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Broadening of ultra-short pulses propagating through weak-to-strong oceanic turbulence

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ABSTRACT

In this paper, the new approach of correlation function of the complex phase perturbed by oceanic turbulence is shown. Based on this new approach, the general formula of the two-frequency mutual coherence function (MCF) of ultra-short pulses in oceanic turbulence is derived. Using a temporal moments approach and combining with this new formula for the MCF, the analytical expression for the pulse width is deduced. Besides, the quantity of Rytov variance σ_R^2 in oceanic turbulence is obtained, which is widely used as a measure of the strength of turbulence. In particular, the on-axis relative pulse broadening and turbulent effective coefficient of ultra-short pulses (i.e., femtosecond–picosecond regime) propagating through oceanic turbulence are investigated.

1. Introduction

One of the major advantages optical communication systems have over conventional radio frequency (RF) systems is their high antenna gain, which allows for higher data transmission rates. However, due to the shorter wavelengths used in optical communication systems, the optical pulse experiences degradation as it passes through atmospheric turbulence. These effects result in higher bit error rates (BER) and diminish the performance of an optical communication system [1]. Until now, some works have been carried out concerning the temporal broadening of pulse beam in atmospheric turbulence based on various turbulent models, such as, von Karman [2], modified von Karman [1], Kolmogorov [3], non-Kolmogorov [3] spectrum and etc. Recently, characterization of temporal pulse broadening for horizontal propagation in strong anisotropic atmospheric turbulence has already been studied [4]. Due to the complexity of oceanic turbulence, pulse beam propagating through oceanic turbulence is relatively less explored compared to that in atmospheric turbulence. The propagation of an ultra-short pulse of light through a linear and absorptive medium such as water, is of great fundamental importance for several reasons. One of the most important of which is that it may be possible to transmit information over much greater distances using ultra-short pulses compared to propagation distances achieved by using pulses with long time durations, including CW (continuous waves) [5]. The first measurements which claimed to observe optical precursors in deionized water were made by Choi and Österberg [6] where they found that the precursors were attenuated non-exponentially with distance. Hence, an understanding of these degrading effects is imperative in seawater. As we know, the two frequency mutual coherence function (MCF) benefits to deduce the temporal broadening. It is essential to obtain an analytical expression for the two-frequency MCF related to oceanic turbulence. In the past decades, many researchers have independently studied the two-frequency MCF [2–4,7–12]. Young has researched the two-frequency MCF and Gaussian pulse broadening in weak atmospheric turbulence based on weak fluctuation theory [12], while Young and co-workers have also studied the two-frequency MCF and the percent broadening of ultra-short optical pulses in moderate to strong atmospheric turbulence [2]. However, there has been no formulation concerning both the two-frequency MCF and the

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pulse width of optical pulses propagating through oceanic turbulence. Therefore, a deep investigation on this problem is imperative. In this paper, we generally formulate two-frequency MCF based on the extended Huygens–Fresnel principle which is valid in various strength of oceanic turbulence and the new approach of correlation function of the complex phase perturbed by oceanic turbulence. In arriving at the results, an analytical expression for the pulse width of optical pulses transmitting through oceanic turbulence is obtained. Based on the quantity of Rytov variance for a plane wave in oceanic turbulence, we also investigate the on-axis relative pulse broadening and turbulent effective coefficient with the propagation length, wavelength, initial pulse half-width and the initial beam radius from weak to strong turbulence.

2. Oceanic turbulence

Since the power spectrum of oceanic turbulence proposed by Nikishov et al. [13], there has been remarkable interest in the study of propagation characteristics using laser beams in seawater. The power spectrum of oceanic turbulence has been simplified for homogeneous and isotropic water media in Ref. [14]. According to Ref. [13], when the eddy thermal diffusivity and the diffusion of salt are assumed to be equal, the power spectrum for homogeneous and isotropic oceanic water is given by:

$$\Phi_n(\kappa) = 0.388\times10^{-8}\varepsilon^{-1/3}\kappa^{-11/3}[1+2.35(\kappa\eta)^{2/3}]\frac{\chi_T}{w^2}(w^2e^{-A_T\delta} + e^{-A_S\delta} - 2we^{-A_{TS}\delta}), \tag{1}$$

where ε is the rate of dissipation of kinetic energy per unit mass of fluid ranging from $10^{-1}\mathrm{m}^2/\mathrm{s}^3$ to $10^{-10}\mathrm{m}^2/\mathrm{s}^3$, χ_T is the rate of dissipation of mean-squared temperature and has the range $10^{-4}\mathrm{K}^2/\mathrm{s}$ to $10^{-10}\mathrm{K}^2/\mathrm{s}$, w defines the ratio of temperature and salinity contributions to the refractive index spectrum, which varies in the interval $[-5;\ 0]$, with -5 and 0 corresponding to dominating temperature-induced and salinity-induced optical turbulence, respectively [15]. Additionally, η is the Kolmogorov micro scale (inner scale), and $A_T = 1.863\times10^{-2}$, $A_S = 1.9\times10^{-4}$, $A_{TS} = 9.41\times10^{-3}$, $\delta = 8.284(\kappa\eta)^{4/3} + 12.978(\kappa\eta)^2$ [15].

3. Two frequency MCF

3.1. Formulae

Let us consider a temporal Gaussian input pulse applied at the transmitter and propagated through the oceanic turbulence to a receiver located at distance L from the transmitter, and assume the input pulse is the modulated signal with the carrier frequency ω_0 that can be represented by [16].

$$p_i(t) = v_i(t)\exp(-\mathrm{i}\omega_0 t), \tag{2}$$

where the amplitude $v_i(t) = \exp(-t^2/T_0)$ represents the pulse shape, and T_0 is the initial pulse half-width. Here, we introduce the Fourier transform of the input pulse by the expression [16].

$$\begin{aligned}P_i(\omega) &= \int_{-\infty}^{\infty} p_i(t)\exp(\mathrm{i}\omega t)dt\\ &= \int_{-\infty}^{\infty} v_i(t)\exp(-\mathrm{i}\omega_0 t)\exp(\mathrm{i}\omega t)dt\\ &= V_i(\omega-\omega_0),\end{aligned} \tag{3}$$

where $V_i(\omega)$ is the Fourier transform of the amplitude $v_i(t)$. Similarly, $p_o(t) = v_o(t)\exp(-\mathrm{i}\omega_0 t)$ and $P_o(\omega) = V_o(\omega-\omega_0)$ represent the output pulse at the receiver and the Fourier transform of output, respectively.

The single-point, two-frequency correlation function of the complex envelop of the output pulse is defined by the ensemble average [12].

$$B_v(\mathbf{r},\mathbf{r},L;\,t_1,t_2) = \frac{1}{(2\pi)^2}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} V_i(\omega_1)V_i^*(\omega_2)\Gamma_2(\mathbf{r},\mathbf{r},L;\,\omega_1,\omega_2)\exp(-\mathrm{i}\omega_1 t_1 + \mathrm{i}\omega_2 t_2)\mathrm{d}\omega_1\mathrm{d}\omega_2, \tag{4}$$

where the Fourier transform of input Gaussian pulse is

$$V_i(\omega) = \sqrt{\pi}T_0\exp\left(-\frac{1}{4}\omega^2T_0^2\right), \tag{5}$$

and the two-frequency MCF is

$$\Gamma_2(\mathbf{r},\mathbf{r},L;\,\omega_1,\omega_2) = \langle U(\mathbf{r},L;\,\omega_1+\omega_0)U^*(\mathbf{r},L;\,\omega_2+\omega_0)\rangle. \tag{6}$$

Here $U(\bullet)$ is the complex amplitude of the wave in oceanic turbulence, $\mathbf{r}$ is the position vector in the transverse plane at propagation distance L from the source.

In particular, using the extended Huygens–Fresnel principle, $U(\bullet)$ in Eq. (6) can be written by

$$U(\mathbf{r},L;\,\omega) = -\frac{\mathrm{i}\omega}{2\pi Lc}\exp\left(\frac{\mathrm{i}L\omega}{c}\right)\int_{-\infty}^{\infty}\mathrm{d}^2\mathbf{r}_1\, U_0(\mathbf{r}_1,0;\,\omega)\exp\left[\frac{\mathrm{i}\omega|\mathbf{r}_1-\mathbf{r}|^2}{2Lc} + \psi(\mathbf{r}_1,\mathbf{r},L;\,\omega)\right], \tag{7}$$

where c is the speed of light, $U_0(\mathbf{r},0;\,\omega) = \exp[-\mathbf{r}^2/W_0^2]$ denotes the optical wave field in the source plane, $\psi(\bullet)$represents the random part of the complex phase of a spherical wave due to the turbulence [16].

On substituting Eq. (7) into Eq. (6), we obtain the expression of MCF in oceanic turbulence, i.e.,

$$\begin{aligned}\Gamma_2(\mathbf{r},\mathbf{r},L;\,\omega_1,\omega_2) = &\frac{\omega_1\omega_2}{4\pi^2L^2c^2}\exp\left[\frac{\mathrm{i}L(\omega_1-\omega_2)}{c}\right]\\ &\int_{-\infty}^{\infty}\mathrm{d}^2\mathbf{r}_1\int_{-\infty}^{\infty}\mathrm{d}^2\mathbf{r}_2 U_0(\mathbf{r}_1,0;\,\omega_1)U_0(\mathbf{r}_2,0;\,\omega_2)\\ &\times\exp\left[\frac{\mathrm{i}\omega|\mathbf{r}_1-\mathbf{r}|^2}{2Lc} - \frac{\mathrm{i}\omega|\mathbf{r}_2-\mathbf{r}|^2}{2Lc}\right]\\ &\langle\exp[\psi(\mathbf{r}_1,\mathbf{r},L;\,\omega_1) + \psi^*(\mathbf{r}_2,\mathbf{r},L;\,\omega_2)]\rangle_m,\end{aligned} \tag{8}$$

where $<\bullet>_m$ denotes average over the ensemble of the turbulent medium [16], $\mathbf{r}_m$ (m=1, 2) is a position vector of a point in the source plane, and the correlation function of the complex phase perturbed by oceanic turbulence.

$$\begin{aligned}&\langle\exp[\psi(\mathbf{r}_1,\mathbf{r},L;\,\omega_1) + \psi^*(\mathbf{r}_2,\mathbf{r},L;\,\omega_2)]\rangle_m\\ &= \left(\frac{2\pi}{c}\right)^2 L\int_0^{\infty}\mathrm{d}\kappa\kappa\Phi_n(\kappa)\int_0^1\mathrm{d}\xi\left[\omega_1^2+\omega_2^2-2\omega_1\omega_2 J_0(\kappa\xi|\mathbf{r}_2-\mathbf{r}_1|)\right],\end{aligned} \tag{9}$$

where $J_0(\bullet)$ is the Bessel function of the first kind and order zero. κ is the magnitude of spatial wavenumber.

In this paper, the quadratic approximation in Rytov's phase structure function (i.e., $\langle\exp[\psi(\mathbf{r}_1,\mathbf{r},L;\,\omega_1) + \psi^*(\mathbf{r}_2,\mathbf{r},L;\,\omega_2)]\rangle_m \cong \exp[-(\mathbf{r}_1-\mathbf{r}_2)^2/\rho_0^2]$) [17–22] and second order approximation (i.e., $J_0(\kappa\xi|\mathbf{r}_2-\mathbf{r}_1|) \approx 1-\kappa^2\xi^2|\mathbf{r}_2-\mathbf{r}_1|^2/4$) [23–25] have not been used in Eq. (9). Replacing $J_0(\bullet)$ in Eq. (9) by $J_0(\kappa\xi|\mathbf{r}_2-\mathbf{r}_1|) = \sum_{n=0}^{\infty}\frac{(-1)^n(\kappa\xi|\mathbf{r}_2-\mathbf{r}_1|/2)^{2n}}{n!\Gamma(n+1)}$ [26], and after some mathematical manipulations, it follows that