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The influence of high-frequency phase distortion on the phase correction effect in atmospheric turbulence

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ABSTRACT

By using the method of the power-spectrum inversion, the turbulence phase screen has been built up, and the propagation characteristics of high-frequency phase of laser beam in atmospheric turbulence have been analyzed; in addition, the phase correction effect of laser beams by using the adaptive deformable mirror has been simulated, and its affecting factors in turbulence have also been analyzed quantitatively. The results show that the phase correction effect of laser beams in turbulence is mostly determined by the percent of high-frequency phase in distorted wavefront. With the increase of the intensity of atmospheric turbulence and the propagation distance in turbulence, the percent of high-frequency phase in distorted wavefront increases, resulting in the degradation of the phase correction effect.

1. Introduction

In the process of propagation in atmospheric space, the wavefront phase of high-power laser beams is often distorted due to the influence of atmospheric turbulence, resulting in the degradation of the beam quality on target position [1–3]. The adaptive optics (AO) system can effectively improve beam quality by optical deformable mirror (DM) to compensate distorted wavefront [4–6]. In the early 1970s, the AO system was used in the research of astronomy, and effectively overcame the influence of atmospheric turbulence on the wavefront of beams [7,8]. Nevertheless, the correction effect of the AO system is not effective enough in strong turbulence, Voitsekhovich, Fried and Vaughn thought presented out that the effect of phase correction is influenced by the intensity of atmospheric turbulence and the propagation distance [9–11]. However, according to the previous research of our team, the phase correction effect of laser beams with AO system is related to the high-frequency phase of distorted wavefront [12,13]. So far to our knowledge, there has been no exact report to study on the propagation characteristics of high-frequency phase and its influence on the effect of adaptive phase correction in atmospheric channel.

This paper focuses mainly on the propagation characteristics of high-frequency phase of laser beams in turbulence and the corresponding phase correction effect. Firstly, the propagation characteristics of distorted wavefront phase in atmospheric turbulence has been discussed by constructing random phase screens with the method of the power-spectrum inversion, and the influence of atmospheric turbulence on high-frequency phase has been further analyzed quantitatively; secondly, the process of phase correction has been simulated numerically with the method of high-pass filtering, and the key factors affecting the correction effect in turbulence have also been discussed.

2. Theoretical model

In order to analyze the propagation characteristics of high-frequency phase and its influence on the effect of adaptive phase correction in atmospheric turbulence, the near field distributions of laser beam and the phase screen of atmospheric turbulence are given as follows.

2.1. The model of beam with wavefront distortion

In the system of national defense, the high-power chemical laser is used to attack the targets. The cavity of high-power chemical lasers is usually unstable, and the output beam is annular beam. The near field distribution of output beam can be expressed as [14]:

$$U_0 = \sum_{|n|=L}^{K} \exp\left(-\left(\frac{\sqrt{x_0^2+y_0^2}-n\cdot w_0}{w_0}\right)^2\right)\cdot \exp(-i\cdot\varphi_0(x_0,y_0)) \cdot (L \le K) \quad (1)$$

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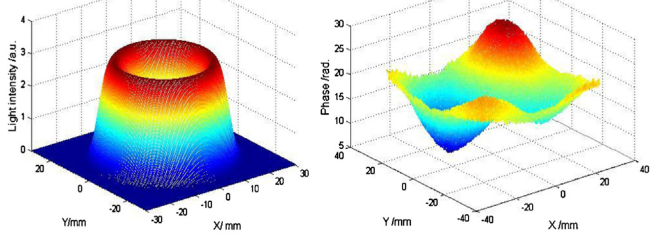

(a) (b)

Fig. 1. Distributions of annular beam. (a) Intensity I_0; (b) phase φ_0.

where w_0 is the radius of centrifugal Gaussian beam, L and K (L, K = 0,1,2...) are the beam order of annular beam, $\varphi_0(x_0,y_0)$ is the initial phase distribution of output beam.

For the high-power chemical laser, the wavefront of output beam is usually distorted, so $\varphi_0(x_0,y_0)$ can be expressed as:

$$\varphi_0(x_0, y_0) = \varphi_{0l}(x_0, y_0) + \varphi_{0h}(x_0, y_0) \tag{2}$$

where $\varphi_{0l}(x_0, y_0)$ denotes the low-frequency phase of distorted wavefront, and $\varphi_{0h}(x_0,y_0)$ represents the high-frequency phase of distorted wavefront.

The low-frequency phase $\varphi_{0l}(x_0,y_0)$ can be expressed as[12]:

$$\varphi_{0l}(x_0, y_0) = A \cdot \text{random}(-1, 1) \otimes \exp\left\{-\left(\left(\frac{x_0}{g_x}\right)^2 + \left(\frac{y_0}{g_y}\right)^2\right)\right\} \tag{3}$$

where A is the amplitude coefficient of low-frequency phase, random(−1,1) denotes two-dimensional random numbers with uniform distribution from −1 to 1, ⊗ denotes convolution, g_x and g_y are the phase parameters along x- and y-directions, respectively.

The high-frequency phase $\varphi_{0h}(x_0, y_0)$ can be expressed as:

$$\varphi_{0h}(x_0, y_0) = \sigma \cdot \text{random}(-1, 1) \tag{4}$$

where σ is the amplitude coefficient of high-frequency phase.

According to Eqs. (1)–(4), the near field distributions of annular beam are shown in Fig. 1 The parameters used for calculation are as follows: L = 3, K = 5 (the corresponding obstruction ratio is 1:3), w_0 = 8 mm, λ = 3.8 μm, A = 0.4, $g_x = g_y$ = 20 mm, σ = 0.8.

2.2. The model of the random phase screen of atmospheric turbulence

For the field of atmospheric turbulence, which meets the statistics law of Kolmonogov, the method of power spectrum inversion is adopted to construct the random phase screen of atmospheric turbulence [15].

When the laser beam propagates in atmospheric space, the additional phase Φ caused by atmospheric turbulence can be obtained, which can be expressed as:

$$\Phi = \Phi_L + \Phi_H \tag{5}$$

where Φ_L is the low-frequency phase, and Φ_H is the high-frequency phase.

The additional phase of high-frequency can be expressed as [3]:

$$\phi_H(x_m, y_n) = \frac{2\pi}{\sqrt{G_x G_y}} \sum_{m'=-N_x/2}^{N_x/2-1} \sum_{n'=-N_y/2}^{N_y/2-1} \exp\left(\frac{2\pi i m m'}{N_x} + \frac{2\pi i n n'}{N_y}\right) \cdot h(f_{xm'}, f_{yn'}) \sqrt{0.00058 r_0^{-5/3} (f_{xm'}^2 + f_{yn'}^2)^{-11/6}} \tag{6}$$

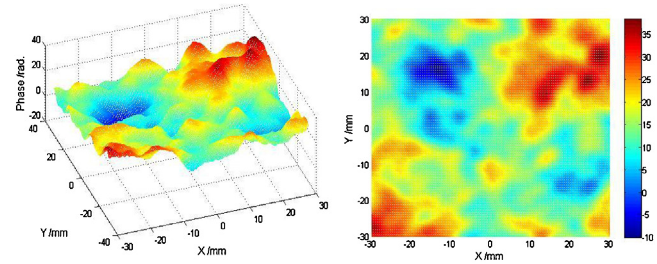

Fig. 2. Distribution of wavefront phase with z = 500 m.

where $G_x \times G_y$ is the size of the turbulence screen, $N_x \times N_y$ is the number of sampling; $x_m = m/G_x$, $y_n = n/G_y$, $-N_x/2 \le m \le N_x/2$, $-N_y/2 \le n \le N_y/2$, $f_{xm'} = m'/G_x$, $f_{yn'} = n'/G_y$; r_0 is the coherence diameter, $h(f_{xm'}, f_{yn'})$ is a complex random numbers with zero mean and unit variance, r_0 and $h(f_{xm'}, f_{yn'})$ can be expressed as:

$$r_0 = 0.185 \left[\frac{\lambda^2}{\int_z^{z+\Delta z} C_n^2(\xi) d\xi}\right]^{3/5} \tag{7}$$

$$\left\langle h(f_{xm'}, f_{yn'}) \right\rangle = 0 \tag{8}$$

$$\left\langle h(f_{xm'}, f_{yn'}) \cdot h^*(f_{xm''}, f_{yn''}) \right\rangle = \delta_{m'm''} \delta_{n'n''} \tag{9}$$

The low-frequency phase can be expressed as [3]:

$$\phi_L(x_p, y_q) = \sum_{p'=-N'_x/2}^{N'_x/2} \sum_{q'=-N'_y/2}^{N'_y/2} \exp\left(\frac{2\pi i p p'}{N'_x} + \frac{2\pi i q q'}{N'_y}\right) \times \beta(f_{xp'}, f_{yq'}) \tag{10}$$

where

$$\beta(f_{xp'}, pf_{yq'}) = \frac{2\pi}{\sqrt{N'_x N'_y G_x G_y}} h(f_{x_{p'}}, f_{y_{q'}}) \times \sqrt{0.00058 r_0^{-5/3} (f_{xp'}^2 + f_{yq'}^2 + (2\pi L_0)^{-2})^{-11/6}} \tag{11}$$

are the Fourier coefficients. Here, $x_p = pG_x$, $y_q = qG_y$, $f_{xp'} = p'/G_x$, $f_{yq'} = q'/G_y$.

3. The propagation characteristics of laser wavefront in atmospheric turbulence

As we know, the effect of adaptive phase correction is affected by the intensity of atmospheric turbulence and the propagation distance in atmospheric channel. But, what is the relationship among the wavefront phases, the intensity of atmospheric turbulence and the propagation distance?

Assume that the structure function of atmospheric refractive index $C_n^2(z)$ is 3×10^{-15} m$^{-2/3}$. When laser beam given in Fig. 1 propagates horizontally for 500 m in atmospheric space, according to Eqs. (1)–(11), the phase distribution of the laser beam after atmospheric space is shown in Fig. 2.

According to Figs. 1 and 2, when laser beam propagates horizontally for 500 m in atmospheric space, the phase distribution of the laser beam is ups and downs with random characteristics, and the peak-valley (PV) value of wavefront is 6.096λ, but the PV value of wavefront before the atmospheric channel is 3.585λ, it indicates that the effect of atmospheric turbulence amplifies the wavefront distortion of laser beam.

In order to study further the spectral characteristics of wavefront phase, the power spectral density (PSD) of wavefront is