Physics Letters A 378 (2014) 2729–2735

Contents lists available at ScienceDirect

Physics Letters A

www.elsevier.com/locate/pla

Effect of spherical aberration on scintillations of Gaussian beams in atmospheric turbulence

Xiaoling Ji *, Jinping Deng

Department of Physics, Sichuan Normal University, Chengdu 610066, China

ARTICLE INFO

Article history:
Received 9 April 2014
Received in revised form 23 June 2014
Accepted 22 July 2014
Available online 25 July 2014
Communicated by V.A. Markel

Keywords:
Scintillation index
Spherical aberration
Atmospheric turbulence

ABSTRACT

The effect of spherical aberration on scintillations of Gaussian beams in weak, moderate and strong turbulence is studied using numerical simulation method. It is found that the effect of the negative spherical aberration on the on-axis scintillation index is quite different from that of the positive spherical aberration. In weak turbulence, the positive spherical aberration results in a decrease of the on-axis scintillation index on propagation, but the negative spherical aberration results in an increase of the on-axis scintillation index when the propagation distance is not large. In particular, in weak turbulence the negative spherical aberration may cause peaks of the on-axis scintillation index, and the peaks disappear in moderate and strong turbulence, which is explained in physics. The strong turbulence leads to less discrepancy among scintillations of Gaussian beams with and without spherical aberration.

1. Introduction

Scintillations are intensity fluctuations caused by the random phase modulation when an optical beam propagates through atmospheric turbulence [1,2]. Scintillations of an optical beam degrade ratio of signal to noise and may increase bit error rate. The scintillation is detrimental to the performance of free-space optical communication systems, remote sensing systems and imaging systems, etc. [1,2].

In recent years, some studies were carried out concerning scintillation reduction. Cai et al. pointed that under certain conditions, the on-axis scintillation index of elliptical Gaussian beams may be smaller than that of circular Gaussian beams in weak turbulence [3]. Qian et al. showed that a decrease of the degree of source coherence may cause scintillations to be suppressed significantly [4]. Gu et al. indicated that an appropriately chosen coherent beam of non-uniform polarization also has smaller scintillation index than a beam of uniform polarization [5]. Gu et al. showed that the scintillation of an Airy beam array is significantly reduced and close to the theoretical minimum [6]. Polynkin et al. stated that scintillations can be effectively suppressed by adjusting the spatial separation of beam arrays [7]. Tellez et al. proposed one method to reduce scintillations at the receiver plane involving the use of multiple channels propagating through independent paths [8]. Liu et al. showed that the on-axis scintillation index can be effectively reduced by an elliptical vortex beam if crucial parameters are properly chosen [9]. Very recently, Gu et al. found that a non-uniformly correlated partially coherent beam with certain parameters can have lower scintillation and higher average transferred intensity than a coherent Gaussian beam over certain distance on propagation through atmospheric turbulence [10]. Liu et al. showed the experimental demonstration of vortex phase-induced reduction in scintillation of a partially coherent beam [11]. Wang et al. found experimentally that a partially coherent radially polarized beam has advantage over a linearly polarized partially coherent beam for reducing turbulence-induced scintillation [12].

Laser beams are always with spherical aberration due to thermal effects in generation process [13,14]. Spherical aberration will also be caused by a non-ideal optical element when an optical beam propagates through it [15,16]. It is important to study the effect of spherical aberration on beam quality and propagation properties. Pu et al. examined the reshaping Gaussian Schell-model beams to uniform profiles by lenses with spherical aberration [17]. We investigated the focal shift in Gaussian beams focused by a spherically aberrated bifocal lens [18], and studied the changes in the kurtosis parameter of super-Gaussian beams passing through a spherically aberrated lens [19]. Alkelly studied the spot size and radial intensity distribution of focused Gaussian beams in spherical and non-spherical aberration lenses [20]. Until now, very a few of papers studied the propagation of laser beams with spherical aberration in turbulence. Wang et al. studied the average intensity and beam size of partially coherent aberrated beams propagating in turbulence [21].

* Corresponding author.
E-mail address: jiXL100@163.com (X. Ji).

http://dx.doi.org/10.1016/j.physleta.2014.07.032
0375-9601/

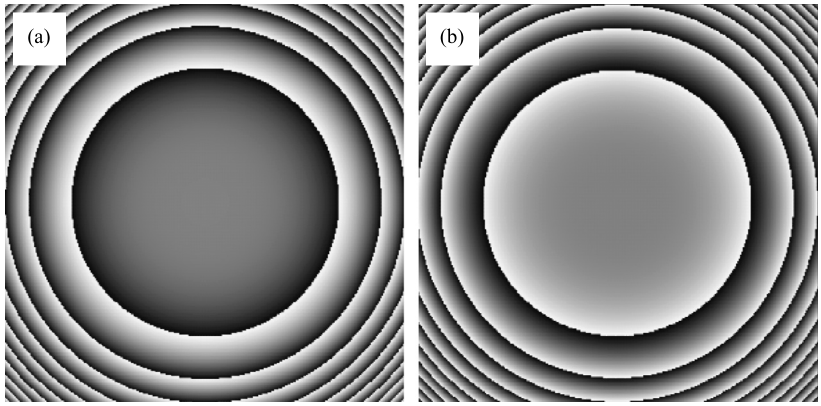

Fig. 1. Phase of spherical aberration at source plane $z=0$. (a) $kC_4=1$, (b) $kC_4=-1$.

Numerical simulation is an important method to study propagation of laser beams through a turbulent atmosphere [22]. Recently, Banakh et al. presented an algorithm for simulating laser beam propagation in a turbulent atmosphere under conditions of thermal blooming for the case where the beam is formed by a multielement aperture [23], and shown effectiveness of the subharmonic method in problems of computer simulation of laser beam propagation in a turbulent atmosphere [24].

In this letter, the effect of spherical aberration on scintillations in weak, moderate and strong turbulence is investigated in detail by numerical simulation method. The results obtained in this letter will be very useful in some applications such as free-space optical communications, remote sensing, tracking, and imaging.

2. Theoretical model

Scalar wave equation in parabolic approximation is expressed as [22]

$$2ik\frac{\partial U}{\partial z}=\nabla_\perp^2 U+k^2\left(n^2-1\right)U, \tag{1}$$

where $\nabla_\perp^2=\partial^2/\partial x^2+\partial^2/\partial y^2$ is the transverse Laplace operator, U is a slowly varying field amplitude, n is the refractive index, and $k=2\pi/\lambda$ is the wave-number (λ is the wave length). The intensity I is given in terms of U, i.e., $I=|U|^2$.

Let $U(r,z_j)$ be the complete solution to Eq. (1) at z_j plane, the solution to Eq. (1) at $z_{j+1}=z_j+\Delta z$ plane can obtained using the second-order accuracy of the symmetrically split operator (see Appendix A in Ref. [22]), i.e.,

$$U(r,z_{j+1})=\exp\left(-\frac{\mathrm{i}}{4k}\Delta z\nabla_\perp^2\right)\times\exp(-\mathrm{i}s)\exp\left(-\frac{\mathrm{i}}{4k}\Delta z\nabla_\perp^2\right)U(r,z_j), \tag{2}$$

where $s=(k/2)\int_{z_j}^{z_{j+1}}\delta\varepsilon\,\mathrm{d}z$ is the phase modulation due to turbulence, $\delta\varepsilon=n^2-1$ is the hydrodynamically induced change in permittivity.

Eq. (2) indicates that, propagating the field over a distance Δz consists of a free-space propagation of the field over a distance $\Delta z/2$, an incrementing of the phase due to turbulence-induced changes, and the followed by a free-space propagation of the resulting field over a distance $\Delta z/2$. The symmetrization in form exhibited in (2) is actually more important, i.e., since after the first upgrading of the phase the half steps of propagation can be combined into single propagation steps according to the rule

$$\exp\left(-\frac{\mathrm{i}}{4k}\Delta z\nabla_\perp^2\right)\exp\left(-\frac{\mathrm{i}}{4k}\Delta z\nabla_\perp^2\right)=\exp\left(-\frac{\mathrm{i}}{2k}\Delta z\nabla_\perp^2\right). \tag{3}$$

In this letter, the numerical evaluation of Eq. (2) is done with the fast Fourier transform (FFT) algorithm. The treatment of turbulence is based on the generation of random phase screens at each calculation step along the propagation path. We make the usual assumption of a Von Karman spectrum, i.e., the spatial power spectrum of the refractive-index fluctuations reads as [1]

$$\Phi_n(\kappa)=0.033C_n^2\left(\kappa_0^2+\kappa_x^2+\kappa_y^2+\kappa_z^2\right)^{-11/6}, \tag{4}$$

where C_n^2 is the index structure constant, and $\kappa_0=2\pi/L_0$, L_0 is the outer scale length.

The field of Gaussian beams with spherical aberration at the source plane ($z=0$) can be expressed as

$$U(x,y,z=0)=\exp\left(-\frac{x^2+y^2}{w_0^2}\right)\exp\left[-\frac{\mathrm{i}kC_4(x^2+y^2)^2}{w_0^4}\right], \tag{5}$$

where w_0 is the waist width of the Gaussian beams, kC_4 denotes the spherical aberration coefficient [15,16]. $C_4>0$ represents the positive spherical aberration, while $C_4<0$ represents the negative spherical aberration. Eq. (5) reduces to the field of Gaussian beams without spherical aberration when $C_4=0$. The phase of spherical aberration at source plane $z=0$ is shown in Fig. 1. From Fig. 1 it can be seen that the phase for the negative spherical aberration case (e.g., $kC_4=-1$) is quite different from that for the positive spherical aberration case (e.g., $kC_4=1$), which results in different effects on scintillations.

The scintillation index is defined as [1]

$$\sigma_I^2=\frac{\langle I^2\rangle-\langle I\rangle^2}{\langle I\rangle^2}, \tag{6}$$

where the angular brackets stand for the average of the realizations of turbulence.

In this letter, to calculate the scintillation index we design the 4D computer code of the time-dependent propagation of optical beams through atmospheric turbulence by using the discrete Fourier transform (DFT) method and the multi-phase screen method. It is noted that in the numerical simulation, the subharmonic method isn't applied in this letter.

3. Numerical calculation results and analysis

In this section, the on-axis scintillation index of Gaussian beams with spherical aberration is calculated using the 4D computer code of optical beams propagating through atmospheric turbulence. In the 4D computer code, 20 random phase screens are used. To calculate the scintillation index σ_I^2, 400 propagation realizations are calculated to obtain the average of $\langle I\rangle$ and $\langle I^2\rangle$ in this letter. In the numerical examples, calculation parameters are taken as