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Analysis to beam quality of partially coherent flat-topped vortex beams propagating through atmospheric turbulence

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ABSTRACT

Based on the extended Huygens-Fresnel principle and the second-order moments of the Wigner distribution function (WDF), the analytical formula for the propagation factor (M^2-factor) of partially coherent flat-topped vortex beams propagating through atmospheric turbulence are derived, and used to analyze beam quality of partially coherent flat-topped vortex beams propagating through atmospheric turbulence. It is shown that the smaller the structure constant and the correlation length are, the bigger the inner scale of turbulence, the beam order and the wave length are, the smaller the normalized propagation factor is, and the better the beam quality of partially coherent flat-topped vortex beams in atmospheric turbulence is. The partially coherent flat-topped vortex beams is less affected by atmospheric turbulence than that of partially coherent flat-topped beams under certain condition, and will be useful in atmospheric optical communications.

1. Introduction

Vortex beams consist of spiralling wavefronts that give rise to angular momentum around the propagation direction, which are widely used in applications such as optical tweezers [1–3], optical microscopy [4], quantum state manipulation [5,6], optical communications [7–10], astronomical planet-finding [11], astrophysics [12,13] and so on [14–16]. There has been much interest in the propagation characteristics of vortex beams through free space and atmospheric turbulence from both theoretical and applicative aspects [17–21]. The generation and evolution of partially coherent vortex beams in free space have been researched in literatures [17–19]. The propagation of vortex beams through weak-to-strong atmospheric turbulence was studied using multiple phase screen simulations by Gbur et al. who found that with decreasing structure constant the standard deviation of the topological charge of such a beam decreases and the appreciable distance increases, and the topological charge could be used as information carrier in optical communications [20]. The trajectory of an optical vortex in atmospheric turbulence using numerical simulations has been investigated by Dipankar et al. in 2009 [21]. Gu and Gbur have suggested a possible method for measuring atmospheric turbulence strength by vortex beam [22]. More recently, the classification of coherent vortices creation and distance of topological charge conservation were dealt with numerically by Li et al., which showed that the coherent vortices are grouped into three classes according to the creation [23,24]. The average intensity, the degree of the polarization, the irradiance pattern and scintillation index of vortex beam in atmospheric turbulence have been researched in [25–27]. Up to now, only few papers were devoted to the beam quality

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of vortex beams in atmospheric turbulence [28,29]. The propagation factor of partially coherent Laguerre–Gaussian vortex beams has been investigated through turbulent atmosphere by using the second-order moments of the Wigner distribution function [28]. The propagation factor of Bessel-Gaussian beams carrying optical vortices through atmospheric turbulence has been reported, which implies that Bessel-Gaussian beams with vortex have the stronger ability over Bessel-Gaussian beams without vortex in resisting the destructive effect of atmospheric turbulence [29]. In this paper, taking the partially coherent flat-topped vortex beams as an example of partially coherent vortex beams, the influence of atmospheric turbulence on the beam quality of vortex beams will be studied by using the propagation factor.

2. Theoretical model

The field of an optical vortex beam at the source plane $z = 0$ reads as [30]

$$U(\boldsymbol{s}, z=0) = u(\boldsymbol{s})[s_x + i\mathrm{sgn}(m)s_y]^{|m|} \quad ,(1)$$

where $\boldsymbol{s} \equiv (s_x, s_y)$ is the two-dimensional position vector at the $z = 0$ plane. $u(\boldsymbol{s})$ denotes the profile of the background beam envelope, sgn(·) specifies the sign function defined as

$$sgn(m) = \begin{cases} 1, & m > 0 \\ 0, & m = 0 \\ -1, & m < 0 \end{cases} \quad ,(2)$$

and m is the topological charge. In the following, we restricted ourselves to the case of $m = \pm 1$.

Assume that $u(\boldsymbol{s})$ takes a flat-topped form, i.e., [31]

$$U(\boldsymbol{s}, z=0) = \sum_{n=1}^{N} \frac{(-1)^{n-1}}{N} \binom{N}{n} \exp[-\frac{n(s_x^2 + s_y^2)}{4w_0^2}][s_x + i\mathrm{sgn}(m)s_y]^{|m|} \quad ,(3)$$

where N denotes the beam order and w_0 is the waist in Gaussian part.

Introducing a Schell model correlator [32], the cross-spectral density of partially coherent flat-topped vortex beams at $z = 0$ plane can be written as

$$\begin{aligned} &W^{(0)}(\boldsymbol{s}_1, \boldsymbol{s}_2, z=0) = [s_{1x}s_{2x} + s_{1y}s_{2y} + i\mathrm{sgn}(m)s_{1x}s_{2y} - i\mathrm{sgn}(m)s_{2x}s_{1y}]^{|m|} \times \\ &\sum_{n_1=1}^{N}\sum_{n_2=1}^{N} \frac{(-1)^{n_1+n_2-1}}{N^4} \binom{N}{n_1} \binom{N}{n_2} \exp(-\frac{n_1\boldsymbol{s}_1^2 + n_2\boldsymbol{s}_2^2}{4w_0^2}) \\ &\times \exp[-\frac{(n_1+n_2)(\boldsymbol{s}_1 - \boldsymbol{s}_2)^2}{4\sigma_0^2}] \end{aligned} \quad (4)$$

where σ_0 denotes the correlation length, $\boldsymbol{s}_1$,$\boldsymbol{s}_2$ specifies the two-dimensional vector in the plane $z = 0$, respectively. For $m = 0$ Eq. (4) reduces to the cross-spectral density function of partially coherent flat-topped beams at the z = 0.

Based on the extended Huygens-Fresnel principle [33], the cross-spectral density function of partially coherent flat-topped vortex beams in atmospheric turbulence is written as

$$\begin{aligned} &\mathrm{W}(\boldsymbol{\rho}, \boldsymbol{\rho}_d, z) = \left(\frac{k}{2\pi z}\right)^2 \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} W^{(0)}(\boldsymbol{s}, \boldsymbol{s}_d, z=0) \\ &\times \exp\left[\frac{ik}{z}(\boldsymbol{\rho} - \boldsymbol{s})(\boldsymbol{\rho}_d - \boldsymbol{s}_d) - H(\boldsymbol{\rho}_d, \boldsymbol{s}_d, z)\right] d^2s d^2s_d \end{aligned} \quad ,(5)$$

where $k = 2p/l$ is the wave number with l being the wavelength. In the above Eq. (5), we have used the following sum and difference vector notation

$$\boldsymbol{s} = (\boldsymbol{s}_1 + \boldsymbol{s}_2)/2,\ \boldsymbol{s}_d = \boldsymbol{s}_1 - \boldsymbol{s}_2,\ \boldsymbol{\rho} = (\boldsymbol{\rho}_1 + \boldsymbol{\rho}_2)/2,\ \boldsymbol{\rho}_d = \boldsymbol{\rho}_1 - \boldsymbol{\rho}_2 \quad .(6)$$

where $\boldsymbol{\rho}_1$, $\boldsymbol{\rho}_2$ are two arbitrary points in the receiver plane, perpendicular to the direction of the propagation of the beam. $H(\boldsymbol{r}_d, \boldsymbol{s}_d, z)$ represents the effect of the turbulence defined as [34–36]

$$H(\rho_d, s_d, z) = 4\pi^2 k^2 z \int_0^1 d\xi \int_0^{\infty} [1 - J_0(\kappa|s_d\xi + (1-\xi)\rho_d|)]\Phi_n(\kappa)\kappa d\kappa \quad ,(7)$$

where $J_0(\cdot)$ is the Bessel function of the first kind and zero order, $\Phi_n(\kappa)$ is the spatial power spectrum of the refractive index fluctuations of the atmospheric turbulence.