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Sichen Lei
lsc429@163.com

Xi'an University of Technology

rongrong zhang
Xi'an University of Technology

pengfei wu
Xi'an University of Technology

zhenkun tan
Xi'an University of Technology

jiao wang
Shaanxi University of Science and Technology

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Coupling Efficiency of Partially-Coherent Airy Beam into Few-Mode Fiber under Atmospheric Turbulence

Sichen Lei [1,2,*], Rongrong Zhang [1] , Pengfei Wu [1,2] , Zhen kun Tan [3], and Jiao Wang [4]

1.Faculty of Automation & Information Engineering, Xi’an University of Technology, Xi’an 710048, China

2.Xi'an Key Laboratory of Wireless Optical Communication and Network Research , Xi’an ,China

3.Faculty of Optoelectronic Engineering, Xi’an Technological University, Xi’an 710021, Shaanxi, China

4.School of Electronic Information and Artificial Intelligence, Shaanxi University of Science and Technology, Xi’an 710021, China

* Correspondence: lsc429@163.com

Abstract: When a signal beam propagates through the atmosphere, it is affected by turbulence. The Airy beam, with its characteristics of diffraction-free propagation, self-healing, and self-focusing, can effectively mitigate the adverse effects of atmospheric turbulence. In this paper, the coupling efficiency is constructed based on the theory of cross-spectral density, using a structure consisting of partially coherent Airy beams, a single lens, and a four-mode optical fiber. In addition, we also investigated the effects of atmospheric turbulence, lens parameters, and beam parameters on the coupling efficiency. The results indicate that under moderate turbulence conditions (scintillation index $A_R/A_C = 5$), the coupling efficiency of the partially coherent Airy beams is 25.7% higher than that of the Gaussian-Schell model beams.

Keywords: atmospheric turbulence, coupling efficiency, partially-coherent airy beam

1. Introduction

With the mature development of fiber optic device technology, the receiving system based on fiber optic coupling technology is getting more and more attention[1,2], and the coupling technology is gradually applied in the fields of LIDAR, imaging and communication. Spatial optical coupling technology refers to the method and technology of using light beams to transmit and couple in random media, which involves the process of controlling, modulating, focusing, and coupling of light beams, and is used to realize the transmission, processing, and manipulation of optical signals, and has a broad application prospect[3,4]. Space light-fiber coupling technology can be used to collect and couple optical signals reflected back from laser beams into optical fibers to achieve target detection and imaging and other functions[5-8]. Through the fiber coupling technology, the spatial light signal can be transmitted in the optical fiber, thus realizing the protection of the optical signal and the extension of the transmission distance[9,10].Numerous academics have studied the coupling between free-space optics and fiber optics since Winzer et al.'s analysis of the effect of fiber coupling efficiency on laser radar performance. Improving coupling efficiency through the analysis of light source properties has gained more attention in recent years due to the development of efficient coupling technologies.[11] Tan et al. examined the coupling efficiency of single-mode fibers through atmospheric turbulence using Gaussian-Schell model beams as the light source[12]. The coupling effectiveness of inhomogeneous correlated beams in air turbulence was studied by Lin et al. The findings shown that the fiber's coupling efficiency can be increased by varying the beam's coherence length [13].

Airy beams have special optical properties like self-focusing, self-healing, and non-diffraction [14,15]. Studies have shown that in turbulent situations, the Airy beam performs better than Gaussian beams in terms of interference resistance and lower intensity scintillation when the energy of the light source and the receiver are equal. It is hence more appropriate for use in optical communications applications[16-18]. The Christodoulides-led research team proposed the Airy beam in 2007 [19]. The self-healing characteristics of accelerating Airy beams were studied theoretically and empirically by Broky et al. [20]. Morris et al. [21] examined how wavelength and spatial coherence affected the propagation properties of Airy beams. The generating process [22], accelerated trajectory control [23], evolution [24], and atmospheric propagation characteristics [25-27] are currently the key areas of study for Airy beams. Airy beams have, however, only been used sparingly in optical communications. This work uses the cross-spectral density of partially coherent beams and the theory of atmospheric turbulence transport to create a theoretical model expression for the coupling efficiency of Partially Coherent Airy (PCA) beams with few-mode fibers (FMF) in atmospheric turbulence. We explore how the coupling efficiency is affected by the beam, coupling lens, and air turbulence.

2. Principle and Theoretical Model

A schematic depiction of the coupling of a single lens and a few-mode fiber to a partially coherent Airy beam under air turbulence is shown in Figure 1. The beam impacts the surface of the coupling lens after traveling z distance in atmospheric turbulence. The deformed beam caused by atmospheric turbulence is converged by the lens and couples into the interior of the fiber.

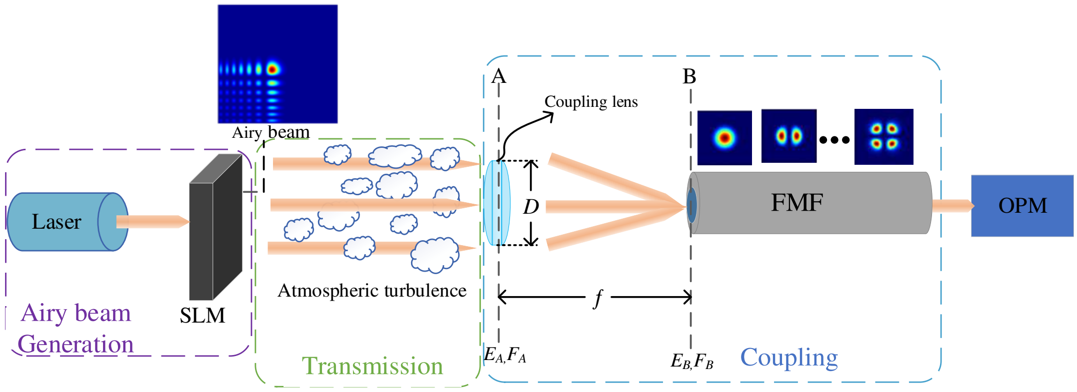

Figure 1. Partially-coherent Airy beam opto-coupled into a few-mode fiber (FMF) in atmospheric turbulence. The setup comprises a spatial light modulator (SLM) and an optical power meter (OPM).

The ratio of the average optical power <Pc> coupled into the fiber to the average optical power <Pa> at the receiver aperture plane is known as the coupling efficiency of the fiber[12]. As seen in Figure 1, it can be found at the entrance pupil plane A or the focal plane B. The fiber coupling efficiency in this study is measured at the entrance pupil plane A[4], which is given by

$$\eta = \frac{\langle P_c \rangle}{\langle P_a \rangle} = \sum \frac{\left\langle \left| \int_A U_o(\mathrm{r}) U_f^*(\mathrm{r}) \mathrm{dr} \right|^2 \right\rangle}{\left\langle \int_A \left| U_o(\mathrm{r}) \right|^2 \mathrm{dr} \right\rangle}, \tag{1}$$

Factorizing the squared integration in Eq. (1) requires the assumption that the average incidence optical intensity is independent on **r**. Noting that the fiber mode is deterministic, and alternating between the ensemble average and integration [12]. The coupling efficiency can be expressed as by modifying the numerator of Eq. (1) and extending the squared integration.

$$\eta = \frac{1}{A_R} \sum \iint_A \mu(\mathrm{r}_1, \mathrm{r}_2, z) U_f^*(\mathrm{r}_1) U_f(\mathrm{r}_2) \mathrm{dr}_1 \mathrm{dr}_2, \tag{2}$$

where $A_R=\pi D^2/4$ denotes the receiver aperture area, ∗ indicates the complex conjugate. assuming that in order to enhance the coupling efficiency, the fiber is positioned at the focal plane of the receiver lens and centered on the optical axis [9], the fiber mode distribution is then given by

$$U_{f,pl}(\mathrm{r}, \varphi) = C_{l,p} \omega \left(\frac{k}{f} \mathrm{r}\, \omega \right)^l \exp\left[-\left(\frac{k\omega}{2f} \mathrm{r} \right)^2 \right] L_p^l \left(\frac{k\omega}{f} \mathrm{r} \right)^2 \begin{cases} \cos l\varphi \\ \sin l\varphi \end{cases}, \tag{3}$$

where $k = 2\pi/\lambda$ is the optical wave number, λ is the laser wavelength, f is the focal length of the coupling lens, and ω is the fiber-mode field radius.

The complex degree of coherence of the PCA beams propagating across atmospheric turbulence at the propagation distance z is indicated by the symbol μ (r_1, r_2, z) in Eq. (2). At the plane of z=0, the optical field distribution of the Airy beam is given by [18]

$$u(\rho, z=0)=Ai\left(\frac{x}{\omega_0}\right)\exp\left(\frac{ax}{\omega_0}\right)Ai\left(\frac{y}{\omega_0}\right)\exp\left(\frac{ay}{\omega_0}\right), \tag{4}$$

where $Ai(\cdot)$ represents the Airy function, ω_0 is transverse scale, and a is the exponential truncation factor.

The cross-spectral density function(CSDF) of the PCA beam source propagating across atmospheric turbulence at propagation distance z is given by the generalized Huygens-Fresnel principle [5].

$$\begin{aligned} W(\mathrm{r}_1,\mathrm{r}_2,z)=&\left(\frac{1}{\lambda z}\right)^2\iint \mathrm{d}^2\mathrm{r}_1\iint \mathrm{d}^2\mathrm{r}_2 W(\rho_1,\rho_2,0)\\ &\times\exp\left[ik\frac{(\mathrm{r}_1\text{-}\rho_1)^2-(\mathrm{r}_2\text{-}\rho_2)^2}{2z}\right]\\ &\times\left\langle\exp\left[\Psi^*(\mathrm{r}_1,\rho_1,z)+\Psi(\mathrm{r}_2,\rho_2,z)\right]\right\rangle, \end{aligned} \tag{5}$$

The CSDF of the PCA beam at the propagation is given by[21,22]

$$\begin{aligned} W(\rho_1,\rho_2,0)=&u(\rho_1,0)u(\rho_2,0)\exp\left(-\frac{(\rho_1\text{-}\rho_2)^2}{2\sigma_0^2}\right)\\ =&Ai\left(\frac{x_1}{\omega_0}\right)\exp\left(\frac{ax_1}{\omega_0}\right)Ai\left(\frac{y_1}{\omega_0}\right)\exp\left(\frac{ay_1}{\omega_0}\right)\\ &\times Ai\left(\frac{x_2}{\omega_0}\right)\exp\left(\frac{ax_2}{\omega_0}\right)Ai\left(\frac{y_2}{\omega_0}\right)\exp\left(\frac{ay_2}{\omega_0}\right)\\ &\times\exp\left(-\frac{(x_1-x_2)^2+(y_1-y_2)^2}{2\sigma_0^2}\right), \end{aligned} \tag{6}$$

where σ_0 is the spatial correlation length. and In Eq.(5) the random part of the complex phase of a spherical wave propagating in turbulence can be approximated by[4]

$$\begin{aligned} \left\langle\exp\left[\Psi^*(\mathrm{r}_1,\rho_1,z)+\Psi(\mathrm{r}_2,\rho_2,z)\right]\right\rangle_m\cong&\exp\left\{-\frac{1}{\rho_0}\left[(\mathrm{r}_1\text{-}\mathrm{r}_2)^2+(\mathrm{r}_1\text{-}\mathrm{r}_2)(\rho_1\text{-}\rho_2)+(\rho_1\text{-}\rho_2)^2\right]\right\}\\ =&\exp\left\{-\frac{\left[(x_1'-x_2')^2+(y_1'-y_2')^2\right]+\left[(x_1-x_2)^2+(y_1-y_2)^2\right]}{\rho_0^2}\right\}\\ &\times\exp\left\{-\frac{\left[(x_1'-x_2')(x_1-x_2)+(y_1'-y_2')(y_1-y_2)\right]}{\rho_0^2}\right\}, \end{aligned} \tag{7}$$

By substituting Eq. (6) and Eq. (7) into Eq. (5), and $W_x(x_1,x_2,z)$ and $W_y(y_1,y_2,z)$ are symmetrically similar $W(r_1,r_2,z)=W_x(r_{x1},r_{x2},z)\,W_y(r_{y1},r_{y2},z)$ [15]. Using the sum and difference vector notation

$$\mathrm{r}_\mathrm{s}=\frac{x_1+x_2}{2},\mathrm{r}_\mathrm{d}=x_1-x_2,\rho_\mathrm{s}=\frac{x_1'+x_2'}{2},\rho_\mathrm{d}=x_1'-x_2' \tag{8}$$

Inserting Eq. (6) and (7) into (5) and after some algebraic manipulations and integral operation , the cross-spectral density function of PCA beam source propagating through atmospheric turbulence at propagation distance z is found to be [5]

$$W_x\left(\mathrm{r_d},\mathrm{r_s},z\right)=\exp\left[B^4\left(3a+\frac{B^2}{3}\right)\right]\times\exp\left[-\frac{\mathrm{r_d}^2}{\omega_0{}^2N^2}+i\left(\frac{1}{2}\gamma-2\chi\left(a+B^2\right)\right)\frac{\mathrm{r_d}}{\omega_0}\right]$$
$$\times\exp\left\{2\left(a+B^2\right)\left[\frac{\mathrm{r}_s}{\omega_0}-\frac{\gamma^2}{2}+\frac{\beta^2\left(4a+B^2\right)}{2}\right]\right\}$$
$$\times Ai\left[\mathrm{r_s}-\left(\frac{\gamma^2}{4}-B^2\left(4a+B^2\right)\right)-\left(i\chi+\frac{1}{2}\right)\mathrm{r_d}-i\left(a+B^2\right)\gamma\right] \tag{9}$$
$$\times Ai\left[\mathrm{r_s}-\left(\frac{\gamma^2}{4}-B^2\left(4a+B^2\right)\right)-\left(i\chi-\frac{1}{2}\right)\mathrm{r_d}+i\left(a+B^2\right)\gamma\right],$$

with the parameters defined as $B=z/kw_0N$,$N^2=2\sigma_0^2\rho_0^2/(2\ \sigma_0^2+\ \rho_0^2)$,$\chi=z(2/N^2+1/\ \rho_0^2)/k$ and $\gamma=z/(kw_0\mathrm{C}_n^2)$.The spatial-coherence radius can be written as $\rho_0=(0.545\mathrm{C}_n^2k^2z)^{-3/5}$ [24],By normalizing the CSD function W(r_1,r_2,z) at the propagation distance z, the complex degree of coherence $\mu(r_1,r_2,z)$ of PCA beam is found to be

$$\mu\left(\mathrm{r_1},\mathrm{r_2},z\right)\approx\exp\left[-\frac{\left(\mathrm{r_1}\text{-}\mathrm{r_2}\right)^2}{N^2\omega_0{}^2}+\frac{i\left(\frac{1}{2}\gamma-2\chi\left(a+B^2\right)\right)\left(\mathrm{r_1}\text{-}\mathrm{r_2}\right)}{\delta}\right], \tag{10}$$

By substituting Eq. (10) and Eq. (3) into Eq. (2), we express the fiber coupling efficiency of the PCA beam through atmospheric turbulence

$$\eta_{01}=\frac{1}{A_R}\iint_A\exp\left[-\frac{\left(\mathrm{r_1}\text{-}\mathrm{r_2}\right)^2}{\rho^2\delta^2}+i\frac{\left(\frac{1}{2}\gamma-2\chi\left(a+\beta^2\right)\right)}{\delta}\left(\mathrm{r_1}\text{-}\mathrm{r_2}\right)\right]$$
$$\times\left(\frac{k^2\omega^2}{2\sqrt{\pi}f^2}\right)\mathrm{r_1}\exp\left[-\left(\frac{k\omega}{2f}\right)^2\mathrm{r_1}^2\right]\left(\frac{k^2\omega^2}{2\sqrt{\pi}f^2}\right)\mathrm{r_2}\exp\left[-\left(\frac{k\omega}{2f}\right)^2\mathrm{r_2}^2\right]\mathrm{dr_1dr_2}, \tag{11}$$

We use the law of cosines given by[4]

$$\left(\mathrm{r_1}-\mathrm{r_2}\right)^2=\mathrm{r_1}^2+\mathrm{r_2}^2-2\mathrm{r_1r_2}\cos\left(\varphi_1-\varphi_2\right), \tag{12}$$

where $\mathbf{r}_1$and $\mathbf{r}_2$are the horizontal coordinate vectors at the propagation plane $z > 0$. $\varphi_1$and φ_2 are the angles between $\mathbf{r}_1$and $\mathbf{r}_2$ and the centered axis at the propagation plane[13]. The fiber-coupling efficiency η_{01} is found to be

$$\eta_{01} = \frac{1}{A_R}\left(\frac{k^2\omega^2}{2\sqrt{\pi}f^2}\right)^2 \int_0^{\frac{D}{2}}\int_0^{\frac{D}{2}}\int_0^{2\pi}\int_0^{2\pi} \exp\left[-\frac{\mathrm{r}_1{}^2+\mathrm{r}_2{}^2\text{-}2\mathrm{r}_1\mathrm{r}_2\cos\left(\varphi_1-\varphi_1\right)}{\rho^2\delta^2}\right]$$
$$\times\exp\left[iG\left(\mathrm{r}_1\text{-}\mathrm{r}_2\right)\right]\exp\left[-\left(\frac{k\omega}{2f}\right)^2 \mathrm{r}_1{}^2+\mathrm{r}_2{}^2\right]\mathrm{r}_1{}^2\mathrm{r}_2{}^2\mathrm{d}\varphi_1\mathrm{d}\varphi_2\mathrm{d}\mathrm{r}_1\mathrm{d}\mathrm{r}_2, \quad (13)$$

The results in the double integral over the angle variables $\varphi_1$and φ_2 are given by[4]

$$\int_0^{2\pi}\int_0^{2\pi} 2Q\mathrm{r}_1\mathrm{r}_2\cos\left(\varphi_1-\varphi_2\right)d\varphi_1 d\varphi_2 = 4\pi J_0\left(2Q\mathrm{r}_1\mathrm{r}_2\right), \quad (14)$$

where $J_0(.)$ denotes the modified Bessel function of first kind and zero order. Inserting (14) into (13) and after some algebraic manipulations and integral operation ,the fiber-coupling efficiency is found to be

$$\eta_{01} = \frac{1}{A_R}\left(\frac{k^2\omega^2}{2\sqrt{\pi}f^2}\right)^2 \int_0^{\frac{D}{2}}\int_0^{\frac{D}{2}} \exp\left[-\frac{\mathrm{r}_1{}^2+\mathrm{r}_2{}^2}{\rho^2\delta^2}\right]\exp\left[-\left(\frac{k\omega}{2f}\right)^2\left(\mathrm{r}_1{}^2+\mathrm{r}_2{}^2\right)\right]$$
$$\times\exp\left[iG\left(\mathrm{r}_1-\mathrm{r}_2\right)\right]4\pi^2 J_0\left(\frac{2\mathrm{r}_1\mathrm{r}_2}{\rho^2\delta^2}\right)\mathrm{r}_1{}^2\mathrm{r}_2{}^2\mathrm{d}\mathrm{r}_1\mathrm{d}\mathrm{r}_2, \quad (15)$$

By normalizing the radial integration variables to the receiver lens radius[4], we define $x_1 = 2\mathbf{r}_1/D$, and $x_2 = 2\mathbf{r}_2/D$, Substituting this result into Eq.(15), the coupling-efficiency expression reduces to a double integral given by

$$\eta_{01} = 16\beta^4 \int_0^1\int_0^1 \exp\left[-\left(\frac{1}{\rho^2\delta^2}+\beta^2\right)\left(x_1{}^2+x_2{}^2\right)\right]J_0\left(\frac{2}{\rho^2\delta^2}x_1x_2\right)$$
$$\times\exp\left[\frac{iGD(x_1-x_2)}{2}\right]x_1{}^2x_2{}^2\mathrm{d}x_1\mathrm{d}x_2, \quad (16)$$

Inserting (3) and (10) into (2) and after some algebraic manipulations and integral operation, the fiber-coupling efficiency is found to be is found to be

$$\eta_{11} = 16\beta^4 \int_0^1\int_0^1 \exp\left[-\left(\frac{1}{\rho^2\delta^2}+\beta^2\right)\left(x_1{}^2+x_2{}^2\right)\right]J_0\left(2\frac{2}{\rho^2\delta^2}x_1x_2\right)$$
$$\times\left[2-2\beta^2x_1^2\right]\left[2-2\beta^2x_2^2\right]\exp\left[\frac{iGD(x_1-x_2)}{2}\right]x_1{}^2x_2{}^2\mathrm{d}x_1\mathrm{d}x_2, \quad (17)$$

$$\eta_{02} = 16\beta^6 \int_0^1\int_0^1 \exp\left[-\left(\frac{1}{\rho^2\delta^2}+\beta^2\right)\left(x_1{}^2+x_2{}^2\right)\right]J_0\left(\frac{2}{\rho^2\delta^2}x_1x_2\right)$$
$$\times\exp\left[\frac{iGD(x_1-x_2)}{2}\right]x_1{}^3x_2{}^3\mathrm{d}x_1\mathrm{d}x_2, \quad (18)$$

$$
\begin{aligned}
\eta_{21} = 4\beta^4 \int_0^1\int_0^1 & \exp\left[-\left(\frac{1}{\rho^2\delta^2}+\beta^2\right)\left(r_1^{\,2}+r_2^{\,2}\right)\right] J_0\left(\frac{2}{\rho^2\delta^2}x_1x_2\right) \\
& \times\left[4\beta^4x_1^{\,4}-12\beta^2x_1^{\,2}+6\right]\left[4\beta^4x_2^{\,4}-12\beta^2x_2^{\,2}+6\right] \\
& \times\exp\left[\frac{iGD(x_1-x_2)}{2}\right]x_1^{\,2}x_2^{\,2}\mathrm{d}x_1\mathrm{d}x_2,
\end{aligned} \tag{19}
$$

where G=0.5γ-2χ(a+B), $\beta = kwD/4f$ is the coupling parameter.

3. Numerical Simulation

The numerical discussions for the PCA beam's fiber coupling efficiency through atmospheric turbulence as a function of the turbulent and source parameters are presented in this part, unless otherwise specified all plots have λ = 1550 nm, σ_0 = 0.08, w_0 = 0.03 m, a = 0.01 (the direction and intensity of Airy beam bending can be controlled by w_0 and a), z = 2 km, D = 0.12 m, f = 0.04 m, β = 1.7, $C_n^2 = 10^{-15}$ m$^{-2/3}$.
Eq. (16) is compared with Eq. (2) by simulation, as indicated in Figure 2(a), specifically by comparing the final obtained result with the original integral formula to prove that the analytical formula for the coupling efficiency is correct. The findings show that there is a good degree of consistency between the coupling efficiency values produced from the analytical formula and the values acquired from the original integral formula. It is also possible to decrease the quadruple integral to a double integral by using an estimate to bring the error down to less than 1%.
The coupling effectiveness changes with truncation factor a for different refractive index structure constants C_n^2, as seen in Figure 2(b). The partial coherent Airy beam's coupling efficiency decreases as the truncation factor increases. The intensity distribution of a partially coherent Airy beam with a truncation factor of a=1 is displayed in Figure 2(b). It is seen that at a=1, the Airy beam's sidelobes have totally decayed and the main lobe intensity has a distribution resembling a Gaussian curve.
A comparative examination of the Airy beam with an a=1 and the Gaussian beam coupling to the fundamental mode is carried out in Figure 2(c). From another angle, the validity of Equation (16) can be shown by comparing the coupling efficiency with the Gaussian beam and observing that the trends of the two curves correspond. For the simulation, a truncation factor of a=0.01 was selected in order to increase coupling efficiency.
The impact of varying propagation distances on the intensity distribution of partially coherent Airy beams is simulated, as illustrated in Figure 2(d). With an increasing truncation factor a, the Airy beam's intensity progressively drops, and the main lobe gradually widens as the sidelobes attenuate. The primary lobe of the Airy beam develops into a Gaussian distribution and the sidelobes progressively vanish as the beam propagates to 2 km, which is consistent with the findings found in reference[24]. This behavior can be explained by the fact that during the propagation process, the

energy of the partially coherent Airy beam's sidelobes continually flows towards the main lobe. As the beam propagates through the atmosphere, it experiences diffusion as a result of atmospheric turbulence. Therefore, the distribution depicted in Figure 2(d) gradually forms as the propagation distance rises. By this time, the beam has lost all of its unique properties.

According to Figure 2(e),The spatial distribution of the main lobe and the degree of attenuation of the sidelobes and major lobe of the beam are both regulated by the truncation factor. The Airy beam's sidelobes and main lobe steadily attenuate as the exponential truncation factor rises. Furthermore, when the exponential truncation factor increases, the major lobe of the Airy beam undergoes a minor shift in the direction of the transverse axis, towards the positive.

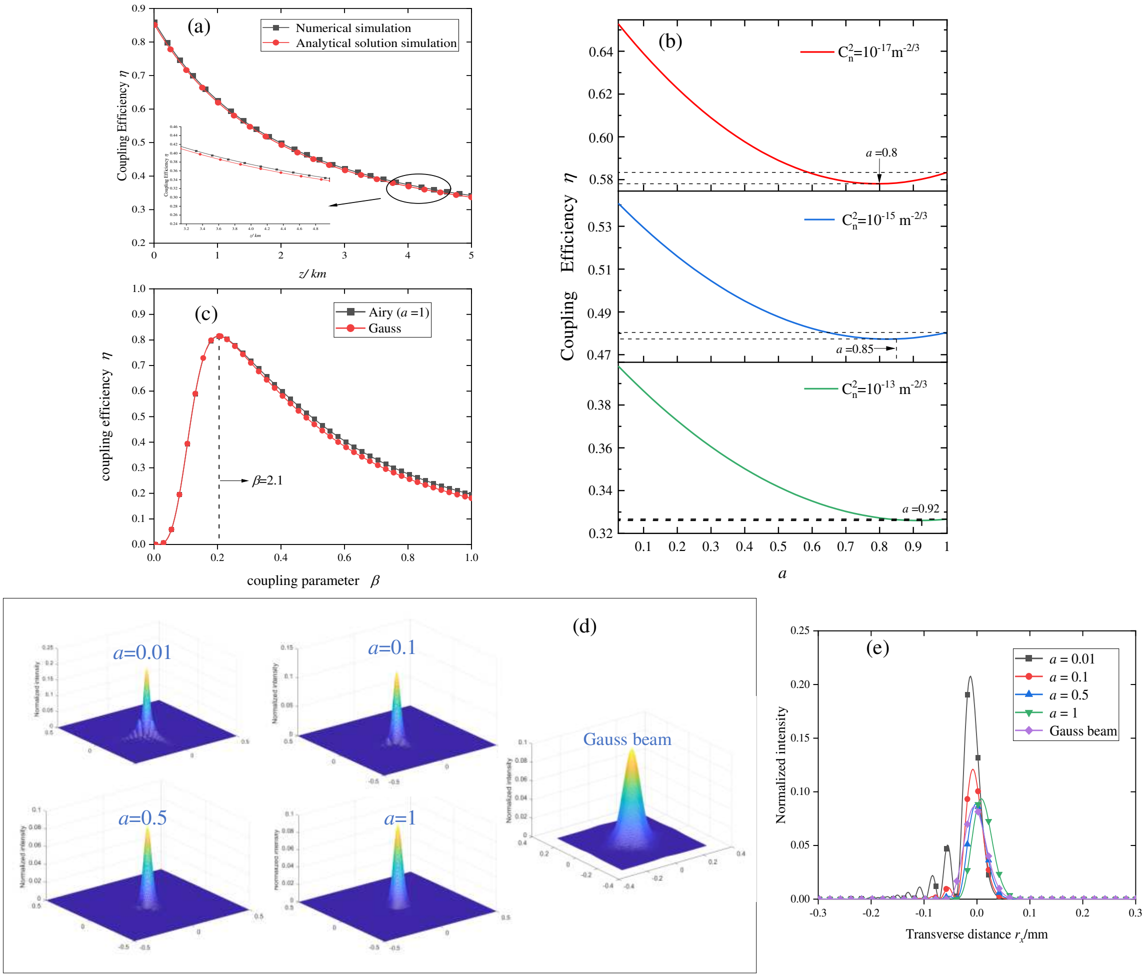

Figure 2. (a) Numerical comparison between analytical original integral formulae of coupling efficiency. **(b)**The fiber coupling efficiency varies with truncation factor a for different refractive index structure constant C_n^2 beams. **(c)** Comparison of the coupling efficiency between and the Airy beam (a=1) and Gaussian beam with the fundamental mode. **(d)** The three-dimensional intensity distribution of the Airy beam under different truncation factors. **(e)** The intensity distribution of the Airy beam under different truncation factors.

Figure 3(a) shows the effect of propagation distance z and wavelength λ on fiber coupling efficiency η. The coupling efficiency drops as the propagation distance z

increases, and the curve displays a convergence trend. At 1550 and 650 nm wavelengths and z = 5 km propagation distance, the PCA beam had a 12.1% and 11.7% greater coupling efficiency than the GSM beam, respectively. When compared to the long-wavelength beam, the coupling efficiency of the short-wavelength beam declines faster because they can conclude that a longer wavelength beam is a better alternative in terms of coupling efficiency.

Figure 3(b) shows the variation in the fiber coupling efficiency of the PCA beam in atmospheric turbulence with beam width. It is found that the PCA beam's coupling effectiveness at the tiny beam waist is higher than the same beam's at the larger beam waist, under the identical turbulence conditions. This is due to the Airy beam's main and side lobes gradually decaying as the original beam radius w_0, grows. As a result, the beam's overall energy falls, which weakens the beam's resistance to turbulence and lowers coupling efficiency. Figure 3(b) shows that, under the identical set of circumstances, the PCA beam's coupling effectiveness is higher than the GSM beam's.

Figure 3(c) illustrates how coupling effectiveness varies with propagation distance z for various coherent lengths σ_0. When $\sigma_0 = +\infty$, the beam is totally coherent. Otherwise, it is moderately coherent. Under the same conditions, the PCA beam has a higher coupling efficiency than the GSM beam, and coupling efficiency attenuation occurs more slowly. The lower the degree of coherence of the Airy beam, the less effective it is against turbulence. It shows that the partially coherent beam can mitigate the effects of atmospheric turbulence to some degree. When the transmission distance was 7.5 km, the few-mode fiber's coupling effectiveness with a PCA beam was 29.8%, making it appropriate for long-distance transmission.

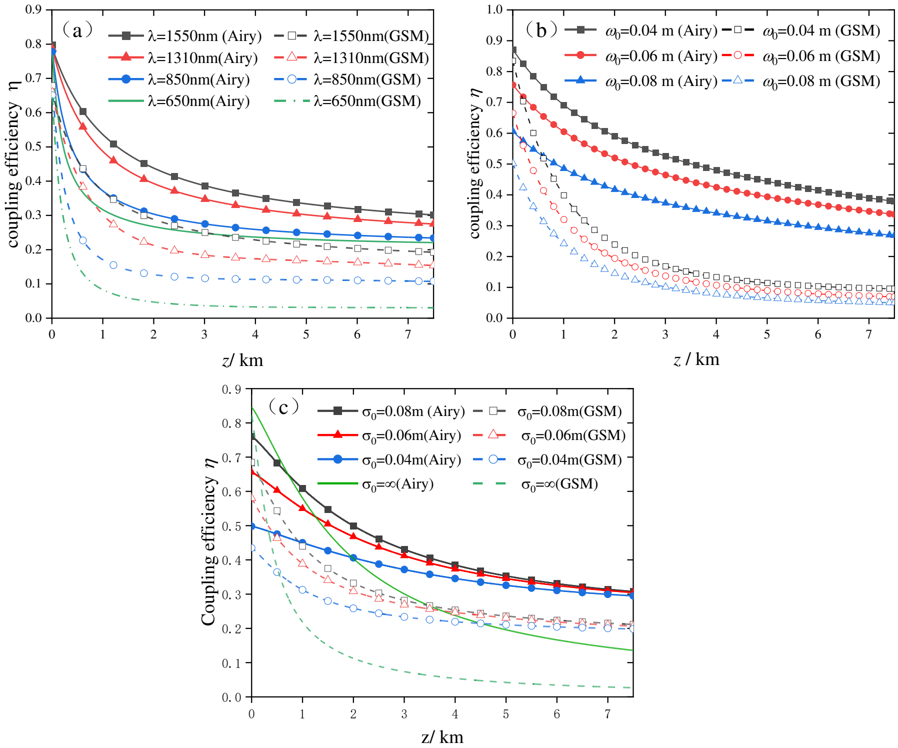

Figure 3. (a) The fiber coupling efficiency η as a function of propagation distance z with different wavelength λ. **(b)** The fiber coupling efficiency η as a function of propagation distance z with different beam width w_0 **(c)** The fiber coupling efficiency η as a function of propagation distance z with different coherent length σ_0.

Figure 4 (a) shows the fiber coupling efficiency η plotted against air coherence length r_0 with varying receiver lens diameter D. The strength of air turbulence can be expressed as the atmospheric coherence length, or r_0. The turbulence strength decreases with increasing atmospheric coherence length. The curve's fluctuating trend indicates that, if the receiver lens's diameter D remains constant, the coupling efficiency progressively rises as the atmospheric coherence length does, until reaching the optimal coupling efficiency. This is due to the fact that turbulence strength, beam drift, and expansion effects all decrease with increasing atmospheric coherence length. It is discovered that, under the identical circumstances, PCA coupling efficiency is significantly higher than GSM coupling efficiency by comparing the curve corresponding to the various receiver lens diameters. When the air coherence length is the same, the coupling efficiency that corresponds to the curve with the big receiver lens diameter is modest.

Figure 4 (b) shows how the fiber coupling effectiveness of a PCA beam in atmospheric turbulence varies with the amount of speckles A_R/A_C. The coupling efficiency reduces as the number of speckles increases. The PCA beam's coupling efficiency changes at a slower rate than the GSM beam's, but its total coupling efficiency is higher under the same turbulence conditions. This occurs as a result of the Airy beam's self-focusing properties during propagation. The self-focusing propagation characteristics improve the coupling efficiency by reducing the spot size and causing energy convergence. They also boost the energy of beam coupling into the fiber after it passes through atmospheric turbulence.

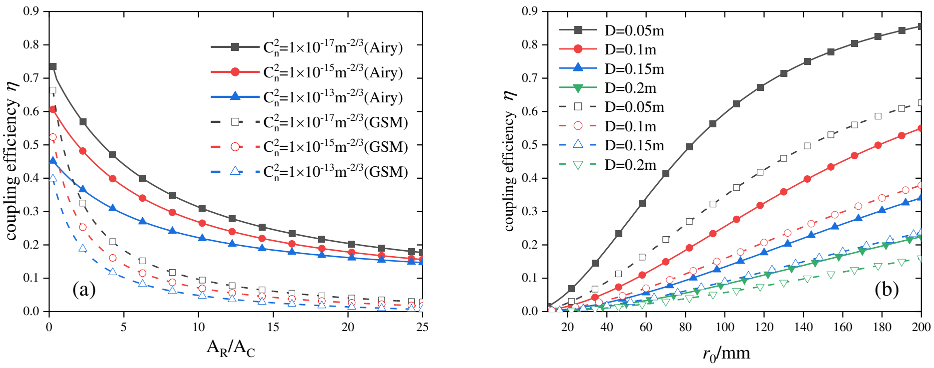

Figure 4. (a) The fiber coupling efficiency η as a function of the number of speckles A_R/A_C with different refractive index structure constant C_n^2 . **(b)** The fiber coupling efficiency η as a function of atmospheric coherence length r_0 with different receiver lens diameter D.

4. Conclusions

After taking into account the impacts of the coupling lens, turbulence, and beam characteristics, we get the equation of the fiber coupling efficiency for the partially coherent Airy beam propagating through atmospheric turbulence. Numerical analyses demonstrate that the PCA beam's fiber coupling efficiency is consistently higher than that of the GSM beam. The following are the relationships between the light source, atmospheric turbulence, and fiber coupling efficiency: the number of speckles A_R/A_C, the refractive index structure constant C_n^2, and the propagation distance z all decrease with increasing fiber coupling efficiency. Furthermore, the results demonstrate that the amount of speckles A_R/A_C is a critical factor influencing fiber coupling efficiency. However, a better coupling efficiency will be attained when both a longer wavelength and an optimum coherent length σ0 are satisfied. Under the same conditions, the fiber coupling efficiency of a PCA beam following atmospheric turbulence exceeds that of a GSM beam. These equations demonstrate that Airy beams' non-diffraction, self-recovery, and self-focusing properties can efficiently mitigate the unfavorable impacts of atmospheric turbulence, enhancing fiber coupling efficiency. Airy beam, as an optical source, has a much better fiber coupling efficiency. Furthermore, an examination of the effect of Airy beam, turbulence, and coupling lens parameters on coupling efficiency can be used to build a fiber-coupled atmospheric communication link using a partially coherent Airy beam.

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