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Influences of oceanic turbulence on Lorentz Gaussian beam

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ABSTRACT

Based on the extended Huygens-Fresnel integral, the propagation of a Lorentz Gaussian beam in oceanic turbulence is investigated. The influences of oceanic turbulence parameters (the rate of dissipation of turbulent kinetic energy per unit mass of fluid, the rate of dissipation of mean square temperature, and the relative strength of temperature and salinity fluctuations) on average intensity of a Lorentz Gaussian beam are analyzed by using the numerical examples. The results show that a Lorentz Gaussian beam propagating in stronger oceanic turbulence will spread faster.

1. Introduction

Laser beams propagating in random media such as atmospheric turbulence and oceanic turbulence are required in applications of underwater and atmosphere laser wireless communication [1]. In recent years, the propagation properties of various kinds of laser beams in oceanic turbulence have been widely investigated, such as stochastic electromagnetic beam [2], partially coherent radially polarized doughnut beam [3], Gaussian Schell-model vortex beam [4], stochastic electromagnetic vortex beam [5], partially coherent Hermite-Gaussian linear array beam [6], Gaussian array beam [7,8], multimode laser beams [9], partially coherent cylindrical vector beam [10], flat-topped vortex hollow beam [11,12], chirped Gaussian pulsed beam [13], Lorentz beam [14], partially coherent four-petal Gaussian beam [15] and partially coherent four-petal Gaussian vortex beam [16].

With the development of diode lasers, the model of diode laser source called Lorentz beam has been introduced [17]. Since then, the propagating properties of Lorentz and Lorentz Gaussian beams propagating through free space, optical system and turbulent atmosphere have been widely investigated [18–20]. However, to the best of our knowledge, the influences of oceanic turbulence on the average intensity of a Lorentz Gaussian beam propagating in oceanic turbulence have not been investigated and reported. In this work, based on the extended Huygens-Fresnel integral formula, we obtained the expression of a Lorentz Gaussian beam propagating in oceanic turbulence, and studied the influences of the parameters of oceanic turbulence such as the rate of dissipation of turbulent kinetic energy per unit mass of fluid, the rate of dissipation of mean square temperature, and the relative strength of temperature and salinity fluctuations on average intensity properties of a Lorentz Gaussian beam by using numerical examples.

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2. Theory analysis

In this work, the propagation direction of laser beam in oceanic turbulence can be taken to z axis, the Lorentz Gaussian beam in the source plane can be expressed as [19]:

$$E(\mathbf{r}_0,0)=\frac{1}{w_{0x}w_{0y}\left[1+\left(\frac{x_0}{w_{0x}}\right)^2\right]\left[1+\left(\frac{y_0}{w_{0y}}\right)^2\right]}\exp\left(-\frac{\mathbf{r}_0^2}{w_0^2}\right) \tag{1}$$

where $\mathbf{r}_0=(x_0,y_0)$ is the position vector at the source plane; w_{0x} and w_{0y} are the parameters related to the beam widths of Lorentz part in the x and y directions, respectively. w_0 is the waist of the Gaussian part. Utilizing the relationship of Lorentz distribution and Hermite-Gaussian function [21]

$$\begin{aligned}\frac{1}{\left(x_0^2+w_{0x}^2\right)\left(y_0^2+w_{0y}^2\right)}&=\frac{\pi}{2w_{0x}^2w_{0y}^2}\sum_{m=0}^{N}\sum_{n=0}^{N}\sigma_{2m}\sigma_{2n}H_{2m}\left(\frac{x_0}{w_{0x}}\right)H_{2n}\left(\frac{y_0}{w_{0y}}\right)\\&\times\exp\left(-\frac{x_0^2}{2w_{0x}^2}-\frac{y_0^2}{2w_{0y}^2}\right)\end{aligned} \tag{2}$$

where N is the number of the expansion. σ_{2m} and σ_{2n} are the expanded coefficients and are given in Ref. [21], with the increasing the even number *2m* and *2n*, the value of σ_{2m} and σ_{2n} dramatically decrease. Therefore, N will not be large in the calculations, in this work, N is set as N = 5. H_{2m} and H_{2n} are the 2 m and 2n order Hermite polynomial, and the Hermite polynomial $H_{2m}(x)$ can be expressed as [22]:

$$H_{2m}(x)=\sum_{l=0}^{m}\frac{(-1)^l(2m)!}{l!(2m-2l)!}(2x)^{2m-2l} \tag{3}$$

By substituting Eq. (2) into Eq. (1), we can obtain, a Lorentz Gaussian beam in the source plane can be rewritten as:

$$\begin{aligned}E(x_0,y_0,0)&=\frac{\pi}{2w_{0x}w_{0y}}\sum_{m=0}^{N}\sum_{n=0}^{N}\sigma_{2m}\sigma_{2n}H_{2m}\left(\frac{x_0}{w_{0x}}\right)H_{2n}\left(\frac{y_0}{w_{0y}}\right)\\&\times\exp\left(-\frac{x_0^2}{u_x^2}-\frac{y_0^2}{u_y^2}\right)\end{aligned} \tag{4}$$

with

$$\frac{1}{u_x^2}=\frac{1}{w_0^2}+\frac{1}{2w_{0x}^2} \tag{5a}$$

$$\frac{1}{u_y^2}=\frac{1}{w_0^2}+\frac{1}{2w_{0y}^2} \tag{5b}$$

Within the framework of paraxial approximation, the propagation of Lorentz Gaussian beam in oceanic turbulence can be investigated by using the extended Huygens-Fresnel diffraction integral [1–14]:

$$E(\mathbf{r},z)=-\frac{ik}{2\pi z}\exp(-ikz)\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}E(\mathbf{r}_0,0)\exp\left[-\frac{ik}{2z}(\mathbf{r}\text{-}\mathbf{r}_0)^2\right]\exp\left[\psi(\mathbf{r}_0,\mathbf{r},z)\right]d\mathbf{r}_0 \tag{6}$$

where $\mathbf{r}=(x,y)$ is the position vector at the output plane; $k=2\pi/\lambda$ is the wave number; $\psi(\mathbf{r}_0,\mathbf{r},z)$ is the solution to the Rytov method that represents the random part of the complex phase for the turbulent media; Then the average intensity of a Lorentz Gaussian beam propagating in oceanic turbulence in the receiver plane can be given as:

$$\begin{aligned}\langle I(\mathbf{r},z)\rangle&=\frac{k^2}{4\pi^2z^2}\iiint\int_{-\infty}^{+\infty}E(\mathbf{r}_{10},0)E^*(\mathbf{r}_{20},0)\exp\left[-\frac{ik}{2z}(\mathbf{r}\text{-}\mathbf{r}_{10})^2+\frac{ik}{2z}(\mathbf{r}\text{-}\mathbf{r}_{20})^2\right]\\&\times\langle\exp\left[\psi(\mathbf{r},\mathbf{r}_{10})+\psi^*(\mathbf{r},\mathbf{r}_{10})\right]\rangle d\mathbf{r}_{10}d\mathbf{r}_{20}\end{aligned} \tag{7}$$

Where the angle bracket indicates the ensemble average over the medium statistics covering the log-amplitude and phase fluctuations due to oceanic turbulence, and the asterisk denotes the complex conjugation. And the last term in Eq. (7) can be expressed as follows:

$$\langle\exp\left[\psi(\mathbf{r},\mathbf{r}_{10})+\psi^*(\mathbf{r},\mathbf{r}_{20})\right]\rangle=\exp\left[-M(\mathbf{r}_{10}-\mathbf{r}_{20})^2\right] \tag{8}$$