ARTICLE IN PRESS

Optics Communications xx (xxxx) xxxx–xxxx

Contents lists available at ScienceDirect

Optics Communications

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

Scintillation index of higher order mode laser beams in strong turbulence

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ARTICLE INFO

Keywords:
Strong atmospheric turbulence
Scintillation
Laser modes
Modified Rytov method

ABSTRACT

The scintillation index of higher order laser modes is examined in strong atmospheric turbulence. In our formulation, modified Rytov theory is employed with the inclusion of existing modified turbulence spectrum which presents the atmospheric turbulence spectrum as a linear filter having refractive and diffractive spatial frequency cutoffs. Variations of the scintillation index in strong atmospheric turbulence are shown against the weak turbulence plane wave scintillation index for various higher order laser modes of different sizes. Use of higher order modes in optical wireless communication links operating in strongly turbulent atmosphere is found to be advantageous in reducing the scintillation noise.

1. Introduction

The effects of various incidences on the intensity fluctuations, quantified by the scintillation index, are investigated in detail in weak Kolmogorov atmospheric [1–9], non-Kolmogorov atmospheric [10–12] and oceanic (underwater) turbulence [13–15]. Among these incidences, higher order laser beams form an important set whose intensity fluctuations are examined in weak Kolmogorov atmospheric [16], non-Kolmogorov atmospheric [17] and oceanic (underwater) turbulence [18]. Evaluations of the scintillations in strong turbulence are also reported in Kolmogorov atmospheric [19–24], non-Kolmogorov atmospheric [25,26] and oceanic (underwater) turbulence [27]. Modified Rytov theory is presented in [21] where a modified turbulence spectrum is presented with which the turbulent atmosphere acts as a filter having low pass and high pass components. Employing this modified turbulence spectrum, it becomes possible to evaluate the scintillation index by Rytov method not only in weak but also in strong turbulence [21]. This approach is known as modified Rytov or asymptotic method and is used to find the intensity fluctuations of various beams in strong atmospheric turbulence [23,24].

Scintillation index is one of the important metrics in the design and performance improvement of wireless atmospheric optical communication systems. Various techniques are applied to reduce the scintillation index in an atmospheric optics link. Especially when the atmospheric optics system has long path length, the link will encounter strong turbulence. In our previous work in which the intensity fluctuations of higher order mode laser beams are investigated, it is found that in some atmospheric turbulence realizations such as the one having weakly turbulent non-Kolmogov spectrum, the scintillations decrease as the mode order becomes large [17]. To our knowledge, scintillation index of higher order mode laser beams in strong turbulence is not evaluated. In this paper, by using the modified Rytov solution, we have evaluated the on-axis intensity fluctuations of higher order mode laser beams in strong atmospheric turbulence. Our motivation is to understand whether the use of higher order laser beams will improve the performance, by reducing the scintillations, of a wireless optical communication link operating in an atmosphere having strong turbulence regime.

2. Formulation

The optical field at the output of a laser generating higher order modes is given by [28]

$$u(\mathbf{s}) = H_n(s_x/\alpha_s)H_m(s_y/\alpha_s)\exp[-0.5\alpha_s^{-2}(s_x^2 + s_y^2)], \qquad (1)$$

where $H_n(.)$ and $H_m(.)$ are the Hermite polynomials, n and m being the mode numbers of the higher order laser beams in x and y directions, respectively, α_s is the Gaussian source size and $\mathbf{s} = (s_x, s_y)$ is the transverse source coordinate. We note that a laser resonator that contains optically homogeneous medium and paralel parabolic mirrors will in general generate cavity modes known as Hermite Gaussian modes which are expressed by transverse electromagnetic modes TEM_{nm}. Each of TEM_{nm} mode with different n and m compose a different higher order mode. The electric field distribution of TEM_{nm} is given in Eq. (1) where the mode numbers n and m indicate the number of zero crossings of the TEM_{nm} field and intensity in the x and y directions of the laser exit plane, respectively. For example, TEM_{24} field and intensity has 2 zero crossings in the x direction and 4 zero crossings in the y direction. The fundamental mode is TEM_{OO} which is the basic Gaussian beam presenting an ideal excitation that can be

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http://dx.doi.org/10.1016/j.optcom.2016.10.001
Received 2 September 2016; Received in revised form 27 September 2016; Accepted 2 October 2016
Available online xxxx

Please cite this article as: Baykal, Y.K., Optics Communications (2016), http://dx.doi.org/10.1016/j.optcom.2016.10.001

achieved especially in low power lasers. In high power lasers, the incident beam is usually composed of different higher order modes or a combination of higher order modes known as multimode excitation.

We have previously formulated the log-amplitude correlation function, B_χ of a general type optical beam [29] where higher order mode laser excitation is one of the beam types considered. Thus, to find B_χ we insert the higher order beam parameters in [29] and obtain [17]

$$B_\chi = \frac{\pi}{[H_n(0)H_m(0)]^2}\mathrm{Re}\left\{\int_0^L d\eta \int_0^\infty \kappa d\kappa \int_0^{2\pi} d\theta[Y(\eta,\kappa,\theta,L)Y(\eta,-\kappa,\theta,L) + |Y(\eta,\kappa,\theta,L)|^2]\Phi_n(\kappa)\right\}, \tag{2}$$

where Re denotes the real part, η is the distance along the propagation axis, $\boldsymbol{\kappa} = (\kappa, \theta)$ is the two-dimensional spatial frequency in polar coordinates, $\kappa = |\boldsymbol{\kappa}|$, $|.|$ is the absolute value, L is the link length, $\Phi_n(\kappa)$ is the turbulence spectrum,

$$Y(\eta,\kappa,\theta,L) = ik\exp\left[-\frac{0.5i(L-\eta)(k\alpha_s^2 + i\eta)\kappa^2}{k(k\alpha_s^2 + iL)}\right]H_n\left[\frac{\alpha_s(\eta-L)}{k\alpha_s^2 - iL}\kappa\cos\theta\right]H_m\left[\frac{\alpha_s(\eta-L)}{k\alpha_s^2 - iL}\kappa\sin\theta\right], \tag{3}$$

$k = 2\pi/\lambda$, λ being the wavelength.

It is known that in Rytov solution, the scintillation index in weak turbulence is given by [1]

$$m^2 = 4B_\chi(L). \tag{4}$$

The same expression in Eq. (4) holds to be true in strong turbulence when the modified Rytov method is applied with the modified turbulence spectrum which is given for zero inner scale as [21]

$$\Phi_n(\kappa) = 0.033C_n^2\kappa^{-11/3}\left[\exp\left(-\frac{\kappa^2}{\kappa_{cox}^2}\right) + \frac{\kappa^{11/3}}{(\kappa^2 + \kappa_{coy}^2)^{11/6}}\right]. \tag{5}$$

The modified turbulence spectrum given in Eq. (5) also describes the strong turbulent regime. Here, for strong fluctuations, the large scale or refractive spatial frequency cutoff and the small scale or diffractive spatial frequency cutoffs are defined as $\kappa_{cox} \cong \frac{k\rho_0}{L}$ and $\kappa_{coy} \cong \frac{1}{\rho_0}$, respectively where $\rho_0 = (1.46C_n^2k^2L)^{-3/5}$ is the plane wave coherence radius [1] valid in both weak and strong atmospheric turbulence [21].

Inserting κ_{cox} and κ_{coy} into Eq. (5), the modified turbulence spectrum is obtained to be

$$\Phi_n(\kappa) = 0.033C_n^2\kappa^{-11/3}\left[\exp\left(-\frac{L^2\kappa^2}{k^2\rho_0^2}\right) + \frac{\kappa^{11/3}}{(\kappa^2+\rho_0^{-2})^{11/6}}\right]$$
$$=0.033C_n^2\kappa^{-11/3}\{\exp[-(Lk^{-1}\rho_0^{-1}\kappa)^2]+\kappa^{11/3}(\kappa^2+\rho_0^{-2})^{-11/6}\} \tag{6}$$

Employing Eqs. (2) and (6) in Eq. (4), the scintillation index of higher order mode laser beams in strong atmsopheric turbulence is found to be

$$m^2 = \frac{0.132\pi C_n^2}{[H_n(0)H_m(0)]^2}\mathrm{Re}\left(\int_0^L d\eta\int_0^\infty \kappa d\kappa\int_0^{2\pi} d\theta[Y(\eta,\kappa,\theta,L)\, Y(\eta,-\kappa,\theta,L) + |Y(\eta,\kappa,\theta,L)|^2] \times\kappa^{-11/3}\{\exp[-(Lk^{-1}\rho_0^{-1}\kappa)^2] + \kappa^{11/3}(\kappa^2+\rho_0^{-2})^{-11/6}\}\right), \tag{7}$$

Eq. (7) is evaluated numerically and the results are presented below. We note that Eq. (7) is valid for horizontal links operating in strong turbulence where C_n^2 is constant along the link path and it yields the scintillation index values at the origin of the receiver plane.

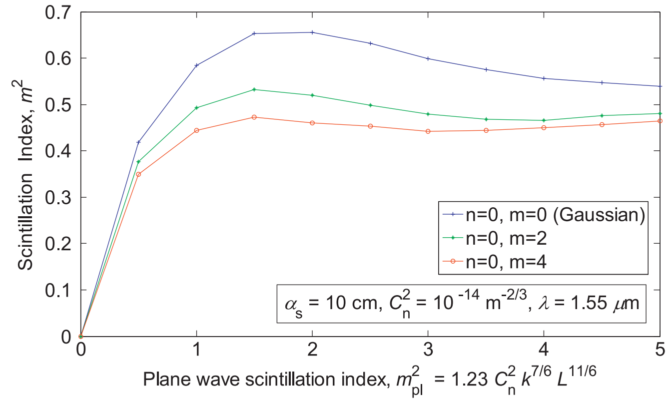

Fig. 1. Scintillation index in strong turbulence versus the plane wave scintillation index of the same size higher order mode laser beams evaluated at a fixed C_n^2 and varying link lengths.

3. Results

In Fig. 1, scintillation index in strong turbulence versus the plane wave scintillation index is shown where the x-coordinate, i.e., the plane wave scintillation index is a unitless quantity. Various higher order mode laser beams are considered that all have the same size. The horizontal axis values are obtained by keeping the wavelength and the structure constant fixed and by varing the link length only. It is observed from Fig. 1 that for all the higher order laser modes, increase in the plane wave scintillation index, i. e., increase in the link length first increases the scintillation index in strong atmospheric turbulence, after reaching a maximum value, the scintillations start to decrease slightly and then increase again slightly, more or less reaching a steady state value. However, for the Gaussian beam, after the slight decrease, eventual increase in the scintillation index is not seen. The observed trend of the decrease in the scintillation index after reaching a maximum is expected because it is known that the scintillation index will not increase monotonically in strong turbulence but at a certain turbulence strength it will start to decrease and reach a saturation value [20,30]. Actually, this is the reason why in strong turbulence, classical Rytov method can not provide the correct solution for the scintillation index, thus instead modified Rytov method is used. At the fixed turbulence parameters, the intensity seems to fluctuate less as the mode number of the higher order laser beam becomes larger.

In Fig. 2, the scintillation index in strong turbulence is plotted for higher order mode laser beams against the variations in the source size where the source sizes are taken to be large. It is concluded from Fig. 2 that within the range of large source sizes and being valid for all the higher order mode laser beams, as the source size becomes larger, the scintillation index monotonically increases. When examined at a fixed

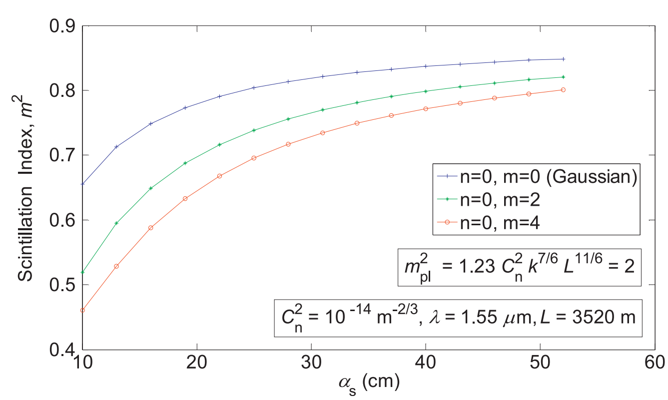

Fig. 2. Scintillation index in strong turbulence versus the large source sizes of higher order mode laser beams.