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Bit error rate performance of free-space optical link under effect of plasma sheath turbulence

Jiangting Li*, Shaofei Yang, Lixin Guo, Mingjian Cheng, Teng Gong

School of Physics and Optoelectronic Engineering, Xidian University, Xi'an 710071, China

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ABSTRACT

Based on the power spectrum of the refractive-index fluctuation in the plasma sheath turbulence, the expressions for wave structure functions and scintillation index of optical wave propagating in a turbulent plasma sheath are derived. The effect of the turbulence microstructure on the propagation characteristics of optical waves are simulated and analyzed. Finally, the bit error performance of a free-space optical (FSO) link is investigated under the effect of plasma sheath turbulence. The results indicate that the spherical waves have a better communication performance in the FSO link. In addition, a greater variance of the refractive index fluctuation causes a more severe fluctuation in electron density, temperature, and collision frequency inside the plasma sheath. However, when the outer scale is close to the thickness of the plasma sheath, the turbulence eddies have almost no influence on the wave propagation. Therefore, the bit error rate (BER) obviously increases with the increase in variance of the refractive index fluctuation and the decrease in the outer scale. These results are fundamental for evaluating the performance of the FSO link under the effect of plasma sheath turbulence.

1. Introduction

During the re-entry process, a hypersonic vehicle is enveloped in a time-varying plasma sheath because of the intense friction between the vehicle and the air. The plasma generated in the periphery of hypersonic aircraft is segmentally ionized and its frequency far exceeds the range from nearly 1–10 GHz, which is just conventional S, C, and X band communication signals frequency. Therefore, this plasma sheath leads to a very intense interference in communication signals, which causes the interruption in communication between the aircraft and ground station, namely, a blackout. This paper takes into account optical waves to weaken the blackout effect. However, the high frequency wave encounters a more complex problem, which is plasma sheath turbulence. This turbulence is a multicomponent mixture consisting of neutral atoms, molecules, free electrons, as well as atomic and molecular ions of both positive and negative charges [1]. The results of experimental research on a hypersonic plasma sheath have confirmed that inherent thermal-chemical reactions and flight dynamics will cause a turbulence effect [2,3]. Turbulence irregularities may scatter wave energy, cause random fluctuation of the wavefront amplitude and phase, lead to acute distortion of the incoming signal, and, ultimately, affect the performance of the free-space optical (FSO) link [4–6].

Optical wave propagation through a turbulent plasma sheath is relatively unexplored compared to that through atmospheric turbulence because of the complexity of the hypersonic plasma sheath. In the atmospheric turbulence, several Kolmogorov, non-Kolmogorov, isotropic, and anisotropic power spectrums [7–10] have been proposed to describe the characteristics of the refractive-index fluctuation. In addition, numerous studies on the characteristics of optical wave propagation in turbulence have also been conducted [11–14]. Understanding the power spectrum of the refractive-index fluctuation is a prerequisite for the application of wave propagation theory in hypersonic turbulence. In [15], Li et al. proposed the power spectrum of the refractive-index fluctuation in the plasma sheath turbulence based on the fractal dimensions that were measured in hypersonic turbulence. They also studied the diffraction effect of the electromagnetic wave propagation through hypersonic turbulence using the fractal phase screen method. Moreover, the turbulence is known to cause signal fading in the turbulence channel. Ghassemlooy [16] introduced the existing mathematical models for describing the fading and discussed the different types of modulation schemes that are suitable for optical wireless communication systems. He analyzed the effect of atmospheric turbulence-induced fading on the pre-modulated subcarrier intensity modulation (SIM) techniques based on phase-shift keying. However, similar research has not yet been performed in relation

* Corresponding author.
E-mail address: jtli@xidian.edu.cn (J. Li).

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to plasma sheath turbulence. In summary, considerable research has been undertaken in optical wireless communication under atmospheric turbulence but research on the influence of plasma sheath turbulence on optical wireless communication has not yet been reported.

In this study, wave structure functions and scintillation index of optical wave propagation in a turbulent plasma sheath are calculated based on the refractive-index fluctuation of its power spectrum. Moreover, the bit error rate (BER) performance of a SIM-FSO system is analyzed and simulated under the effect of plasma sheath turbulence.

2. Analytical formulae of wave structure function

The spectrum of refractive-index fluctuation in the turbulent plasma sheath is proposed based on the fractal dimensions of hypersonic turbulence that can be expressed as follows [15]:

$$\Phi_n(\kappa) = 0.077 < n_1^2 > L_0^{-4/5}\kappa^{-19/5}, \tag{1}$$

where $<n_1^2>$ is the variance of the refractive index fluctuation, L_0 is the outer scale, the scaling exponent is 4/5, and the spectral index is 19/5. According to the Rytov approximation, the wave structure function (WSF) of a plane wave propagating through plasma turbulence is defined by [17,18] as

$$D_p(\rho, L) = 8\pi^2k^2L\int_0^\infty \kappa\Phi(\kappa)[1 - J_0(\kappa\rho)]d\kappa, \tag{2}$$

where k is the wave number, L is the propagation distance (e.g., the thickness of the plasma sheath), $J_0(x)$ is the Bessel function of the first kind, and $\rho = |\mathrm{r}_1 - \mathrm{r}_2|$ is a vector in the receiver plane transverse to the propagation axis. Substituting Eq. (1) into Eq. (2), we have,

$$D_p(\rho, L) = 8\pi^2k^2L\cdot 0.077 < n_1^2 > L_0^{-4/5}\cdot \int_0^\infty \kappa^{-14/5}[1 - J_0(\kappa\rho)]d\kappa. \tag{3}$$

Using the integral formula [19],

$$\int_0^\infty x^\mu J_\upsilon(ax)dx = 2^\mu\cdot a^{-\mu-1}\cdot\frac{\Gamma\left(\frac{1}{2}+\frac{1}{2}\upsilon+\frac{1}{2}\mu\right)}{\Gamma\left(\frac{1}{2}+\frac{1}{2}\upsilon-\frac{1}{2}\mu\right)}, \tag{4}$$

we can obtain

$$D(\rho, L) = 9.595 < n_1^2 > L_0^{-4/5}k^2L\rho^{9/5}. \tag{5}$$

The WSF of a spherical wave propagating through the turbulent plasma sheath can be expressed as [17,18]

$$D_s(\rho, L) = 8\pi^2k^2L\int_0^1\int_0^\infty \kappa\Phi(\kappa)[1 - J_0(\kappa\rho\xi)]d\kappa d\xi. \tag{6}$$

Substituting Eq. (1) into Eq. (6), we have,

$$D_p(\rho, L) = 8\pi^2k^2L\cdot 0.077 < n_1^2 > L_0^{-4/5}\times\int_0^1\int_0^\infty \kappa^{-14/5}[1 - J_0(\kappa\rho\xi)]d\kappa d\xi. \tag{7}$$

Following a similar procedure as used in the plane wave case, we can get the final expression for the WSF of a spherical wave propagating through the plasma sheath turbulence as,

$$D(\rho, L) = 3.427 < n_1^2 > L_0^{-4/5}k^2L\rho^{9/5}. \tag{8}$$

For Gaussian beam [17], the WSF of the turbulent plasma sheath can be written as

$$D_G(\rho, L) = 8\pi^2k^2L\int_0^1\int_0^\infty \kappa\Phi(\kappa)\exp(-\Lambda L\kappa^2\xi^2/k)\times\{I_0(\Lambda\kappa\xi\rho) - J_0[(1-\bar{\Theta}\xi)\kappa\rho]\}d\kappa d\xi, \tag{9}$$

where $I_0(x)$ is the modified Bessel function. Λ and $\bar{\Theta}$ are the beam parameters that can be expressed as follows:

$$I_0(x) = J_0(ix),\quad \Lambda = \frac{\Lambda_0}{\Theta_0^2+\Lambda_0^2},\quad \Theta = \frac{\Theta_0}{\Theta_0^2+\Lambda_0^2},\quad \bar{\Theta} = 1-\Theta. \tag{10}$$

Therefore, Eq. (9) can be written as

$$D_G(\rho, L) = D_{G,1}(\rho, L) - D_{G,2}(\rho, L), \tag{11}$$

where

$$D_{G,1}(\rho, L) = 8\pi^2k^2L\cdot 0.077 < n_1^2 > L_0^{-4/5}\cdot\int_0^1\int_0^\infty \kappa^{-14/5}\times\exp(-\Lambda L\kappa^2\xi^2/k)J_0(i\Lambda\kappa\xi\rho)d\kappa d\xi, \tag{12}$$

$$D_{G,2}(\rho, L) = 8\pi^2k^2L\cdot 0.077 < n_1^2 > L_0^{-4/5}\cdot\int_0^1\int_0^\infty \kappa^{-14/5}\times\exp(-\Lambda L\kappa^2\xi^2/k)J_0[(1-\bar{\Theta}\xi)\kappa\rho]d\kappa d\xi. \tag{13}$$

Using the integral formula [19],

$$\int_0^\infty x^\mu\exp(-a^2x^2)J_p(bx)dx = \frac{b^p\Gamma\left(\frac{p+\mu+1}{2}\right)}{2^{p+1}a^{p+\mu+1}\Gamma(p+1)}\times{}_1F_1\left(\frac{p+\mu+1}{2}; p+1; -\frac{b^2}{4a^2}\right), \tag{14}$$

Eq. (11) can be written as

$$D_G(\rho, L) = 3.427 < n_1^2 > L_0^{-4/5}k^{11/10}L^{19/10}\times\left[\left(\frac{1-\Theta^{14/5}}{1-\Theta}\right)\left(\frac{k\rho^2}{L}\right)^{9/10} + 0.391\Lambda^{19/10}\left(\frac{k\rho^2}{L}\right)\right],\quad \Theta\ge 0, \tag{15}$$

where ${}_1F_1(a; c; z)$ is the confluent hypergeometric function. In the above derivation, the under approximate condition given below is used [17]:

$${}_1F_1(a; c; -z) \cong \begin{cases} 1-\dfrac{az}{c}, & |z| < < 1 \\ \dfrac{\Gamma(c)}{\Gamma(c-a)}z^{-a}, & \mathrm{Re}(z) > > 1. \end{cases} \tag{16}$$

When calculating the propagation characteristics of the optical waves, the plasma sheath is regarded as a turbulent model whose parameters are selected from numerical simulations [20] based on the Radio Attenuation Measurements (RAM) experimental conditions [21]. The numerical simulations and the experiment indicated that the range of the fluid field distribution in the plasma sheath was approximately 0.4 m. Therefore, the maximum values of the outer scale of the turbulent plasma sheath and the propagation distance were restricted to 0.4 m. According to [16], the incident wavelength was taken as 850 nm. The separation distances from the two points on the phase front transverse to the axis of propagation are given by $\rho = 1\times 10^{-3}$ m. In this paper, the above-mentioned parameters are used unless otherwise specified. Fig. 1(a) and 1(b) show the evolution of the WSFs with the variance of the refractive-index fluctuation and the outer scale, respectively.

Fig. 1(a) shows the impact of the variance of the refractive-index fluctuation on the WSFs of optical waves propagating in a turbulent plasma sheath by changing $<n_1^2>$ from 0 to 4×10^{-8} and taking the outer scale as $L_0 = 0.2$m. Results show that the WSF of a plane wave has the largest value in the case of plasma sheath turbulence. As the variance of the refractive index fluctuation increases, the WSFs increase. This is because a larger variance of the refractive index fluctuation results in a more acute fluctuation of the electron density in the plasma sheath, which will aggravate the scattering effect and elevate the WSF.

Fig. 1(b) shows the impact of the outer scale on the WSFs of optical waves propagating in a turbulent plasma sheath by changing L_0 from 0