Simulation of the Thermal Aberration of Fused Silica Reflective Optics Under High-power Laser Irradiation

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Simulation of the thermal aberration of fused silica reflective optics under high-power laser irradiation

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Abstract

The output beam quality of high-power laser systems is limited by laser-induced thermal aberration of fused silica reflective optics. A numerical model for the simulation of thermal aberration was proposed and verified by the experimental results. Simulations on the thermal aberration of fused silica optics under 3~10 kW laser irradiation with laser beam diameters of 5 mm ~ 45 mm were carried out with the verified model. The simulation results showed that the peak-valley (PV) value of thermal aberration increases with increasing incident laser power under the same incident laser spot size and reduces with increasing incident laser spot size under the same incident laser power. There are the same PV values of thermal aberration under different incident power or power densities. An analytic formula of thermal aberration PV as a function of incident laser power and beam spot size was proposed. The analytic results are in good agreement with the simulations. With these conclusions, the thermal aberration of fused silica optics under high incident power and power density can be evaluated by that under low incident power and power density. It is helpful for the design of high-power laser systems to obtain reasonable output beam quality.

Key words: thermal aberration, high-power laser, fused silica, thermal-structure simulation

Introduction

The output beam quality of a high-power laser system is a crucial performance index [1-3]. It determines the laser power density at aim and the effect of the laser system. There is an optic transfer module that connects the high-power laser source and emission tower. The optic transfer module usually includes several fused silica reflective optics suffering high-power laser irradiation. Although these reflective optics were manufactured with high reflectivity (more than 99.99%), a proportion of incident laser power was still absorbed by the high reflectivity films on the surface of fused silica optics [4]. Fused silica optics were heated by absorbed laser power, and aberrations were introduced by asymmetric heating [5-7]. The wavefront of the transfer laser was modulated by the thermal aberration of the transfer fused silica optics. Finally, it results in degradation of the output beam quality of high-power laser systems [8-10]. The evaluation of optical thermal aberrations is the basis of adaptive optics for aberration compensation [11-15] and is essential for the design of a high-power laser system with the desired output beam quality.

Developing simulation technology on optics-mechanics-thermodynamics multiphysics provides an excellent method to investigate the thermal aberrations of fused silica optics. Many thermal aberration simulation studies have been published [16-22]. In this work, a numerical model for thermal aberration simulation was built and verified by the experimental results. Then, efforts were made to investigate the influence of incident laser power, beam spot size and average power density on the thermal aberration of fused silica reflective optics. An experience formulation of thermal aberration PV as a function of incident laser power and beam spot size was also proposed.

Simulation

1) Numerical model

The basic conception of this numerical model can be described as follows: a fused silica optic with high reflectivity film is irradiated by a high power laser beam. The optic is free to bound and surrounded by air at room temperature.

The temperature distribution of the fused silica optic is obtained by solving the unsteady heat exchange differential function:

$$\rho C(T) \cdot \partial T/\partial t + \nabla\cdot(-K(T)\nabla T) = Q \quad (1)$$

T is a function of the temperature distribution, ρ is the density of fused silica, $C(T)$ is the heat capacity at constant pressure, K(T) is the thermal conductivity, t is the irradiation time, and Q is the thermal source.

There are two kinds of laser thermal sources in this numerical model: surface thermal sources and volume thermal sources. A surface thermal source is generated by absorption of the film to the incident laser, with the following format:

$$Q_{sur} = \alpha I \quad (2)$$

α is the absorption coefficient of the film to the incident laser, and I is the power density function of the incident laser. The laser thermal source has the format of a Gauss function.

The volume thermal source is due to the absorption of fused silica volume material and can be expressed as:

$$Q = \beta(1-R)I\exp(-\beta z) \quad (3)$$

β is the absorption coefficient of the volume material to the incident laser, R is the reflectivity of fused silica reflecting optics, and z is the propagating distance in the volume material.

Then, the structural stress and deformation are generated by the results of the temperature distribution and by the coefficient of thermal expansion.

2) Model verify

Experimental and simulation tests were carried out to verify the simulation model. The setup of experiment is shown in figure 1. A fused silica sample with a 99.99% reflectivity film with a size of Φ50 mm×5 mm was irradiated by a 3 kW laser with a beam spot diameter of 8 mm. Laser power was measured by a power meter. The surface temperature and morphology were measured by a thermal camera and Shack-Hartmann sensor, respectively.

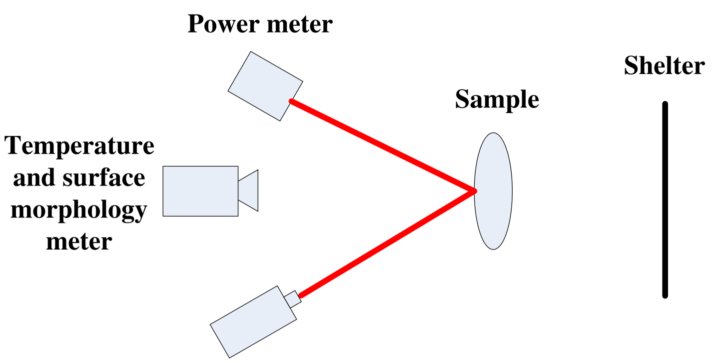


Figure 1 the sketch of thermal aberration experiment

The results showed that the surface temperature rose from 20℃ to 25℃, and the PV of thermal aberration was 5 nm.

An FEM model was built in the EasyLaser simulation software (EasyLaser is a trademark of

Institute of Applied Physics and Computational mathematics), which provides an integrated optomechanical analysis method and a GUI interface. The FEM model of the system includes 39002 domain elements. The conditions of initialization and boundary were consistent with the experiment. The parameters of the material and conditions are shown in Table 1.

Table 1 Simulation parameters of the material and conditions

Property	**Value**	**Unit**
Young' modulus	72e9	Pa
Poisson's ratio	0.17	1
Density	2200	kg/m^3
Thermal conductivity	1.4	W/(m·K)
Heat capacity at constant pressure	840	J/(kg·K)
Coefficient of thermal expansion	0.56e-6	1/K
Initial temperature	20	℃
Heat transfer coefficient	5	W/(m^2·K)
Constrains	Free	1

Figure 2 shows the incident laser power distribution, the mesh of the FEM model and a set of results. The simulation results are in agreement with the experiment: after 30 seconds irradiation, the surface temperature of the sample is raised from 20 °C to 25.7 °C, and the PV of thermal aberration in spot size is 4.5 nm.

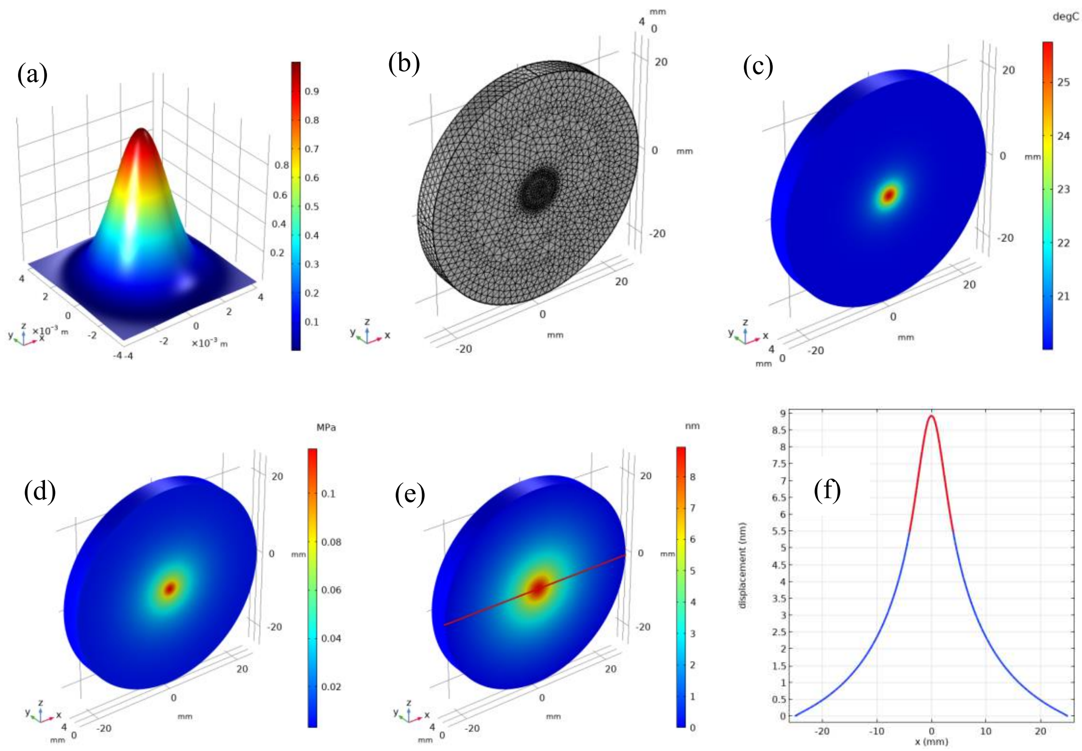


Figure 2 (a) Incident laser power distribution, (b) Mesh of the FEM model, (c) Temperature distribution, (d) and (e) Stress and displacement distribution, (f) profile of surface displacement.

The agreement of the experiment and simulation shows that the numerical model of fused silica thermal aberration is reliable. Based on this verified numerical model, a simulation of the thermal aberration of fused silica reflective optics under high-power laser irradiation was carried out to explore the influence of incident power, beam spot size and power density on thermal aberration.

Results

1) Influence of incident power

The simulation results of the temperature and stress distributions at incident laser powers of 3 kW to 10 kW and beam sizes of 45 mm are shown in Figure 3 and Figure 4, respectively. The distribution forms of temperature and stress are the same at different incident powers, but only the values change. Figure 5 shows the profiles of the temperature and displacement distributions. The morphology of the temperature distribution is close to that of the incident laser power. The maximum value of the temperature increase is located at the center of the sample due to the Gaussian distribution of the incident laser power and low thermal conductivity of the fused silica material, while the temperature at the edge hardly rises. Accordingly, the morphology of the displacement distribution is high at the center and low close to the edge. The PV value of the surface thermal aberration increases from 4 nm to 13 nm as the incident laser power rises from 3 kW to 10 kW. As seen in Figure 6, the PV value of the surface thermal aberration is directly proportional to the incident laser power.

The output beam quality of a high-power optic system is strongly dependent on the thermal aberration of the optics. Therefore, the results indicate that there is a limit of incident laser power given the size of the fused silica sample to obtain a designed output beam quality of a high-power optic system.

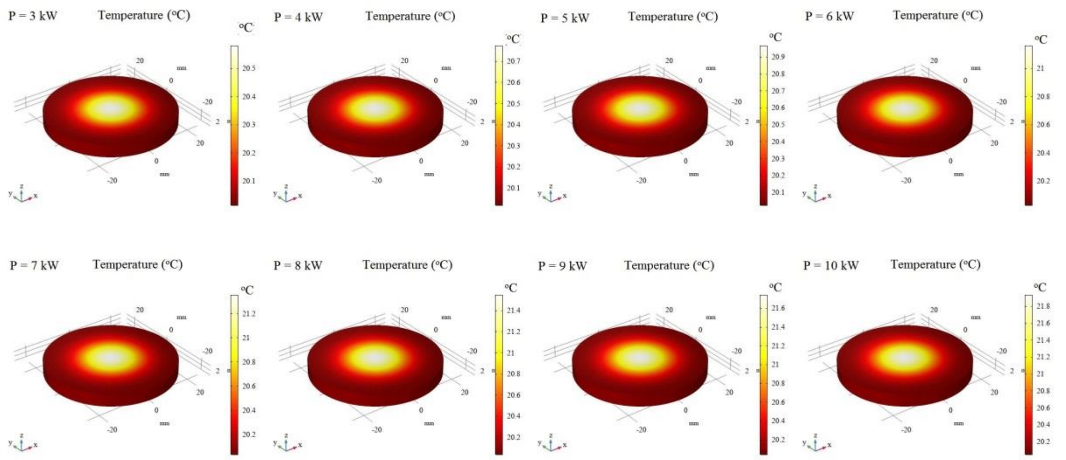


Figure 3 Temperature distributions at incident laser powers of 3 kW to 10 kW.

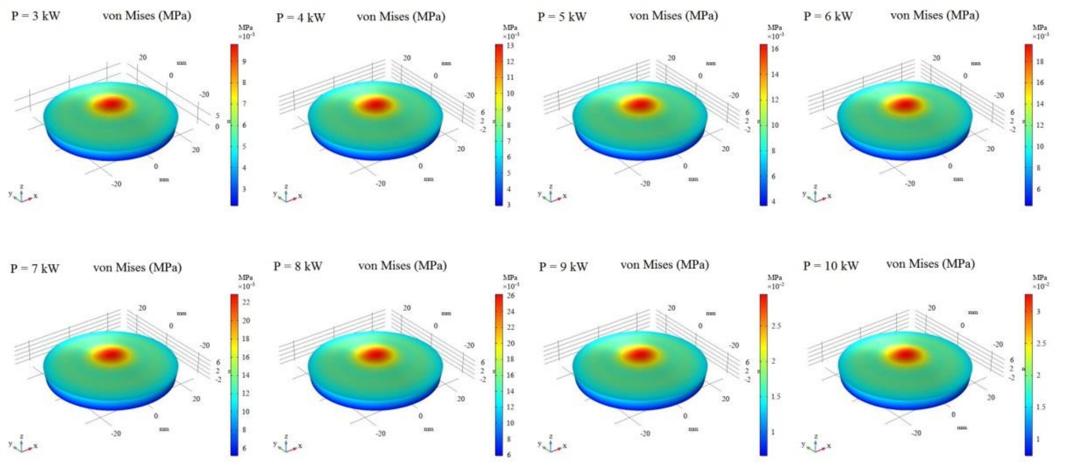


Figure 4 Stress distributions at incident laser powers of 3 kW to 10 kW.

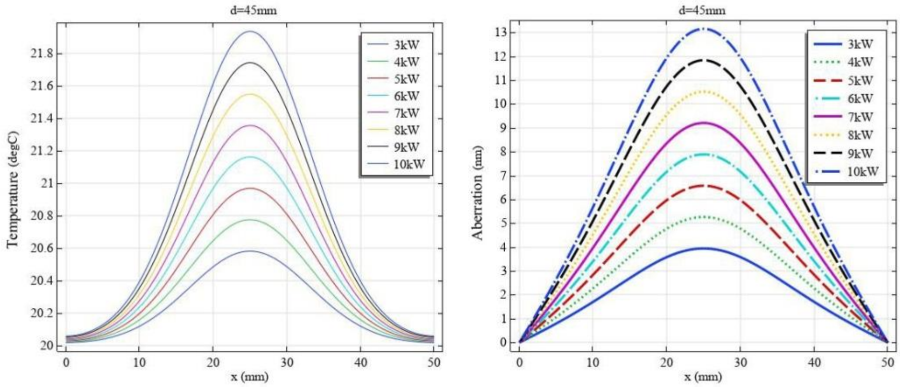


Figure 5 Profiles of temperature and displacement distributions

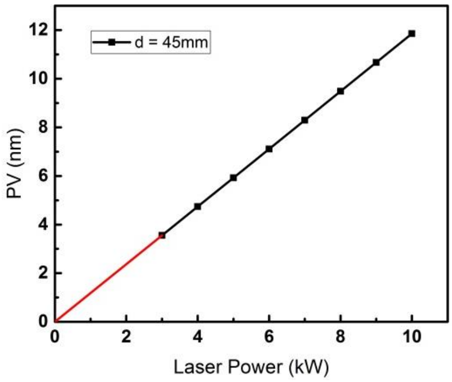
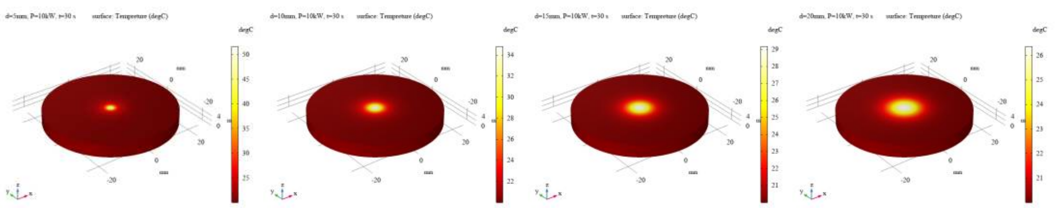


Figure 6 Thermal aberration as a function of incident laser power

2) Influence of incident beam spot size

Figure 7 and figure 8 show the simulation results of temperature and stress distributions with incident beam spot sizes from 5 mm to 40 mm at an incident laser power of 10 kW, respectively. Figure 9 shows the surface profiles of the temperature and stress distributions. As seen in these figures, the distribution of temperature and stress are strongly dependent on the incident beam spot size. The scales of temperature rise and displacement increase with increasing incident beam spot size, while the maximum value of temperature and the PV value of surface displacement decrease as the incident beam spot size increases. This may be because the local power density is higher at the smaller beam spot size than at the larger beam spot size.

For a given incident laser power, increasing the incident beam spot size is helpful to decrease the thermal aberration of fused silica optics. In this simulation, the PV value of the thermal aberration decreases from 45 nm to 13 nm as the incident beam spot size increases from 5 mm to 40 mm. The PV value of the surface thermal aberration is inversely proportional to the square of the incident laser beam size, as shown in Figure 10.



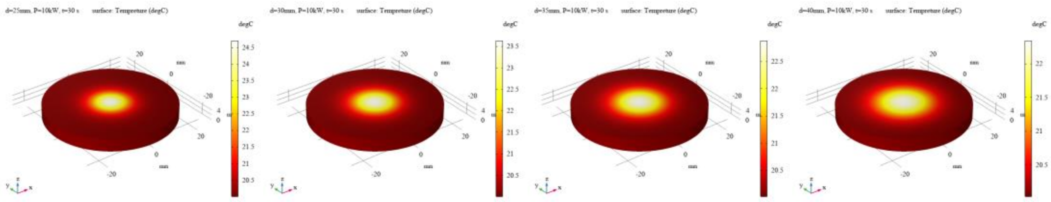


Figure 7 Temperature distributions with incident beam spot sizes from 3 kW to 10 kW.

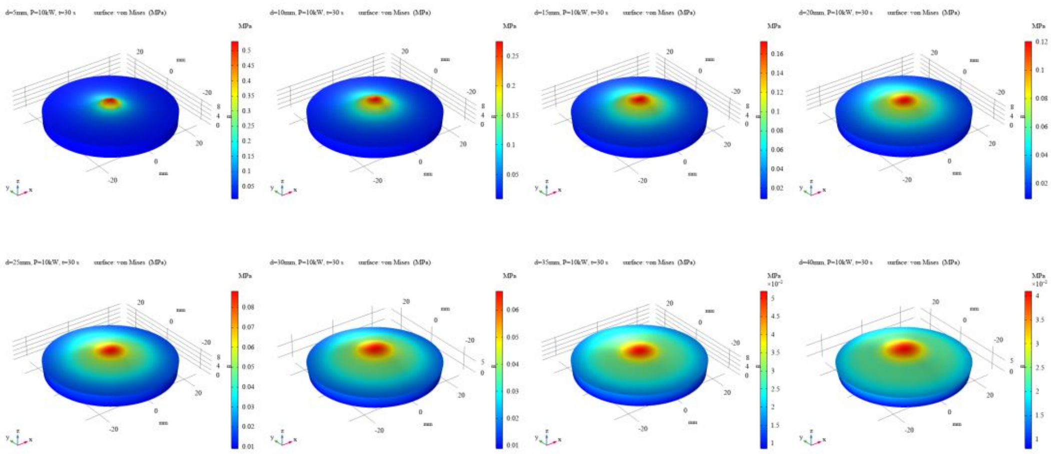


Figure 8 Stress distributions with incident beam spot sizes from 3 kW to 10 kW.

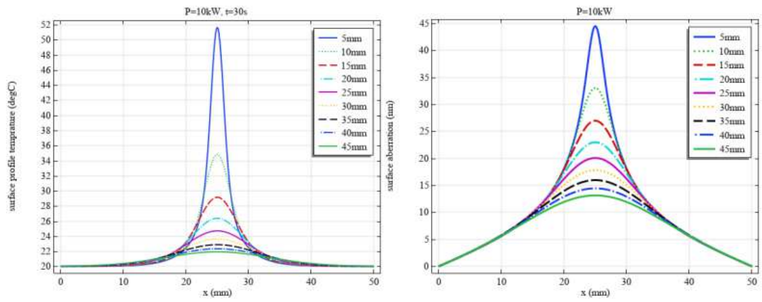


Figure 9 Profiles of temperature and displacement distributions

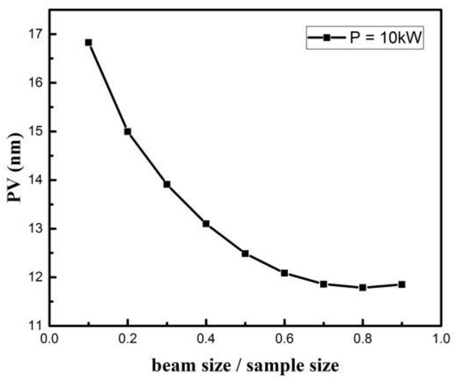


Figure 10 Thermal aberration as a function of incident beam spot size

3) Influence of incident average power density

Simulations with beam spot diameters from 5 mm to 45 mm at irradiation laser power from 3 kW to 10 kW were carried out to explore the influence of the incident average power density on the thermal aberration. The results are shown in figure 11. This is consistent with the discussions above:

the PV value of the surface thermal aberration is directly proportional to the incident laser power for a given incident beam spot size and inversely proportional to the square of the incident laser beam size at a given incident laser power. However, the PV value of the surface thermal aberration is not directly proportional to the incident average power density. The PV value of the surface thermal aberration may be the same at different incident average power densities. According to these discussions, the influence of the incident average power density on the thermal aberration may be supposed with the following form:

$$\mathrm{PV} = \mathrm{P}\cdot(\mathrm{A}\cdot r^{-2} + \mathrm{B}\cdot r^{-1} + C) \tag{3}$$

where PV is the PV value of the surface thermal aberration, P is the incident laser power, r is the incident beam spot diameter, and A, B and C are constants dependent on the fused silica material. In this simulation, the constants A, B and C are calculated as -0.0067, 0.1320 and 1.0326, respectively. Figure 12 compares the analytic and simulative results. It is in good agreement with each other. The proposed equation is useful to evaluate the magnitude of thermal aberration at high laser power irradiation according to the experimental results at low laser power. Moreover, it could be used to find the equivalent thermal aberration at different incident laser powers with various incident beam spot sizes.

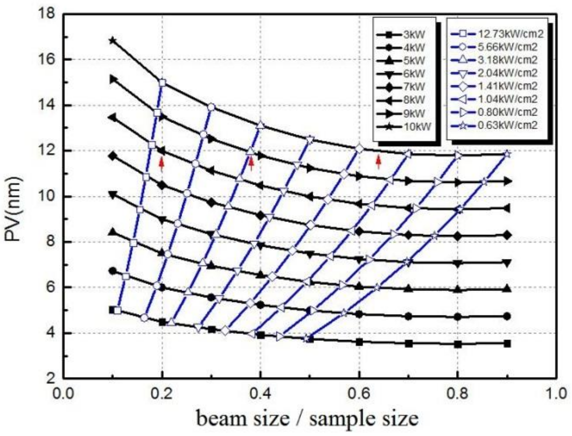


Figure 11 Influence of the incident average power density on the thermal aberration

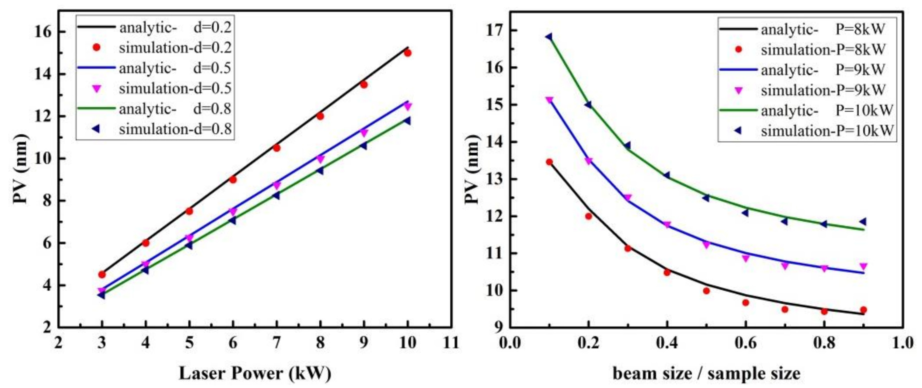


Figure 12 compares of analytic and simulation

Conclusions

In summary, a numerical model for the thermal aberration of fused silica reflective optics was built, and the simulation was in good agreement with the experimental results. The influence of incident power, beam spot size and average power density on thermal aberration was simulated based on the verified numerical model. The PV value of surface thermal aberration increases from 4 nm to 13 nm as incident laser power rises from 3kW to 10kW with 45 mm incident beam spot diameter, but decreases from 45 nm to 13 nm, as the incident beam spot size increases from 5 mm to 40 mm under 10kW laser power irradiation. The results showed that the PV value of the thermal aberration is directly proportional to the incident laser power but inversely proportional to the square of the incident laser beam size, while the PV value of the thermal aberration is not proportional to the incident laser power density. Finally, the analytic function of the thermal aberration PV value dependent on the incident laser power and beam size was proposed and compared with the simulation. The analytic solution is consistent with the simulation. These conclusions are beneficial to evaluate the thermal aberration of fused silica reflective optics under high-power laser irradiation, in the design and usage of high-power laser systems to obtain reasonable output beam quality.

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Author Contributions

Y.X.Q., W.F., Z.K. and Y.H. developed and directed the project. Y.L., Y.H.M. and L.J.M. conducted the experiment(s). Y.L., W.J. and L.J. analyzed the results help with writing the paper. All authors reviewed the manuscript.

Additional Information

Competing Interests: The authors declare that they have no competing interests.