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Propagation of optical coherence lattices in oceanic turbulence

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ABSTRACT

Based on the extended Huygens–Fresnel principle, an analytical expression for the cross-spectral density of optical coherence lattices (OCL) in oceanic turbulence is derived. With the help of this expression, we investigate the propagation of OCL in oceanic turbulence. In order to increase underwater optical communication distance, we investigated the effects of source parameters, such as lattices constant, wavelength and beam width, on intensity distribution of OCL in oceanic turbulence. Results indicate that the light intensity received by receiver increases with the increase of lattice constant, the increase of beam width and the decrease of wavelength, which may have some potential applications in underwater optical communication.

1. Introduction

Spatial correlations of optical fields affect interfere between different points, which are determinant for the propagation characteristics of optical field [1]. The propagation of partially coherent beam in free space [2] and atmospheric turbulence [3] is of considerably theoretical and practical interests, motivated by potential applications in free space optical communications [4,5], optical imaging [6] and particle trapping [7]. Besides, several classes of partially coherent beam with different correlation functions such as, Gaussian Schell-model beam [1], multi-Gaussian Schell model beam [8], non-uniformly correlated Gaussian Schell model beam [9], Bessel-correlated Schell model beam [10] and Laguerre-Gaussian correlated Schell-model beam [11], have been introduced. More recently, a new class of partially coherent beam with periodic coherence properties, so-called optical coherence lattices, is introduced by L. Ma [12]. Making use of a synthesis of multiple partially coherent Schell-model beams, experimental generation of optical coherence lattices (OCL) is reported [13]. The propagation characteristics of OCL beam in free space [14] and atmospheric turbulence [15] are reported, which has potential application in free-space information transfer and optical communications.

The propagation and parametric characteristics of laser beams through oceanic turbulence have been investigated widely for many potential and practical applications in optical communication and optical imaging in underwater media. Turbulent fluctuations of temperature and salinity in sea water result in fluctuations of refractive index. More recently, an analytical model for power spectrum of the refractive index fluctuations has been developed [16]. Based on this model, the propagation behaviors of scalar partially coherent beam [17–19], electromagnetic partially coherent beam [20], Gaussian array beams [21], Lommel-Gaussian beam [22] and Hermite-Gaussian vortex beam [23] in oceanic turbulence have been investigated, respectively. The intensity fluctuations for spherical wave through weak [24] and strong [25] oceanic turbulence are reported, respectively. It is worthwhile to investigate optical coherence lattices through oceanic turbulence.

In this paper, we investigate the propagation properties of OCL in oceanic turbulence. Based on extended Huygens–Fresnel principle, we obtained an analytical expression for OCL cross-spectral density in any transverse plane through oceanic turbulence, in Section 2. With the help of this expression, the intensity distributions for OCL through oceanic turbulence are investigated in details, in Section 3.

2. Theoretical model

Let us consider OCL propagating from the $z = 0$ into the half-space z>0 through a oceanic turbulence whose cross spectral density at the source has the form [12,13]

$$W(x_1', y_1', x_2', y_2', 0) = \prod_{s'=x',y'} \sum_{n_s=0}^{N} \frac{v_{n_s}}{\sqrt{\pi}} \exp\left[-\frac{s_1'^2 + s_2'^2}{2w_0^2} - \frac{2i\pi n_s(s_1' - s_2')}{aw_0}\right] \tag{1}$$

The term n_s is a non-negative integer; w_0 is the root-mean-square (rms) width of the source intensity profile; a is a dimensionless lattice

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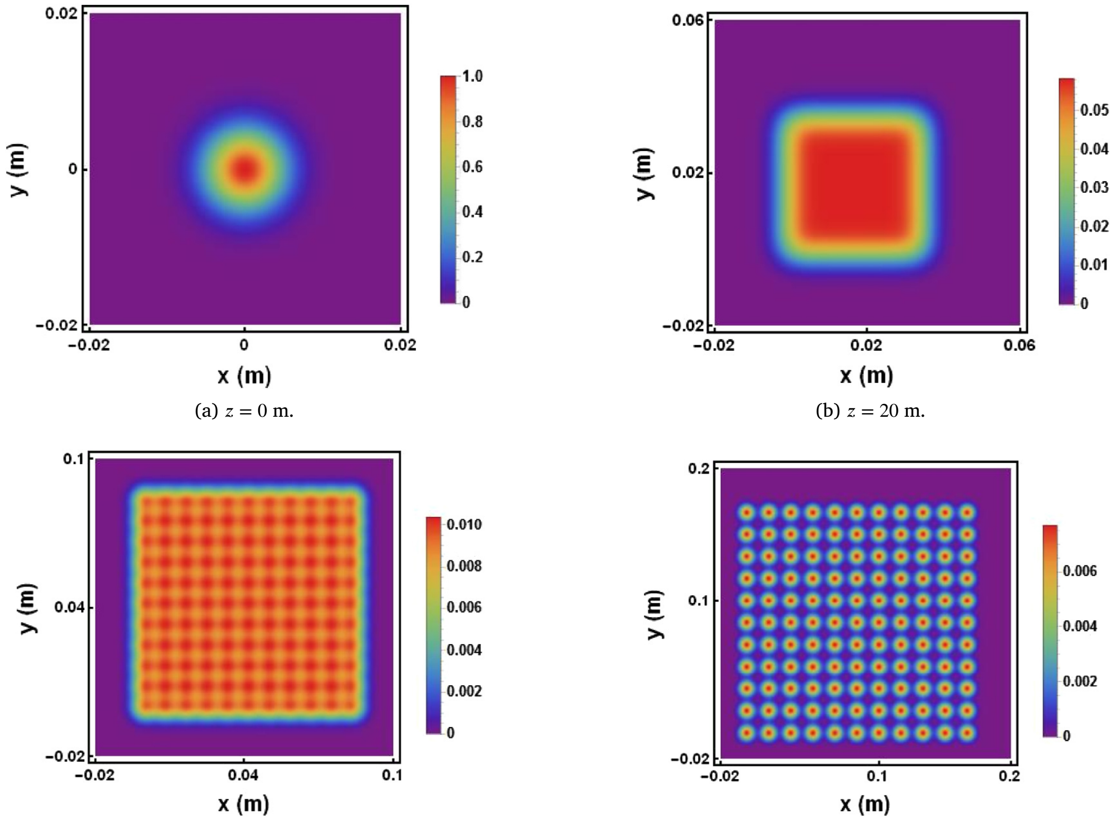

(a) $z = 0$ m.
(b) $z = 20$ m.
(c) $z = 50$ m.
(d) $z = 100$ m.

Fig. 1. Normalized intensity distribution of optical coherence lattices in oceanic turbulence at different propagation distances.

constant; v_{n_s} is the mode weight distribution specify associated with each mode.

The cross-spectral density propagating through oceanic turbulence obeys the extended Huygens–Fresnel principle [26]

$$W(\vec{\rho}_1,\vec{\rho}_2,z)=\frac{1}{(\lambda z)^2}\exp\left[-\frac{ik}{2z}(\vec{\rho}_1^{\,2}-\vec{\rho}_2^{\,2})\right]$$
$$\times\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}W(\vec{r}_1,\vec{r}_2,0)\exp\left[-\frac{ik(\vec{r}_1^{\,2}-\vec{r}_2^{\,2})}{2z}\right]\exp\left[\frac{ik}{z}(\vec{\rho}_1\cdot\vec{r}_1-\vec{\rho}_2\cdot\vec{r}_2)\right], \tag{2}$$
$$\times\langle\exp[\Psi(\vec{r}_1\cdot\vec{\rho}_1)+\Psi^{*}(\vec{r}_2\cdot\vec{\rho}_2)]\rangle\, d^2\vec{r}_1 d^2\vec{r}_2$$

where $\vec{r}_1 \equiv (x_1', y_1')$ and $\vec{r}_2 \equiv (x_2', y_2')$, $k = 2\pi/\lambda$ is the wave number. $\langle\rangle$ denotes ensemble averaging over the oceanic turbulence, and can be expressed as [16,20]

$$\langle\exp[\Psi(\vec{r}_1\cdot\vec{\rho}_1)+\Psi^{*}(\vec{r}_2\cdot\vec{\rho}_2)]\rangle$$
$$=\exp\left[-\frac{\left(\vec{\rho}_1-\vec{\rho}_2\right)^2+\left(\vec{\rho}_1-\vec{\rho}_2\right)\left(\vec{r}_1-\vec{r}_2\right)+\left(\vec{r}_1-\vec{r}_2\right)^2}{\rho_0^2}\right]. \tag{3}$$

The term ρ_0 is the coherence length of the spherical wave in oceanic turbulence, which can be expressed as [27]

$$\rho_0=\left[\frac{\pi^2k^2z}{3}\int_0^{\infty}\kappa^3\Phi_n(\kappa)\,d\kappa\right]^{-1/2}, \tag{4}$$

with the function $\Phi_n(\kappa)$ denoting the spatial power spectrum of the refractive-index fluctuations of the oceanic turbulence. To model the oceanic turbulence, the spatial power spectrum in homogeneous and isotropic oceanic turbulence is used [16,18]

$$\Phi_n(\kappa)=0.338\times10^{-8}\varepsilon^{-1/3}\chi_t\kappa^{-11/3}\left[1+2.35(\kappa\eta)^{2/3}\right]$$
$$\times\left[\exp\left(-A_T\delta\right)+\varpi^{-2}\exp\left(-A_S\delta\right)-2\varpi^{-1}\exp\left(-A_{TS}\delta\right)\right], \tag{5}$$

where κ is the spatial frequency of the turbulent fluctuations, ε is the rate of dissipation of turbulent kinetic energy per unit mass of fluid, χ_t is the rate of dissipation of temperature variance, η is the inner scale of turbulence, $A_T = 1.863\times10^{-2}$, $A_S = 1.9\times10^{-4}$, $A_{TS} = 9.41\times10^{-3}$, $\delta = 8.284(\kappa\eta)^{4/3} + 12.978(\kappa\eta)^2$, ϖ is the ratio of temperature and salinity contributions to the refractive index spectrum ranging from −5 to 0, with −5 and 0 corresponding to dominating temperature-induced and salinity-induced optical turbulence, respectively. With Eq. (5), the spatial coherence length of the spherical wave in oceanic turbulence ρ_0 can be given by [18,29].

$$\rho_0=\left[1.801C_m^2k^2z\eta^{-1/3}\left(0.483\varpi^2-0.835\varpi^{-1}+3.38\varpi^{-2}\right)\right]^{-1/2}, \tag{6}$$

The term $C_m^2 = 10^{-7}\varepsilon^{-1/3}\chi_t$ character the "equivalent" temperature structure constant for given ϖ with a unit $\mathrm{m}^{-2/3}\mathrm{K}^2$. ϖ is the relative strength of temperature and salinity fluctuation, which varies in the interval $[-5, 0]$.

Making the transformations

$$x_u'=\frac{x_1'+x_2'}{2},\qquad x_v'=x_1'-x_2',$$
$$x_u=\frac{x_1+x_2}{2},\qquad x_v=x_1-x_2,$$
$$y_u'=\frac{y_1'+y_2'}{2},\qquad y_v'=y_1'-y_2',$$
$$y_u=\frac{y_1+y_2}{2},\qquad y_v=y_1-y_2,$$

one can express the OCL cross-spectral density at the source as

$$W(x_1',y_1',x_2',y_2',0)=\prod_{s'=x',y'}\sum_{n_s=0}^{N}\frac{v_{n_s}}{\sqrt{\pi}}\exp\left[-\frac{s_u'^2+4s_v'^2}{2w_0^2}-\frac{2i\pi n_s s_v'}{aw_0}\right], \tag{7}$$