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Propagation of specular and anti-specular Gaussian Schell-model beams in oceanic turbulence

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ABSTRACT

On the basis of the extended Huygens-Fresnel principle and the unified theory of coherence and polarization of light, we investigate the propagation properties of the specular and anti-specular Gaussian Schell-model (GSM) beams through oceanic turbulence. It is shown that the specularity of specular GSM beams and the anti-specularity of anti-specular GSM beams are destroyed on propagation in oceanic turbulence. The spectral density and the spectral degree of coherence are also studied in detail. The results may be helpful for underwater communication.

1. Introduction

In the past decades, much attention has been paid to the propagation characteristics of laser beams, especially since the unified theory of coherence and polarization of stochastic electromagnetic beams was introduced by Wolf in 2003 [1]. In the frame of this theory, a variety of novel light beams propagating in both free space and turbulent media have been investigated extensively [2–5]. Among the turbulent media, atmospheric turbulence and oceanic turbulence are mostly considered, due to the extensive applications in optical communication, imaging, remote sensing and so on [6–10]. Compared with the turbulent atmosphere, light beams propagating through oceanic turbulence are less explored, however, in recent years, more and more attention has been paid to the beams propagation in the oceanic turbulence because of the interest in underwater applications [11–13].

The concept of specular cross-spectral density function was firstly introduced by Gori et al. in 1988 [14], which satisfies the conditions $W(-x_1, x_2) = W(x_1, x_2)$ and $W(x_1, -x_2) = W(x_1, x_2)$. However, in the following decades, the phenomenon of specularity has received little attention, except for the study lunched by Ponomarenko and Agrawal [15], who studied the specular properties of partially coherent solitons propagating through non-instantaneous nonlinear media. Recently, the concept of specularity was extended to two dimensions by Partanen et al. [16], and the concept of anti-specularity was proposed. What is more, the specular and anti-specular Gaussian Schell-model (GSM) beams have also been experimentally generated. The specular and anti-specular GSM beams have some peculiar features in potential applications, for example, particles trapping [17]. However, to the best of our knowledge, the propagation properties of such novel light beams in oceanic turbulence have not been studied, which may be helpful for underwater communication.

In this paper, an analytical expression for the cross-spectral density function of the specular and anti-specular GSM beams is derived by using an isotropic GSM beam as the incident field of the wavefront-folding interferometer (WFI). Then the spectral density and the spectral degree of coherence of these beams in oceanic turbulence are studied in detail.

2. Theory

Fig. 1 is the structure of WFI [18]. It is mainly composed of a beam splitter (BS), two perpendicularly oriented right-angle prisms PR_1 and PR_2 which retroreflect the incident field in the x and y directions respectively. Assume a single partially coherent beam with the field $E_0(x', y')$ is incident on WFI, and is split into two beams by the beam splitter. Due to the folding effect of the right-angle prisms, the output field of WFI can be written as [16]

$$E(x', y') = \frac{1}{\sqrt{2}}\left[E_0(x', -y') + E_0(-x', y')\exp(i\theta)\right], \tag{1}$$

where θ is the phase difference between the two beam paths. According to the coherence theory [19], the correlation properties

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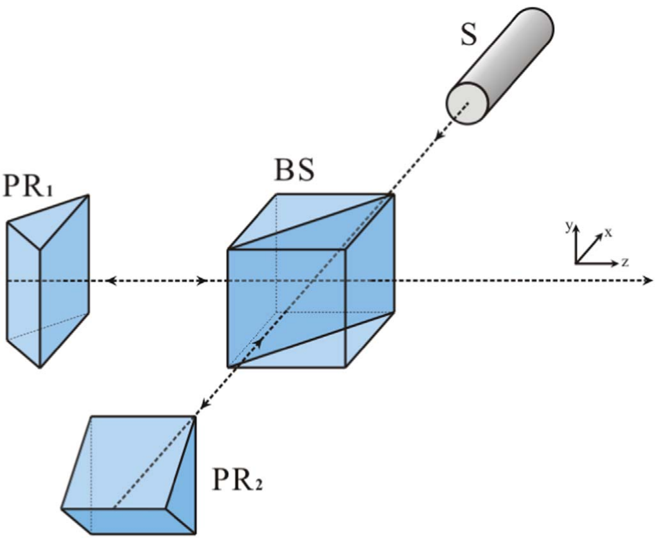

Fig. 1. The structure of wavefront-folding interferometer.

of the incident field could be expressed by the cross-spectral density function (CSDF)

$$W_0(x_1', y_1', x_2', y_2') = \left\langle E_0^*(x_1', y_1')E_0(x_2', y_2')\right\rangle, \tag{2}$$

where the angular brackets denote ensemble averaging and the asterisk denotes complex conjugate. Thus, the CSDF of the output field is given by

$$\begin{aligned} W\left(x_1', y_1', x_2', y_2'\right) &= \left\langle E^*(x_1', y_1')E(x_2', y_2')\right\rangle \\ &= \frac{1}{2}\left[W_0\left(x_1', -y_1', x_2', -y_2'\right) \right. \\ &\quad \left. + W_0\left(-x_1', y_1', -x_2', y_2'\right)\right] \\ &\quad + \frac{1}{2}\left[W_0\left(x_1', -y_1', -x_2', y_2'\right)\exp(i\theta) \right. \\ &\quad \left. + W_0\left(-x_1', y_1', x_2', -y_2'\right)\exp(-i\theta)\right]. \end{aligned} \tag{3}$$

Now we consider an isotropic GSM beam [20] incident on the WFI. For simplicity, we suppose the incident field is of unit-amplitude

$$W_0(\boldsymbol{\rho}_1, \boldsymbol{\rho}_2) = \exp\left(-\frac{\boldsymbol{\rho}_1^2 + \boldsymbol{\rho}_2^2}{w_0^2}\right)\exp\left[-\frac{(\boldsymbol{\rho}_1 - \boldsymbol{\rho}_2)^2}{2\sigma_0^2}\right], \tag{4}$$

where w_0 is the beam width, σ_0 represents the coherence width. On substituting from Eq. (4) into Eq. (3), one can obtain the CSDF of the output field

$$W_s(\boldsymbol{\rho}_1, \boldsymbol{\rho}_2) = \exp\left(-\frac{\boldsymbol{\rho}_1^2 + \boldsymbol{\rho}_2^2}{w_0^2}\right)\left\{\exp\left[-\frac{(\boldsymbol{\rho}_1 - \boldsymbol{\rho}_2)^2}{2\sigma_0^2}\right] + \cos\theta\exp\left[-\frac{(\boldsymbol{\rho}_1 + \boldsymbol{\rho}_2)^2}{2\sigma_0^2}\right]\right\}. \tag{5}$$

It is obvious that the field is specular, i.e., $W_s(-\boldsymbol{\rho}_1, \boldsymbol{\rho}_2) = W_s(\boldsymbol{\rho}_1, \boldsymbol{\rho}_2)$, if $\theta = 2n\pi$ with n being an integer. On the contrary, one has $W_s(-\boldsymbol{\rho}_1, \boldsymbol{\rho}_2) = -W_s(\boldsymbol{\rho}_1, \boldsymbol{\rho}_2)$, if $\theta = (2n+1)\pi$, which indicates an anti-specular case.

We regard the output field of the WFI as a secondary source which propagates into the half-space $z > 0$. By applying the extended Huygens-Fresnel integral formula, the CSDF of the electric field at two points $\mathbf{r}_1$ and $\mathbf{r}_2$ in the detective plane is given by [21]

$$\begin{aligned} W(\mathbf{r}_1, \mathbf{r}_2, z) = \left(\frac{k}{2\pi z}\right)^2 \int d^2\boldsymbol{\rho}_1 \int d^2\boldsymbol{\rho}_2 W_s(\boldsymbol{\rho}_1, \boldsymbol{\rho}_2) \exp\left\{-\frac{ik}{2z}\left[\left(\mathbf{r}_1 - \boldsymbol{\rho}_1\right)^2 - \left(\mathbf{r}_2 - \boldsymbol{\rho}_2\right)^2\right]\right\} \\ \times\left\langle \exp\left[\psi^*\left(\mathbf{r}_1, \boldsymbol{\rho}_1, z\right) + \psi\left(\mathbf{r}_2, \boldsymbol{\rho}_2, z\right)\right]\right\rangle. \end{aligned} \tag{6}$$

here $k = 2\pi/\lambda$ is the wave number, ψ represents the complex phase perturbation caused by the random medium, the angular brackets denote ensemble average over the medium. The term in the sharp brackets in Eq. (6) can be written as

$$\begin{aligned} &\left\langle \exp\left[\psi^*(\mathbf{r}_1, \boldsymbol{\rho}_1, z) + \psi(\mathbf{r}_2, \boldsymbol{\rho}_2, z)\right]\right\rangle \\ &= \exp\left\{-\frac{\pi^2 k^2 z}{3}\left[\left(\mathbf{r}_1 - \mathbf{r}_2\right)^2 + \left(\boldsymbol{\rho}_1 - \boldsymbol{\rho}_2\right)^2 \right.\right. \\ &\quad \left.\left. + \left(\mathbf{r}_1 - \mathbf{r}_2\right)\left(\boldsymbol{\rho}_1 - \boldsymbol{\rho}_2\right)\right]\int_0^\infty \kappa^3 \Phi_n(\kappa) d\kappa\right\}, \end{aligned} \tag{7}$$

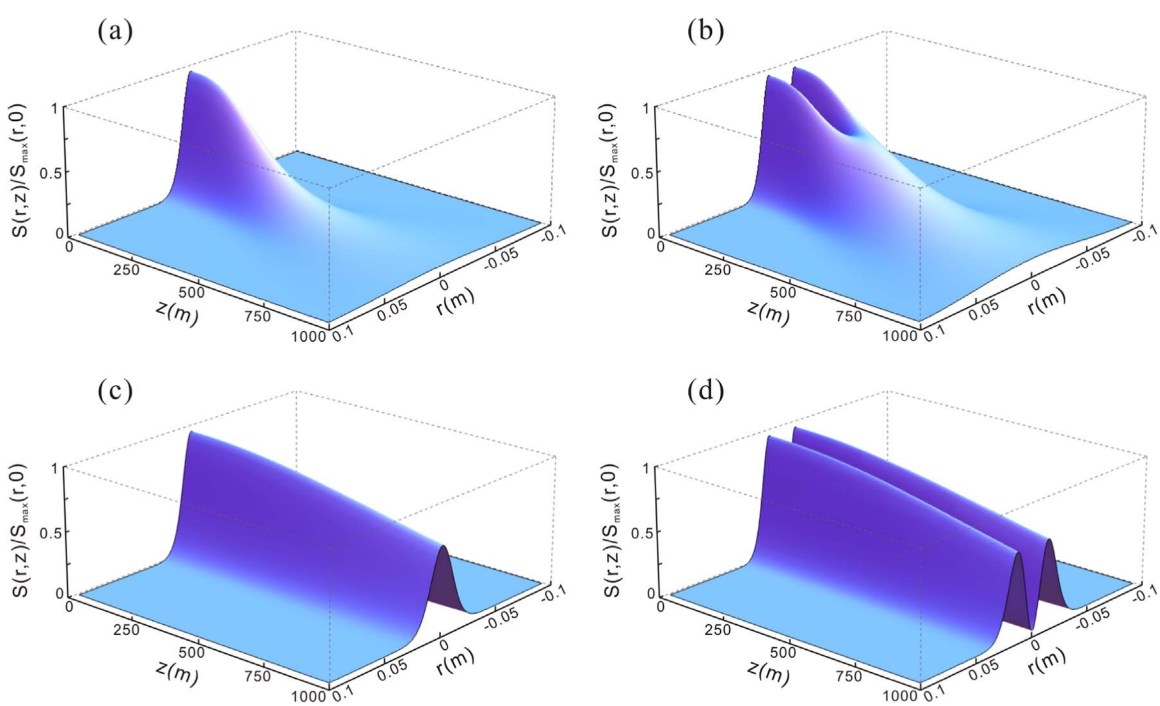

Fig. 2. Evolution of normalized spectral density for specular GSM beams and anti-specular GSM beams propagating in oceanic turbulence and free space.