical signals carrying OAM propagation through an oceanic medium, it will suffer attenuation and wavefront distortion caused by the fluctuations of the refractive index of water and the various constituents in the ocean [27,28], which results in the OAM crosstalk between modes and diminishes the performance of an optical communication system. Importantly, the existed results show that different OAM beams have different propagation properties in the underwater

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environment. For example, Huang et al. investigated the propagation of Gaussian Schell-model vortex beams through oceanic turbulence, and showed that both position and number of coherent vortices were changed with the increasing of propagation distance [1]. The propagation of a partially coherent cylindrical vector Laguerre-Gaussian (LG) beam passing through oceanic turbulence was investigated in [4], and the results showed that the smaller the initial coherence length of beam was, the larger the influence of ocean turbulence was. Cheng et al. revealed that the effect of a partially coherent LG beam with longer wavelength and smaller topological charge was less affected by ocean turbulence [5], Bessel-Gaussian(BG) beam is better than LG beam to resist the effects of ocean turbulence due to the non-diffraction and self-healing properties [8]. As for partially coherent Lorentz-Gauss OAM beam, Liu et al. found that the effect of turbulence was greater with smaller topological charge of beam [9].

On the other hand, Airy vortex beam carrying OAM mode, called Airy-OAM beam, has the properties of non-diffraction, self-healing and self-accelerating. It has attracted a lot of attentions on its generation, properties and potential applications recently [29–31]. However, as far as we have known, the propagation properties of Airy-OAM beam in underwater turbulence have not been reported.

In this paper, we investigate the propagation properties of Airy-OAM beam through anisotropic oceanic turbulence. The detection probability of Airy-OAM beam at the receiver side is derived with Rytov approximation theory, and the influence of oceanic turbulence on Airy-OAM beam with different oceanic environment and different source parameters are presented by numerical simulations.

The organization of the paper is as follows. In Section 2, the detection probability of Airy-OAM mode in weak oceanic turbulence is analyzed. In Section 3, the performance of Airy-OAM beam propagating in oceanic turbulence is discussed. Finally, Section 4 concludes the paper.

2. The detection probability of Airy-OAM beam in an underwater environment

In this section, we will derive the detection probability of Airy-OAM beam when it is passed through the underwater turbulent channel.

Fig. 1 shows the schematic diagram of the propagation property of Airy-OAM beam in an underwater environment. At transmitter, Airy-OAM beam with topological charge m_0 was prepared by a special device, such as, spatial light modulator (SLM). Here, $m_0 = 5$ was used. The energy distribution at transmitter showed that all the energy was concentrated at $m_0 = 5$ position. Then, the Airy-OAM beam was passed through an underwater turbulence channel. Here, Rytov approximation theory was adopted to describe the interference caused by the turbulent channel. The underwater turbulence would cause both phase and intensity fluctuations on Airy-OAM beam, resulting in the energy of Airy-OAM beam dispersed from $m = 1$ to $m = 9$. In order to estimate the mode dispersion caused by underwater turbulence, the detection probability P_{m_0} is used to evaluate the property of Airy-OAM beam in the underwater environment, which is defined as

$$P_{m_0} = \frac{E_{m_0}}{\sum_m E_m}, \tag{1}$$

where E_{m_0} denotes the energy detected for the received Airy-OAM mode with topological charge m_0, m represents the topological charge of all possible received Airy-OAM modes.

The normalized complex amplitude of an Airy-OAM beam in the paraxial approximation can be expressed as [32]

$$\mathrm{Ai}_0(r, \varphi, z) = -\frac{\mathrm{ik}}{z}\omega_0(r_0 - \omega_0\alpha^2)J_{m_0}\left(\frac{\mathrm{krr}_0}{z}\right)\exp\left(\mathrm{ik}\frac{r^2}{2z} + \frac{\alpha^3}{3} + \mathrm{i}m_0\varphi\right), \tag{2}$$

where (r, φ, z) are cylindrical coordinates, r is a radial distance from the propagation axis, φ is an azimuthal angle, z is a propagation distance. $k = \frac{2\pi}{\lambda}$ is wavenumber and λ is wavelength, $J_{m_0}(\cdot)$ is the Bessel function of the first kind. ω_0 is associated with the arbitrary transverse scale, r_0 represents the radius of the main ring, α is the exponential truncation, m_0 represents topological charge, and it is OAM quantum number.

The influence caused by underwater turbulence can be regarded as pure interference on the phase [13]. The second order cross

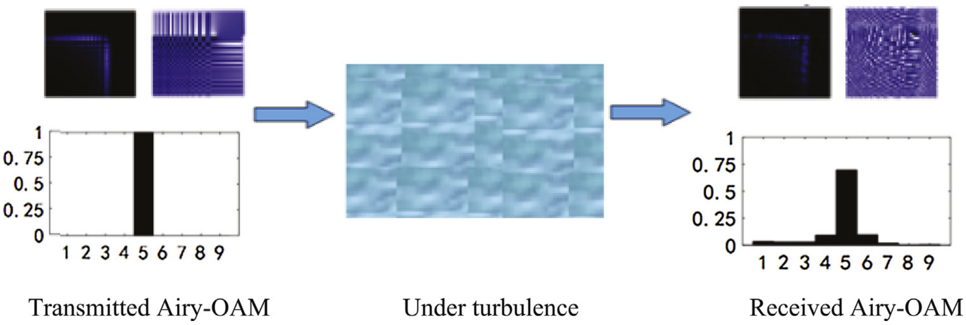

Fig. 1. Schematic diagram of the propagation property of Airy-OAM beam in an underwater environment.