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Demonstration of horizontal free-space laser communication with the effect of the bandwidth of adaptive optics system

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ABSTRACT

The performance of free-space laser communication (FSLC) is greatly decreased by horizontal atmospheric turbulence. Adaptive optics is used to overcome horizontal turbulence. This study investigated the effect of the 3 dB bandwidth of an adaptive optics system (AOS) on FSLC performance by using power-in-bucket (PIB) method, which considers the effect of receiving aperture and then, can accurately evaluate of the effect of system bandwidth on the communication performance. A 9 km horizontal maritime link experiment was performed through adaptive correction to validate the theoretical analysis. Results indicate that the effect of system bandwidth can be accurately evaluated using PIB method. This work provides a basis for designing and evaluating AOSs for FSLC.

1. Introduction

Free-space laser communication (FSLC) has been widely studied because of its advantages of high bandwidth, strong ability to resist interception, and anti-interference [1–4]. However, the communication performance of FSLC in earth-to-satellite and horizontal links is greatly decreased due to the effect of atmospheric turbulence [5–9]. To solve this problem, previous studies adopted adaptive optics (AO) technique in FSLC systems and analyzed the effects of adaptive correction on communication bit error rate (BER) [10–15]. Many researchers have also studied the effect of residual aberrations on FSLC performance while different Zernike modes are corrected [16–21]. The influence of the 3 dB bandwidth (f_{3dB}) of AO was also studied with variations in Greenwood frequency (f_G) [22,23]. Kaufmann studied the effect of f_G/f_{3dB} on the performance of coherent communication and used Strehl ratio (SR) to represent the receiving energy efficiency of FSLC to calculate BER [24]. By using this method, Liu et al. performed numerical simulation [25] and Cao et al. conducted validation experiment in laboratory [26].

Previous works used SR to represent the receiving energy efficiency of FSLC but did not consider the influence of the laser-receiving end face area. However, the small size of the end could affect the coupling efficiency (CE) and BER of FSLC. As such, SR method cannot precisely evaluate the receiving energy efficiency. To overcome this shortcoming, our group proposed power-in-the-bucket (PIB) method [27]. In the present study, we aim to establish the relation between PIB and f_G/f_{3dB} and accurately evaluate the effect of the system bandwidth on communication BER. We also conducted an experiment using 9 km maritime laser communication to validate the theoretical model.

2. Analysis of the effect of system bandwidth through PIB method

2.1. CE

The adaptive correction of FSLC is simplified in Fig. 1. A laser beam with initial phase ϕ_0 is distorted by atmospheric turbulence, and distorted wave-front is represented with ϕ. The distortion is corrected by deformable mirror (DM), and residual error is $\phi_r = \phi - \phi'$, where ϕ' is the compensation signal. After the correction, the laser is received by an optical system with entrance pupil diameter D and focal length f, and then coupled into a fiber with cross-sectional radius R. The entrance pupil and focal planes are expressed with the polar coordinates (ρ, θ) and (γ, φ), respectively.

The receiving energy of the fiber should be first obtained to calculate CE. Based on our previous work, receiving energy disturbed by

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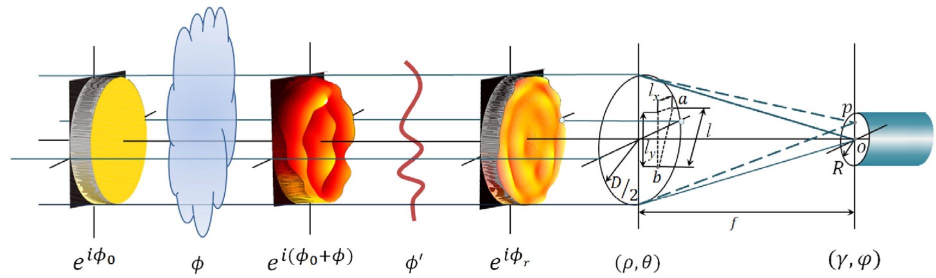

Fig. 1. Diagram of FSLC with adaptive correction.

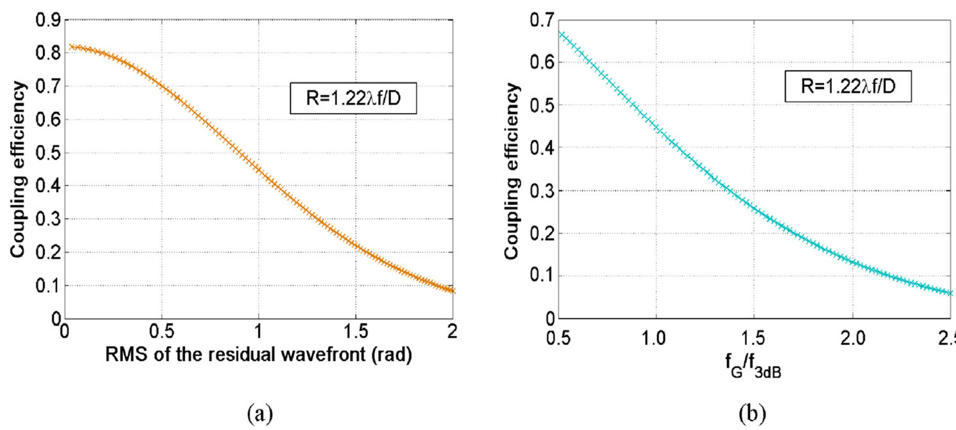

Fig. 2. CE varies with (a) correction error and (b) f_G/f_{3dB} with $R = 1.22\lambda f/D$.

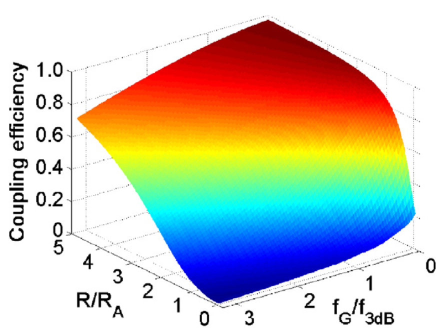

Fig. 3. CE as a function of f_G/f_{3dB} and R/R_A.

turbulence can be computed accurately with PIB method [27]:

$$\begin{aligned}\langle PIB\rangle &= \zeta \int_0^2 \left\langle \int_S \exp[i\phi(\rho)]\exp^*[i\phi(\rho+l)]\,d\rho \right\rangle \times \frac{2RJ_1(\pi Rl)}{l}dl \\ &= \pi^2\left(\frac{AD^2}{4\lambda f^2}\right)^2 \int_0^2 \left(0.15l^4 - 0.275l^3 - l^2 + 2l\right) \\ &\quad \cdot \int_{-\infty}^{\infty} \cos(\Phi)\, f(\Phi)\, d\Phi \times \frac{2RJ_1(\pi Rl)}{l}dl,\end{aligned} \tag{1}$$

where $\Phi = \phi(\rho) - \phi(\rho+l)$, l is the distance between any two points in the pupil area S, A is the amplitude of the incident optical field; λ is the wavelength of the laser, J_1 is the first-order Bessel function, and $f(\Phi)$ is the distribution density function of Φ. This function follows the normal distribution, and the expectation is zero. Thus, $f(\Phi)$ may be expressed as:

$$f(\Phi) = \frac{1}{\sqrt{2\pi\langle\Phi^2\rangle}} \exp\left(-\frac{\Phi^2}{2\langle\Phi^2\rangle}\right). \tag{2}$$

While the laser transmits through atmospheric turbulence, the variance of ϕ can be determined with Kolmogorov model [28]:

$$\langle\Phi^2\rangle = \left\langle[\phi(\rho) - \phi(\rho+l)]^2\right\rangle. \tag{3}$$

For wave-front after the correction, the following equation may be obtained:

$$\Phi_r = \phi_r(\rho) - \phi_r(\rho+l). \tag{4}$$

After substituting $\phi_r = \phi - \phi'$ into Eq. (4), Φ_r can be rewritten as:

$$\begin{aligned}\Phi_r &= \left[\phi(\rho) - \phi'(\rho)\right] - \left[\phi(\rho+l) - \phi'(\rho+l)\right] \\ &= \left[\phi(\rho) - \phi(\rho+l)\right] - \left[\phi'(\rho) - \phi'(\rho+l)\right] \\ &= \Phi - \Phi'\end{aligned} \tag{5}$$

As Φ obeys normal distribution and compensation signal Φ' is conjugated to Φ, Φ' also obeys normal distribution. According to Eq. (5), Φ_r also obeys normal distribution. Therefore, the variance of ϕ_r may be written as [29]:

$$\sigma_r^2 = \langle\Phi_r^2\rangle = \left\langle\left[\phi_r(\rho) - \phi_r(\rho+l)\right]^2\right\rangle, \tag{6}$$

where σ_r is the average RMS of ϕ_r (unit is rad).

After the adaptive correction, the receiving energy of FSLC may be expressed as:

$$\begin{aligned}\langle PIB\rangle_r &= \pi^2\zeta \int_0^2 \left(0.15l^4 - 0.275l^3 - l^2 + 2l\right) \times \\ &\quad \left[\int_{-\infty}^{\infty} \cos(\Phi_r)\frac{1}{\sqrt{\pi\cdot 2\sigma_r^2}}\exp\left(-\frac{\Phi_r^2}{2\sigma_r^2}\right)d\Phi_r\right] \\ &\quad \times \frac{2RJ_1(\pi Rl)}{l}dl.\end{aligned} \tag{7}$$

CE is usually computed by:

$$CE = \frac{\langle PIB\rangle_r}{Power_{No\_turb}} = \frac{\langle PIB\rangle_r}{A^2\left(\frac{\pi D^2}{4}\right)}, \tag{8}$$