ADAPTIVE OPTICS FOR REDUCTION OF THERMAL BLOOMING EFFECTS BY THE PHASE COMPENSATION

Shuyun Wu,1,2,3 Xi Luo,1,2* and Xinyang Li1,2

1 Key Laboratory on Adaptive Optics, Chinese Academy of Sciences
Chengdu 610209, China

2 Institute of Optics and Electronics, Chinese Academy of Sciences
Chengdu 610209, China

3 University of Chinese Academy of Sciences
Beijing 100049, China

*Corresponding author e-mail: luoxi@ioe.ac.cn

Abstract

We study the employment of an adopted optics system for the reduction of thermal blooming effects by the phase correction of a 1.064 μm laser. The energy concentration of the beam spot in the far-field substantially increases if the adaptive optics system is performed in a closed loop. The phase compensation of the adapted optics system is effective for a Bradley–Hermann distortion number of less than 130. The experimental results obtained are in good agreement with the simulation results. This study provides many physical explanations and important conclusions for using adaptive optics to reduce the thermal blooming effect.

Keywords: thermal blooming, adaptive optics, phase compensation.

1. Introduction

Heat-induced changes in optical parameters of a medium leads to changes in the radiation propagation of high-energy laser (HEL) beams. This change is referred to as “thermal blooming” [1–6]. Thermal blooming causes a negative-lens-like optical effect in the atmosphere that blooms energy out of the beam. This phenomenon can defocus, scatter, and distort the optical beam [7]. An adaptive optics (AO) system corrects the effects of thermal blooming by applying a positive-lens-like compensation to the HEL beam; in theory, by focusing the HEL beam, this should override the blooming [8].

Bradley and Herrmann investigated the use of AO systems to mitigate nonlinear optical effects induced by thermal blooming. They demonstrated an improvement in the system performance with the phase compensation of thermal blooming [9]. Since then, several research institutions have studied the HEL propagation in the atmosphere and its phase correction, such as MIT Lincoln Laboratory [10,11], Lawrence Livermore National Laboratory [12], and the Air Force Weapons Laboratory [13]. However, there are few experimental reports on the phase compensation of thermal blooming by AO systems.

The purpose of this research is to demonstrate the use of an AO system to correct the phase of a collimated Gaussian beam and reduce thermal blooming. The AO system was also used to increase the peak far-field irradiance by correcting the phase of aberrations in the optical system used for the blooming experiments.
2. Theoretical Analysis

The irradiance distribution \( I(x, y) \) of a collimated Gaussian beam is expressed as

\[
I(x, y) = \frac{2P}{\pi w^2} \exp \left[ -2 \frac{x^2 + y^2}{w^2} \right],
\]

(1)

where \( P \) is the initial beam power, and \( D = 2w \) is the \( 1/e^2 \) intensity beam diameter. The phase distortion \( \phi_B \) accumulated along the propagation path \( L \) and induced by steady-state thermal blooming, which was assumed to be a constant absorption coefficient, \( \alpha \), and a transverse wind speed, \( V \) (such as along \( X \)-axis positive direction), is given by

\[
\phi_B(x, y) = n_T \frac{\alpha}{\rho_0 C_p} \frac{kL}{V} \int_{-\infty}^{x} I(x', y) \, dx',
\]

(2)

where \( n_T = \frac{dn}{dT} \) is a change in the refractive index with respect to the medium temperature at the constant pressure, and \( \rho_0, k, \) and \( C_p \) are the density, wave number, and specific heat at the constant pressure, respectively [14].

By substituting Eq. (1) into Eq. (2), the blooming phase \( \phi_{BG} \) is obtained as

\[
\phi_{BG} = -\frac{\Delta \phi_G}{2} \exp \left[ -2 \left( \frac{y}{w} \right)^2 \right] \left[ 1 + \text{erf} \left( \frac{x\sqrt{2}}{w} \right) \right],
\]

(3)

The maximum phase shift is

\[
\Delta \phi_G = (1/2\sqrt{\pi})N_D,
\]

(4)

where

\[
N_D = \frac{4\sqrt{2}(-n_T)k\alpha PL}{\rho_0 C_p V D}
\]

(5)

is the Bradley–Hermann distortion number commonly used as a measure of the strength of thermal blooming [14]. Information on the phase distortion can be obtained by the Shack–Hartmann wavefront sensor in an open-loop adaptive optics system. In view of Eq. (5), one obtains the Bradley–Hermann thermal distortion parameter \( N_D \) of the experiment.

3. Numerical Calculation Results and Analysis

The thermal blooming effect of laser beams propagating through the horizontal atmosphere was studied by performing numerical simulations on Easy Laser software [15]. In particular, the phase screen simulation method was based on a procedure that replaced a continuous medium of radiation by a sequence of thin screens simulating distortions acquired by the optical wave through its propagation [16]. Figure 1 shows a simulation of the AO system correcting the thermal blooming by applying the phase compensations. For the simulation, we used an AO system that performed the phase compensation using a Shack–Hartmann (SH) wavefront sensor (WFS), a tilt mirror (TM), and a deformable mirror (DM) with 127 actuators.
Fig. 1. Schematic diagram of the AO system correcting the thermal blooming by applying the phase compensations in software.

Fig. 2. Schematic of the AO system for the phase compensation of the thermal blooming setup.

In Fig. 2, we show a schematic of the AO system for the phase compensation of the thermal blooming setup. In this scenario, a beacon signal was transmitted from the target plane to the source plane with the effects of current phase screen due to thermal blooming. The phase of the beacon in the source plane was then applied directly to the HEL beam, and the idealized phase compensation process was repeated.

In Table 1, we present the parameters used in the simulation.
### Table 1. Simulation Parameters.

| Simulation                                      | Set up                   |
|------------------------------------------------|--------------------------|
| Effective aperture of SH WFS, mm                | 148                      |
| SH WFS subapertures size (Relay optical path), mm | 12.33                    |
| Layout of SH WFS subapertures                   | 12×12                    |
| SH WFS subaperture pixel                        | 20                       |
| SH WFS subaperture single-pixel field angle     | 24.5                     |
| (relay optical path), μrad                      |                          |
| Number of deformable mirror actuators           | 127                      |
| Distance between deformable mirror actuators    | 12.2                     |
| (relay optical path), mm                        |                          |
| System sampling frequency, Hz                   | 1,000                    |
| Simulated laser distribution                    | Collimated Gaussian beam |
| Simulated beacon distribution                   | Plane wave beam          |
| Simulated laser wavelength, μm                  | 1.064                    |
| Simulated beacon wavelength, μm                 | 0.532                    |
| Beacon beam diameter (Relay optical path), mm   | 148                      |
| Telescope magnification                         | 5                        |
| Telescope focal length                          | Infinity                 |
| Transmission aperture of collimated beam        | 740                      |
| in horizontal atmosphere, mm                    |                          |
| Transmission distance of collimated beam        | 2                        |
| in horizontal atmosphere, km                    |                          |
| Absorption coefficient, 1/km                    | 0.07                     |
| Transverse wind speed, m/s                      | 2                        |
| Density, kg/m³                                  | 1.213                    |
| Specific heat at constant pressure, J/kg·K      | 1,006                    |
| Refractive index change with respect to temperature, 1/K | $-1.0424^{-6}$          |

In the simulations, the Bradley–Hermann distortion parameter $N_D$ can be changed by adjusting the laser power (from 3000 to 39,000 W). A quantitative assessment of the relative power-in-the-bucket (PIB) was performed to analyze the far-field spot. The most common metric for gauging the performance of HEL systems is PIB, the power within a circular region in the cross section of the laser beam, which is situated at the laser aimpoint on the target [17]. The higher the distortion parameter, the likelier the increase in the bucket size. Comparison of bucket radii (PIB= 63.2%) in the far field (equivalent focal length = 3,365.992 m) with different Bradley–Hermann distortion numbers ($N_D = 10, 20, 30, 50, 70, 100, 120,$ and 130) between open-loop and closed-loop AO systems is given in Fig. 3.
Fig. 3. Comparison of bucket radii (PIB = 63.2%) in the far field with different Bradley–Hermann distortion numbers ($N_D = 10, 20, 30, 50, 70, 100, 120,$ and $130$) of open-loop (dotted curve) and closed-loop (solid curve) AO systems.
Figure 4 shows the bucket radii (PIB=63.2%) in far-field under different Bradley–Hermann distortion numbers with open-loop and closed-loop operations of the AO system.

Then, the magnification of the beam quality factor $\beta$ is used to evaluate the ability of the phase compensation of the AO system and reduce the thermal blooming effect. This evaluation method can effectively reduce system aberrations $\beta$ defined as

$$\beta = \frac{\theta_{\text{REAL}-\text{PIB}}}{\theta_{\text{IDEAL}-\text{PIB}}}$$

(6)

where $\theta_{\text{REAL}-\text{PIB}}$ and $\theta_{\text{IDEAL}-\text{PIB}}$ are the bucket sizes in the far field with specific powers of real and ideal scenarios, respectively [18]. Since $\theta_{\text{IDEAL}-\text{PIB}}$ does not depend on the open/closed loop of the AO system, the magnification of $\beta$ reads

$$\beta_{\text{Times}} = \frac{(\theta_{\text{REAL}-\text{PIB}})_{\text{Open-loop}}}{(\theta_{\text{REAL}-\text{PIB}})_{\text{Close-loop}}}.$$  

(7)

In this equation, $\beta_{\text{Times}} > 1$ means that compensation of the AO system influences the thermal blooming effect. The higher the $\beta_{\text{Times}}$, the greater the influence. The different values of $\beta_{\text{Times}}$ as a function of $N_D$ are shown in Fig. 5.

The simulation results of Fig. 5 reveal that the thermal blooming effect for a collimated Gaussian beam propagating through uniform wind can be significantly reduced using the AO system to make an appropriate phase compensation. The accumulation of heat at the beginning of the curve is weak, the influence of thermal blooming on the shape of the far-field spot is not severe, and the effect of the phase compensation is not particularly obvious. An important characteristic of the thermal blooming process is its effect on limiting the peak irradiance independently of the power available at the transmitter. The AO system mentioned above is effective in reducing the thermal blooming in the range of $N_D = 10 – 130$. Unfortunately, the HEL beam only concentrates the energy contained within the beam and further heats up the surrounding atmosphere. The AO system attempts to correct the increased blooming with even higher positive-lens-like compensation, and the process reinforces itself, ultimately causing failure of the AO system through thermal accumulation.

4. Experimental Results and Analysis

It is difficult to setup a full-scale experiment to investigate the phase compensation of thermal blooming. Such an experiment would require an HEL system, an AO system robust enough to handle the
HEL beam powers needed for thermal blooming, a test range, and a facility large enough to conduct the experiment. Therefore, from the perspective of feasibility, in this experiment, we used CH$_3$CH$_2$OH as the absorption medium and a low-power laser to generate severe thermal blooming. The experimental arrangement is illustrated in Fig. 6, and a picture of the experimental layout is shown in Fig. 7.

![Fig. 6. Schematic of the experiment with AO system for the phase compensation of thermal blooming.](image)

Parameters of the system used in the experiment are presented in Table 2.

**Table 2. Experimental Parameters of CH$_3$CH$_2$OH as the Absorption Medium.**

| Experiment Parameter                                      | Value               |
|-----------------------------------------------------------|---------------------|
| Effective wavelength of SH WFS, $\mu m$                   | 0.633               |
| SH WFS subapertures size (Clear aperture), mm             | 10×10               |
| Layout of SH WFS subapertures                             | 12×12               |
| SH WFS sampling frequency, Hz                             | 2,500               |
| DM actuators delivering the mechanical stroke, $\mu m$    | ±3                  |
| Number of DM actuators                                    | 127                 |
| Distance between DM actuators (Relay optical path), mm    | 12.2                |
| Effective wavelength of DM ($\mu m$)                      | 0.633 and 1.064     |
| Experimental laser distribution                           | Collimated Gaussian beam |
| Experimental beacon distribution                          | Plane wave beam     |
| Experimental laser wavelength, $\mu m$                    | 1.064               |
| Experimental beacon wavelength, $\mu m$                   | 0.633               |
| Laser power, W                                            | 1–3                 |
| Absorption coefficient of ethanol, cm$^{-1}$               | 0.11 [19]           |
| Length of the thermal blooming cell, cm                    | 15                  |
| Moving speed of the thermal blooming cell, mm/s            | 1–20                |
| Beam diameter in the thermal blooming cell, mm             | 8                   |
Layout of deformable mirror with 127 actuators is shown in Fig. 8. It should be noted that the theoretical range of $N_D$ that can be generated by a thermal blooming cell in the above scenario is approximately from 37 to 410. In the experiment, the transverse wind speed $V$ (from 1 to 20 mm/s) was simulated by transversing the platform [20]. A vast difference between the open-loop and closed-loop operations of the AO system can be observed. In Fig. 9, we show the results of the experiment with wave-front errors PV/RMS for the AO system’s operations for cases where $V$ was 5, 10, and 15 mm/s, respectively. In Fig. 9, a significant decrease in wavefront errors can be observed after the phase compensation of the closed-loop operation of the AO system for thermal blooming. It should be noted that the wavefront phase information provided by SH WSF while the AO system was performing the open-loop operation can deduce $N_D$ from Eq. (4). In these three scenarios, the $N_D$’s are 82.18, 74.08, and 49.27, respectively. Typical results of far-field images are shown in Fig. 10. In Fig. 10a, the beam spot in the far field affected by the thermal blooming with open-loop operation of the AO system shows a typical crescent shape. Figure 10b shows the correction capability of the AO system for thermal blooming. The far-field beam spot size of the corrected beam is reduced, and the shape is approximately circular with a slightly crescent-shaped trace.

Figure 11 shows the far-field bucket radius (PIB = 63.2%) under $N_D$ before and after compensation of the AO system. As shown in Fig. 11, the phase compensation of the AO system can substantially increase the energy concentration of the beam spot in the far field when $N_D$ are 82.18, 74.08, and 49.27, respectively. To quantitatively analyze the effect of phase compensation of the AO system, we derived $\beta_{\text{Times}}$ under different thermal distortion number conditions. The $\beta_{\text{Times}}$ are 2.26, 2.70, and 3.59 when $N_D$ are 82.18, 74.08, and 49.27, respectively. Therefore, the effect of phase compensation of an AO system on thermal blooming is significant.
Fig. 9. Comparison of wavefront peak-to-valley/root-mean-square (PV/RMS) between open-loop and closed-loop AO systems. Here, the platform velocity $V = 5 \text{ mm/s}$, the wavefront in open-loop AO system PV $= 6.84\lambda$ and RMS $= 1.42\lambda$, and the wavefront in closed-loop AO system PV $= 0.45\lambda$ and RMS $= 0.084\lambda$ (a), the platform moving velocity $V = 10 \text{ mm/s}$, the wavefront in open-loop AO system PV $= 5.75\lambda$ and RMS $= 1.28\lambda$, and the wavefront in closed-loop AO system PV $= 0.36\lambda$ and RMS $= 0.073\lambda$ (b), and the platform moving velocity $V = 15 \text{ mm/s}$, the wavefront in open-loop AO system PV $= 4.38\lambda$ and RMS $= 0.86\lambda$, and the wavefront in closed-loop AO system PV $= 0.32\lambda$ and RMS $= 0.06\lambda$ (c).

Fig. 10. Far-field images of main laser with open-loop operation of the AO system (a) and with closed-loop operation of the AO system (b). Image size is 500×500 pixels.

In Fig. 12, we compare the $\beta_{\text{times}}$ of simulations with those of the experiments. To obtain the error range, the mean value of the far-field bucket radius (PIB $= 63.2\%$) with open-loop operation was divided by its maximum and minimum values with the closed-loop operation.
When the speed of the mobile platform was low, the thermal blooming effect would generate a large amount of accumulated heat, and the range of phase compensation of the AO system is limited. Therefore, the range of $N_D$ generated by the experiments was smaller than the range generated by the simulations. Hence, the experimental results are consistent with the simulation results.

5. Conclusions

In this paper, we present the results of our study of the phase compensation of AO system for thermal blooming reduction through simulations and experiments. In the simulation, the AO system was used to compensate the thermal blooming phase distortion by 1.064 $\mu$m laser propagating through the horizontal atmosphere. In the experiment, CH$_3$CH$_2$OH was used as the absorption medium instead of the horizontal atmosphere, and the transverse wind speed was generated by moving the platform carrying CH$_3$CH$_2$OH. Thermal distortion was induced by the low-power laser in the medium. Simulation results show that the closed-loop operation of AO can enhance the phase compensation of thermal blooming when $N_D$ is approximately 50. When $N_D$ is less than 130, the AO system will improve the beam quality of the far-field spot. Additionally, the experimental results
showed that the beam quality of the far field was improved; it is consistent with the results obtained numerically. This research can provide a reference value for engineering applications requiring efficient high-energy laser propagation.

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