Optics & Laser Technology 47 (2013) 315–322

Contents lists available at SciVerse ScienceDirect

Optics & Laser Technology

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

Beam propagation through an optical system with the two-adaptive-optics configuration and beam shaping

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ARTICLE INFO

Article history:
Received 10 July 2012
Received in revised form
6 September 2012
Accepted 10 September 2012
Available online 13 October 2012

Keywords:
Beam propagation
The two-adaptive-optics configuration
Beam shaping

ABSTRACT

Beam propagation through an optical system with the two-adaptive-optics configuration and beam shaping has been investigated. In theory, we analyzed beam propagation through the optical system in turbulent atmosphere and calculated performance of the optical system under the H-V 5/7 turbulent model, the ITU-R turbulent model, the Shanxi district turbulent model and the Hefei district turbulent model in China, respectively. The theoretical results showed that performance of the optical system can be significantly improved by beam shaping. With ideal adaptive optics correction precision, power efficiency of the received beam can be improved from 81.27% to 92.00%, and the system performance factor can be improved from 0.61 to 0.67 under the H-V 5/7 turbulent model. In experiment, we found an experimental optical system under the laboratory conditions by using two Liquid Crystal Spatial Light Modulators, and carried out the reduced-scale experiment. The experimental results showed that power efficiency of the received beam can be improved from 71.89% to 87.88%, and power proportion in the bucket with 5 pixels radius at the target can be improved from 44.53% to 52.78% by beam shaping.

1. Introduction

In optical systems such as the laser relay mirror system and the free-space optical communication system, beam propagates long-distance through the turbulent atmosphere,and the uplink beam is received as a new source for further propagation [1–3]. Previous research have shown that two ingredients seriously degrade the system performance: one is the aberrations induced by atmospheric turbulence along the propagation path [3,4]; the other is the serious power losses induced by receiver inner obstruction and outer truncation [5,6]. Application of the two-adaptive-optics configuration is an effective way to compensate the aberrations induced by atmospheric turbulence [4,7]. In an optical system with the two-adaptive-optics configuration, a cooperative beacon and two adaptive optics (AO) installations are employed: the cooperative beacon that propagates from the receiver to the launcher is used to sense atmospheric distortions along the propagation path in real time; the AO installation that locates at the launcher plane is used to induce phase pre-correction to the atmospheric turbulence; the AO installation that locates at the receiver plane is used to clean phase of the received beam [3,4,7,8]. As reference [8] described, if the AO system does a good job of correcting the phase, the resulting performance will be near the diffraction limit. Based on the two-adaptive-optics configuration, beam shaping is introduced to decrease power losses in the optical system. Phase distribution of the source is optimized by the AO installation to adjust beam intensity distribution at the receiver plane, and then improve power efficiency of the optical system [9,10]. Phase modulation induced by the AO installation at the launcher includes two parts, which are phase pre-correction to the turbulence and phase modulation used for beam shaping [9,10].

Beam propagation through an optical system with the two-adaptive-optics configuration and beam shaping is a new area of scientific research. In the present paper, we theoretically analyze beam propagation through an optical system with the two-adaptive-optics configuration and beam shaping, simulate performance of an optical system with determinate parameters under different turbulent models, and carry out a reduced-scale experiment under the laboratory conditions.

2. Models and theoretical analysis

2.1. Models and performance evaluation factor

A typical model of optical systems with the two-adaptive-optics configuration and beam shaping is shown in Fig. 1. The optical system is composed of the source, the launcher Cassegrain telescope, the receiver Cassegrain telescope, the cooperative

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http://dx.doi.org/10.1016/j.optlastec.2012.09.012

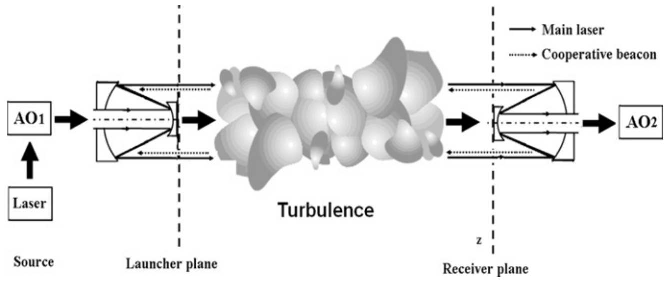

Fig. 1. Model of an optical system with the two-adaptive-optics configuration and beam shaping.

beacon, two AO installations and other units [3,4,7,8]. Beam propagates from the launcher telescope to the receiver telescope, phase distribution of the source is modulated by AO1 and phase distribution of the uplink beam at the receiver is cleaned up by AO2. The received beam is used as a new source for further propagation. Phase modulation induced by AO1 includes two parts, which are phase pre-correction to the turbulence and phase modulation used for beam shaping. The cooperative beacon propagates from the receiver to the launcher, which is used to sense atmospheric aberrations in the propagation process in real time. By using the Huygens–Fresnel principle, optical field at the receiver plane can be expressed as

$$U_1(x,y,z)=\frac{e^{jkz}}{j\lambda z}\iint U_0(\varepsilon,\eta)e^{j\phi(\varepsilon,\eta)}e^{j\varphi(\varepsilon,\eta)}e^{j\frac{k}{2z}[(x-\varepsilon)^2+(y-\eta)^2]}d\varepsilon d\eta \tag{1}$$

$$\varphi(\varepsilon,\eta)=\varphi_1(\varepsilon,\eta)+\varphi_2(\varepsilon,\eta) \tag{2}$$

where λ is the wavelength, $k=2\pi/\lambda$ is the wave number, z is beam propagation distance, $U_0(\varepsilon,\eta)$ denotes the optical field of the source, $\varphi(\varepsilon,\eta)$ denotes the turbulence phase-screen at the launcher plane, $\varphi(\varepsilon,\eta)$ denotes phase modulation induced by AO1, $\phi_1(\varepsilon,\eta)$ denotes phase pre-correction to the turbulence, $\phi_2(\varepsilon,\eta)$ denotes phase modulation used for beam shaping. By using the Zernike polynomials, $\varphi(\varepsilon,\eta)$ can be expressed as

$$\varphi(\varepsilon,\eta)=\sum_{j=1}^{N_1}a_jZ_j(\varepsilon,\eta) \tag{3}$$

where Z_j denotes the j-th Zernike polynomial, a_j denotes the j-th Zernike polynomial coefficient, N_1 denotes the highest correction order of AO1. Optical field of the received beam can be expressed as

$$U_d(x,y,z)=U_1(x,y,z)t(D_0,D_1)e^{i\psi(x,y)} \tag{4}$$

$$t(D_0,D_1)=\begin{cases}1 & \frac{D_0}{2}\le\sqrt{x^2+y^2}\le\frac{D_1}{2}\\ 0 & else\end{cases} \tag{5}$$

$$\psi(x,y)=\sum_{j=1}^{N_2}b_jZ_j(x,y) \tag{6}$$

where $t(D_0,D_1)$ is the truncation function of the receiver, D_0 is the inner diameter and D_1 is the outer diameter, $\psi(x,y)$ denotes phase modulation induced by AO2, N_2 denotes the highest correction order of AO2. Power of the received beam can be expressed as

$$P_1=\int\int U_d(x,y,z)U_d(x,y,z)^*dxdy \tag{7}$$

where the asterisk denotes the complex conjugation. Power efficiency of the received beam can be expressed as

$$T=P_1/P_0 \tag{8}$$

where $P_0=\int\int U_0(\varepsilon,\eta)U_0(\varepsilon,\eta)^*d\varepsilon d\eta$ denotes the source power. BPF is a factor widely used to evaluate beam quality [11,12], which is defined as ratio of power in diffraction limit radius bucket in far field and the source power. In the optical system, BPF of the received beam can be expressed as

$$BPF=P_t/P_1 \tag{9}$$

$$P_t=\iint_{\sqrt{w^2+v^2}\le R_0}U_t(w,v)U_t(w,v)^*dwdv \tag{10}$$

where P_t denotes power in diffraction limit radius bucket in far field, $U_t(w,v)$ denotes the optical field in far field, R_0 denotes the diffraction limit radius. Therefore, power in diffraction limit radius bucket in far field of the received beam can be expressed as

$$P_t=P_0\times T\times BPF \tag{11}$$

Thus, we introduce a factor J which is defined as ratio of power in diffraction limit radius bucket in far field and the source power

$$J=P_t/P_0 \tag{12}$$

From Eq. (11), we can get that J denotes the product of power efficiency and beam quality of the received beam. In the present paper, we take J as the evaluation factor of the system performance.

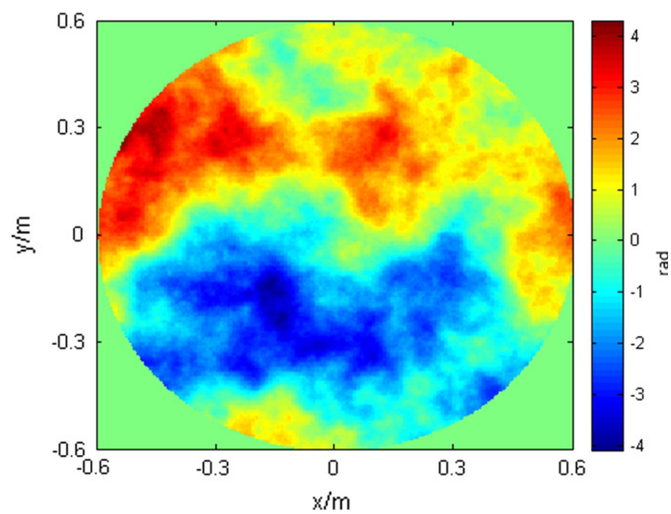

Fig. 2. Distribution of the turbulence phase-screen.

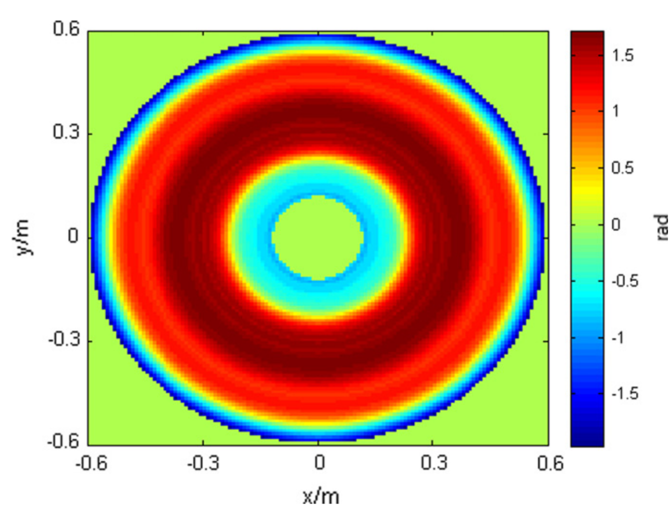

Fig. 3. Distribution of the optimal phase used for beam shaping.