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Polarization of quantization Gaussian Schell-beams through anisotropic non-Kolmogorov turbulence of marine-atmosphere

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ABSTRACT

Polarization and spatial coherence of quantization Gaussian Schell-beams propagating through the anisotropic non-Kolmogorov turbulence of marine-atmosphere channel are studied based on the quantized Huygens–Fresnel principle and the degree of quantum polarization. The spatial coherence length and the polarization degree of linearly polarization quantization Gaussian Schell-beams are developed. The effects of outer scale on the lateral coherence length are not obvious as same as the effects of wavelength on the degree of polarization. The degree of polarization decreases as the source transverse coherent width, anisotropic factor, the number of received photons, spectral index, the inner scale of turbulent eddies and source transverse radius decrease or generalized refractive-index structure parameter increases. The refractive-index structure parameter, spectral index and inner scale have also effect on the changes of lateral coherence length. Those results can be used to improve the performance of a polarization-encoded quantum communication system.

1. Introduction

Polarization is one of the most important properties of light with a large number of applications, both in the quantum and classical domains. The polarization fluctuations of classical coherent and incoherent light in weak fluctuation turbulent atmosphere paths have been investigated and those results have shown that the fluctuations can be negligible [1–4]. It is shown that the degree of polarization of a partially coherent light beam generally changes on propagation in free space [5] and atmospheric turbulence [6,7], and the quantum degree of polarization of quantization polarization light is a decrease function of the atmospheric turbulence strength and the propagation distance [8].

The regularities of atmospheric turbulence have been widely described by the Kolmogorov spectrum model [9]. Nevertheless, several experimental results have shown that atmospheric turbulence in the near ground layer, upper troposphere and stratosphere deviates from predictions of the Kolmogorov spectrum model [10,11], which has prompted research on a more generalized spectrum model and a non-Kolmogorov power spectrum model have been put forward. The non-Kolmogorov power spectrum model has a generalized power law exponent that deviates from 11/3 of the Kolmogorov spectrum model. Furthermore, in the free atmosphere above the atmospheric boundary layer, the effect of terrene surface friction on the air motion cannot be neglected, and the optical turbulence can be anisotropic (mostly at large scales). The vertical extension of the outer scale eddies is confined to a few meters, while the horizontal size of the seed dies spans a distance typically tens of meters across, or, in some cases, kilometers across [12,13]. In this case, the isotropic power spectrum of the fluctuating refractive index does not adequately describe the turbulent behavior. Lately some authors have focused on both experimental and theoretical investigations of a power spectrum model that includes both anisotropic and non-Kolmogorov turbulence [9,14–18]. Robert et al. shown the evidence of anisotropy in the stratosphere, and the validity of the spectrum was varied by balloon-borne experiments [14] based on the power spectrum with anisotropic and isotropic components. Toselli et al. proposed power spectrum models of non-Kolmogorov turbulence to theoretically investigate the effect of anisotropy [15] utilizing the power spectrum reported by Kon [16] and Gurvich et al. [17] analyzed the impact of the power-law variations on the long-term beam spread and scintillation index of the plane wave and spherical wave for several anisotropic coefficient values [18] in the weak turbulence condition. The effect of anisotropic Kolmogorov

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turbulence on the log-amplitude correlation function for plane wave and spherical wave fields is investigated in [19,20]. A theoretical consequence of the long-exposure turbulence modulation transfer function for both plane and spherical waves propagating through anisotropic non-Kolmogorov turbulence is reported by Ciu et al. [21]. Yao et al. [22] investigated the effects of anisotropic turbulence on the propagation of polarization and the states of coherence for electromagnetic Gaussian Schell-mode (GSM) beams. Kotiang and Choi [9] derived new analytic expressions for the atmospheric-induced frequency spread of optical plane and spherical waves propagating in a horizontal path and experiencing anisotropic non-Kolmogorov turbulence. The effects of anisotropic weak turbulence on the OOK FSO link performance by scintillations, probability of fade, SNR, and BERs are examined in [23] and the variance of angle of arrival fluctuations based on the Rytov approximation theory are derived for plane and spherical waves propagation through weak anisotropic non-Kolmogorov turbulence atmosphere [24]. The closed-form expression for the mean square temporal width of Gaussian-beam-wave pulses passing horizontally through strong anisotropic atmospheric turbulence is developed based on the extended Huygens–Fresnel principle [25].

As the turbulence in the near hyposurface is aerosol turbulence, the passive scalar turbulence behavior above the hyposurface boundary deviates from predictions of the Kolmogorov spectrum model [26]; it should be described by the Kolmogorov spectrum model. Also, as the effects of hyposurface on turbulent formation and evolution are similar to terrene surface. The influence of hyposurface friction on the air motion for the free atmosphere above the marine-atmospheric boundary layer need consider. It may be confirmed that the optical turbulence can be anisotropic and non-Kolmogorov. But, to the best of our knowledge, there is no report on the polarization fluctuations of GSM photon beams propagating in anisotropic non-Kolmogorov turbulence of marine-atmosphere channel.

Recently, Muschinski et al. [27] investigated Hill's model by comparing scalar spectra predicted by Hill's model with scalar spectra estimated from direct numerical simulation output data, it is shown that the agreement between the direct numerical simulation results and the predictions of Hill's model is very good, in addition to universal dimensionless constant of Hill's model a=0.072 should replace by a=0.065. To consistent with first-principle fluid Mechanics, Muschinski [28] indicated Andrews's model meet the ad hoc approximations to numerical solutions of Hill's “Model 4” [29] for the Prandtl number $Pr = 0.72$ and the Obukhov–Corrsin coefficient of the shell-averaged spectrum $\beta = 0.72$.

The aim of this paper is to develop a theoretical model for the polarization fluctuation of GSM beams in marine-atmosphere channel with anisotropic non-Kolmogorov turbulence spectrum in the constraint of Prandtl number $Pr = 0.72$ and the Obukhov–Corrsin coefficient of the shell-averaged spectrum $\beta = 0.72$. In sections 2 and 3 the model for the effects of the sources transverse size and the transverse coherent width of sources on the degree of polarization of GSM beams are investigated in detail. Numerical results and discussions are given in section 4. Conclusions are presented in section 5.

2. Anisotropic non-Kolmogorov power spectrum of marine- and terrene-atmosphere

For this paper we employ the anisotropic non-Kolmogorov power spectrum reported in [18,19] for marine- or terrene-atmosphere by using a generalized von Karman model [18,20] and marine- or terrene-atmosphere model [30,31].

The discussions of [28] shown that the power spectrum of refractive-index fluctuation of Kolmogorov turbulence in ad hoc approximations to numerical solutions of Hill's “Model 4” for the Prandtl number $Pr = 0.72$ and the Obukhov–Corrsin coefficient of the shell-averaged spectrum $\beta = 0.72$. As the Prandtl number $Pr = 0.72$ can be considered a universal constant in present context [32], to make the power spectrum of refractive-index fluctuations of non-Kolmogorov turbulence meet the ad hoc approximations to numerical solutions of Hill's “Model 4” [27,29] in the Prandtl number $Pr = 0.72$ and the Obukhov–Corrsin coefficient of the shell-averaged spectrum $\beta = 0.72$, we discuss the issue of quantization GSM beams in the narrow range of the spectral index of non-Kolmogorov turbulence $3.47 < \alpha < 3.87$. In the narrow range of the spectral index of non-Kolmogorov turbulence $3.67(1-0.05) < \alpha < 3.67(1+0.05)$, Hill's “Model 4” of Kolmogorov turbulence can approximatively extended to non-Kolmogorov turbulence and is constituted by a homogeneous, ordinary, second-order differential equation [27] for $E(x\kappa_*)$:

$$\frac{d}{dx}\left\{x^{14/3}(x^{2b}+1)^{-1/3b}\frac{d}{dx}[x^{-2}E(x\kappa_*)]\right\} = \frac{22\beta}{3\text{Pr}}\tilde{a}^{4/3}x^2E(x\kappa_*) \tag{1}$$

where $x = \kappa/\kappa_*$ is the dimensionless wavenumber being scaled by the wavenumber κ_*, κ is the wavenumber being the magnitude of the wave vector $\boldsymbol{\kappa}$, $\tilde{a} = \kappa_*\eta$ is a universal, dimensionless constant, $\eta = \nu^{3/4}/\varepsilon^{1/4}$ is the Kolmogorov length with ν as the kinematic viscosity of the medium, ε is the dissipation rate of turbulent kinetic energy per unit mass, the Prandtl number $Pr = \nu/\alpha_t$ is the ratio of ν and the thermal diffusivity α_t, $E(x\kappa_*) = 4\pi\phi(\kappa)\kappa^2$ and the temperature spectrum of non-Kolmogorov turbulence [33]

$$\phi(\kappa) = A(\alpha)C_T^2\kappa^{-\alpha}g\left(\kappa\eta, Pr\right) \tag{2}$$

where $A(\alpha) = \frac{\Gamma(\alpha-2)}{4\pi^2}\sin[\pi(\alpha-3)/2]$, α is the spectral index of non-Kolmogorov turbulence, $C_T{}^2$ is the temperature structure parameter, $\Gamma(\alpha)$ is the Gamma function, $g(\kappa\eta, Pr)$ is a universal, dimensionless function, which goes to 1 for $\kappa\eta \ll 1$ and to 0 for $\kappa\eta \gg 1$. In the optical-turbulence community, it is customary to express the similarity function $g(\kappa\eta, Pr)$ in terms of $\kappa l_0 = y$, l_0 is the inner scale of turbulence, i.e. $g(\kappa\eta, Pr) = h(y)$. Further, by $x = \frac{1}{\tilde{a}}\frac{\eta}{l_0}y$ [27], we can rewrite the $h(y)$ in $f(x) = h(y)$.

Inserting the alternative similarity function

$$g\left(\kappa\eta, Pr\right) = f(x) \tag{3}$$

Rewriting Eq. (1) in terms of Eq. (2) gives

$$\frac{d}{dx}\left\{(x^{2b}+1)^{-1/3b}\left[-\alpha f(x) + x\frac{df(x)}{dx}\right]\right\} = \frac{22}{3}cx^{(4-\alpha)}f(x) \tag{4}$$

where $c = \beta\tilde{a}/\text{Pr}$.

Supposing the relationship of $\frac{l_0}{\eta} = [\frac{27\Gamma(1/3)}{5}\frac{\beta}{Pr}]^{3/4}$ [27] is approximate available in the narrow range of the spectral index of non-Kolmogorov turbulence $3.47 < \alpha < 3.87$, we obtain

$$h(y) \approx f\left[\frac{1}{\tilde{a}}\left(\left(\frac{27\Gamma(1/3)}{5}\frac{\beta}{Pr}\right)^{3/4}\right)y\right] \tag{5}$$

As Eq. (5) approximately equal Eq. (23) in Ref. [27], it can be inferred that the agreement between the direct numerical simulation results and the predictions of Hill's model of non-Kolmogorov turbulence also is very good.

Furthermore, according to the discussion in [15], we apply the approximation of the anisotropy existing along the direction of