Optics Communications 331 (2014) 1–5

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Propagation of electromagnetic non-uniformly correlated beams in the oceanic turbulence

Jia Xu, Miaomiao Tang, Daomu Zhao *

Department of Physics, Zhejiang University, Hangzhou 310027, China

ARTICLE INFO

Article history:
Received 12 April 2014
Received in revised form
19 May 2014
Accepted 24 May 2014
Available online 3 June 2014

Keywords:
Electromagnetic non-uniformly correlated beams
Oceanic turbulence
The spectral density
The spectral degree of polarization

ABSTRACT

We investigate the propagation of an electromagnetic non-uniformly correlated beam propagating through oceanic turbulence. The elements of the cross-spectral density matrix of such a beam propagating through the oceanic turbulence are obtained. We study the spectral density and the spectral degree of polarization on its propagation with the help of numerical calculations. It is shown that the intensity self-focusing will be affected under the influence of oceanic turbulence.

1. Introduction

The propagation characteristics of laser beams have been widely studied, especially after the unified theory of coherence and polarization of the stochastic electromagnetic beam was presented by Wolf in 2003 [1]. Until now a lot of work has been done to discuss the properties of laser beams on propagation both in free space [2,3], and through turbulent media (just like atmospheric turbulence [4], and oceanic turbulence [5]). However, most of the studies are assumed sources with so-called Gaussian Schell-model correlations where the typical correlation (i.e. δ) is uniform over the whole field.

Recently, there has been substantial interest in investigating the properties of a new type of random beams with nonuniform correlations which have locally varying degree of coherence. Based on the general theory suggested by Gori [6], some distinctive changes in the intensity distribution of the beams with spatially varying correlations on propagation have been discussed in [7]. Since then, the characteristics of scalar beams with nonuniform correlations in isotropic random media have been illustrated [8], the behavior of electromagnetic non-uniformly correlated beams has been studied in detail [9], the propagation of electromagnetic beams with nonuniform correlations in the turbulent atmosphere [10] and some experimental studies of such a beam have also been investigated [11,12]. Oceanic turbulence is another medium which can evidently impact propagation properties of a stochastic beam [5], and the electromagnetic non-uniformly correlated beam has huge potential applications, however, to the best of our knowledge, the properties of electromagnetic non-uniformly correlated beams propagating in the oceanic turbulence have not been studied and reported.

In this paper, we will study the propagation of an electromagnetic non-uniformly correlated beam in the oceanic turbulence. The spectral density and the spectral degree of polarization of such a beam on propagation will be investigated in detail.

2. Theory

The elements of the cross-spectral density matrix of an electromagnetic non-uniformly correlated beam at the source plane (i.e. $z=0$) can be expressed as [9,10]

$$W_{ij}^{0}(\boldsymbol{\rho}_1', \boldsymbol{\rho}_2', \omega) = A_i A_j B_{ij} \exp\left[-\frac{\boldsymbol{\rho}_1' 2 + \boldsymbol{\rho}_2' 2}{2{\sigma_0}^2}\right] \exp\left\{-\frac{[(\boldsymbol{\rho}_1' - \boldsymbol{\gamma}_i)^2 - (\boldsymbol{\rho}_2' - \boldsymbol{\gamma}_j)^2]^2}{\delta_{ij}^4}\right\}, \quad (1)$$

where $i,j = x,y$, A_i and A_j are the field amplitudes of the electric field components, $B_{ij} = |B_{ij}|e^{i\varphi_{ij}}$ is the single-point correlation coefficient, a complex number, with φ_{ij} being its phase difference, $\boldsymbol{\rho}_1' = (x_1', y_1')$ and $\boldsymbol{\rho}_2' = (x_2', y_2')$ are two-dimensional position vectors in the source plane, σ_0 is the beam size in the source plane, δ_{ij} are the r.m.s. source correlations, $\boldsymbol{\gamma}_i$ and $\boldsymbol{\gamma}_j$ are real-valued two-dimensional vectors describing shifts of the correlation maximum from the axis. In order to be a legitimate correlation function, W_{ij}^0

* Corresponding author. Fax: +86 571 87951328.
E-mail address: zhaodaomu@yahoo.com (D. Zhao).

http://dx.doi.org/10.1016/j.optcom.2014.05.053
0030-4018/

must have the integral representation of the form [6,9,10]

$$W^0_{ij}(\rho'_1,\rho'_2)=\int p_{ij}(\upsilon)H^*_i(\rho'_1,\upsilon)H_j(\rho'_2,\upsilon)d\upsilon, \tag{2}$$

where star denotes complex conjugate, $p_{ij}(\upsilon)$ is a nonnegative, Fourier-transformable function, and $H^*_i(\rho'_1,\upsilon)H_j(\rho'_2,\upsilon)$ is an arbitrary kernel. For (1) to satisfy the condition specified (2), we must have

$$p_{ij}(\upsilon)=\frac{B_{ij}k\delta^2_{ij}}{2\sqrt{\pi}}\exp\left[-\frac{1}{4}k^2\delta^4_{ij}\upsilon^2\right], \tag{3}$$

where $k=2\pi/\lambda$ is the wave number of light with λ being wavelength, and

$$H_i(\boldsymbol{\rho}',\upsilon)=A_i\exp\left(-\frac{\boldsymbol{\rho}'^2}{2\sigma_0^2}\right)\exp[-ik(\rho'-\boldsymbol{\gamma}_i)^2\upsilon], \tag{4}$$

$$H_j(\boldsymbol{\rho}',\upsilon)=A_j\exp\left(-\frac{\boldsymbol{\rho}'^2}{2\sigma_0^2}\right)\exp[-ik(\rho'-\boldsymbol{\gamma}_j)^2\upsilon]. \tag{5}$$

Let us consider an electromagnetic non-uniformly correlated beam propagating close to the z axis from the source plane (i.e.$z=0$) to the half-space $z\ge 0$ in an oceanic turbulence. The elements of the cross-spectral density of such a beam in the output plane $z>0$ can be obtained from the knowledge of the cross-spectral density in the source plane $z=0$ with the help of the extended Huygens–Fresnel integral [13], viz.,

$$W_{ij}(\boldsymbol{\rho_1},\boldsymbol{\rho_2},z;\omega)=\frac{k^2}{4\pi^2z^2}\iint d^2\boldsymbol{\rho}'_1\iint d^2\boldsymbol{\rho}'_2W^0_{ij}(\rho'_1,\rho'_2)\exp\left[-ik\frac{(\rho_1-\rho'_1)^2-(\rho_2-\rho'_2)^2}{2z}\right]$$
$$\times\exp\left\{-\frac{\pi^2k^2z}{3}[(\boldsymbol{\rho_1}-\boldsymbol{\rho_2})^2+(\boldsymbol{\rho_1}-\boldsymbol{\rho_2})(\boldsymbol{\rho}'_1-\boldsymbol{\rho}'_2)+(\boldsymbol{\rho}'_1-\boldsymbol{\rho}'_2)^2]\int\kappa^3\Phi_n(\kappa)d\kappa\right\}, \tag{6}$$

where $\Phi_n(\kappa)$ is the spatial power spectrum of the refractive index fluctuations of the oceanic water.

The model we used for the spatial power spectrum of the refractive index fluctuations of the oceanic water was obtained in [14,15], as a linearized polynomial of two variables: the temperature fluctuations and the salinity fluctuations. The model is valid under the assumption that the turbulence is isotropic and homogeneous and, hence, we require only specification of the one-dimensional spectrum, which has the form

$$\Phi_n(\kappa)=0.388\times10^{-8}\varepsilon^{-1/3}\kappa^{-11/3}[1+2.35(\kappa\eta)^{2/3}]f(\kappa,w,\chi_T), \tag{7}$$

here ε is the rate of dissipation of turbulent kinetic energy per unit mass of fluid which may vary in range from 10^{-4} to $10^{-10}m^2/s^3$, $\eta=10^{-3}m$ being the Kolmogorov microscale (inner scale), with

$$f(\kappa,w,\chi_T)=\frac{\chi_T}{w^2}(w^2e^{-A_T\delta}+e^{-A_S}\delta-2we^{-A_{TS}\delta}), \tag{8}$$

and χ_T being the rate of dissipation of mean-square temperature, $A_T=1.863\times10^{-2}$, and $\delta=8.284(\kappa\eta)^{4/3}+12.978(\kappa\eta)^2$, w being the relative strength of temperature and salinity fluctuations, where in the ocean water can vary in the interval $[-5;0]$, 0 value corresponding to the case when temperature-driven turbulence dominates, -5 value corresponding to the situation when salinity-driven turbulence prevails.

On substituting from Eq. (2) into (6), we obtain

$$W_{ij}(\boldsymbol{\rho_1},\boldsymbol{\rho_2},z;\omega)=\frac{k^2}{4\pi^2z^2}\int p_{ij}(\upsilon)H^*_i(\boldsymbol{\rho_1},\upsilon,z)H_j(\boldsymbol{\rho_2},\upsilon,z)d\upsilon, \tag{9}$$

where

$$H^*_i(\boldsymbol{\rho_1},\upsilon,z)H_j(\boldsymbol{\rho_2},\upsilon,z)=$$
$$\iint d^2\boldsymbol{\rho}'_1\iint d^2\boldsymbol{\rho}'_2H^*_i(\rho'_1,\upsilon)H_j(\rho'_2,\upsilon)\exp\left\{-\frac{ik[(\rho_1-\rho'_1)^2-(\rho_2-\rho'_2)^2]}{2z}\right\}$$
$$\times\exp\left\{-\frac{\pi^2k^2z}{3}[(\boldsymbol{\rho_1}-\boldsymbol{\rho_2})^2+(\boldsymbol{\rho_1}-\boldsymbol{\rho_2})(\boldsymbol{\rho}'_1-\boldsymbol{\rho}'_2)+(\boldsymbol{\rho}'_1-\boldsymbol{\rho}'_2)^2]\int\kappa^3\Phi_n(\kappa)d\kappa\right\}. \tag{10}$$

Now let $\boldsymbol{\rho_1}=\boldsymbol{\rho_2}=\boldsymbol{\rho}$, on introducing new variables $\mathbf{u}=(\boldsymbol{\rho}_1+\boldsymbol{\rho_2})/2$, $\mathbf{t}=\boldsymbol{\rho_1}-\boldsymbol{\rho_2}$ and substituting from Eqs. (4) and (5) into Eq. (10), after tedious calculation, Eq. (10) can be simplified as

$$H^*_i(\boldsymbol{\rho},\upsilon,z)H_j(\boldsymbol{\rho},\upsilon,z)=\frac{4\pi^2z^2\sigma_0^2A_iA_j}{k^2w^2(z,\upsilon)}\exp[ik(\boldsymbol{\gamma}_i^2-\boldsymbol{\gamma}_j^2)\upsilon-k^2\sigma_0^2\upsilon^2(\boldsymbol{\gamma}_i-\boldsymbol{\gamma}_j)^2]$$
$$\times\exp\left\{-\frac{[\boldsymbol{\rho}-(\boldsymbol{\gamma}_i+\boldsymbol{\gamma}_j)z\upsilon+ik\upsilon\sigma_0^2(1-2z\upsilon)(\boldsymbol{\gamma}_i-\boldsymbol{\gamma}_j)]^2}{w^2(z,\upsilon)}\right\}, \tag{11}$$

where

$$w^2(z,v)=\sigma_0^2(1-2z\upsilon)^2+\frac{z^2}{k^2\sigma_0^2}+\frac{4\pi^2z^3}{3}\int\kappa^3\Phi_n(\kappa)d\kappa. \tag{12}$$

The spectral density and the degree of polarization of the beam at the point $(\boldsymbol{\rho},z)$ in the propagation field are given by [1]

$$S(\boldsymbol{\rho},z)=\mathrm{Tr}\overleftrightarrow{W}(\boldsymbol{\rho},\boldsymbol{\rho},z), \tag{13}$$

$$P(\boldsymbol{\rho},z)=\sqrt{1-\frac{4\mathrm{Det}\overleftrightarrow{W}(\boldsymbol{\rho},\boldsymbol{\rho},z)}{[\mathrm{Tr}\overleftrightarrow{W}(\boldsymbol{\rho},\boldsymbol{\rho},z)]^2}}. \tag{14}$$

where Det and Tr stand for the determinant and trace of the matrix, respectively, the double arrow means $\overleftrightarrow{W}(\boldsymbol{\rho},\boldsymbol{\rho},z)$ is a matrix.

According to Eqs. (9)–(14), we can perform some numerical calculations of an electromagnetic non-uniformly correlated beam propagating through turbulent ocean which are shown in the next section.

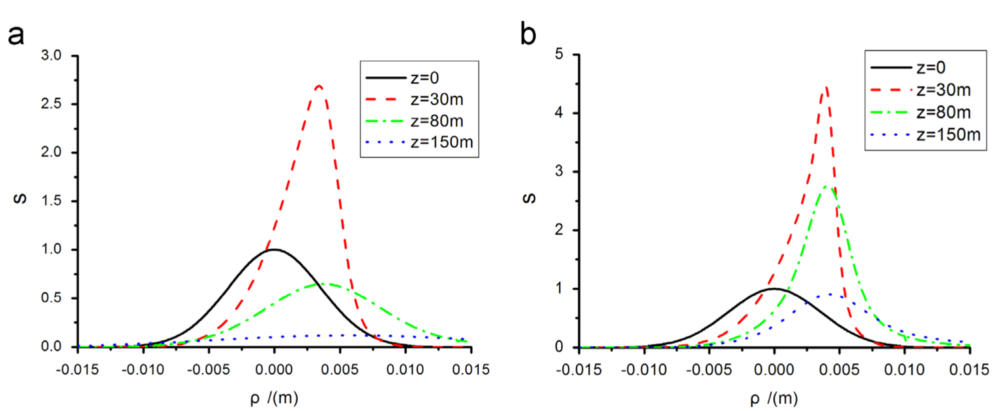

Fig. 1. The spectral intensity of an electromagnetic non-uniformly correlated beam passing through the oceanic turbulence at several propagation distances compared with that of such a beam propagating in free space. (a) Oceanic turbulence, (b) free space.