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Wavefront pre-compensation for thermal deformations in a high power inner optical system

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ABSTRACT

The phase aberration caused by thermal deformations in a high power inner optical system is simulated and the wavefront pre-compensation for correcting the aberration is studied experimentally. Choosing Strehl ratio (SR) and the root-mean-square (RMS) of distorted phase as the characteristic parameters, the beam quality of outgoing laser is calculated when the wavefront of incident laser is compensated. Based on the computed results, the laboratory experiment is designed to model the thermal deformations aberration and the correction process by using two Liquid Crystal on Silicon Spatial Light Modulators (LCoS-SLM). The negative influence of astigmatism and defocusing on laser beam quality in far field is obvious and the astigmatism induces the non-axisymmetrical divergence of intensity distribution. After wavefront pre-compensation the power in the bucket (PIB) value of outgoing laser beam is close to the flat wavefront laser source. Both simulated and experimental results indicate that the method of wavefront pre-compensation can greatly correct the aberrations caused from thermal deformation, and the laboratory experiment is a feasible method to modeling the inner optical system with phase aberration.

1. Instruction

The phase aberrations caused by thermal deformations is one of the main limitations in a beam control system [1,2]. It would significantly reduce the effectiveness of high-power lasers system as devices for beaming power over long paths through the atmosphere and reduce the intensity at the target at power level. In order to counteract the phase aberrations, the wavefront of outgoing laser must be compensated. In order to approach this problem, we place conjugation wavefront compensation on the incident laser to minimize the phase aberrations of emitted laser. This method is analyzed base on the principle of phase conjugation and the schematic diagram of this method is shown in Fig. 1. The thermal deformations aberration of mirrors can be detected by a wavefront sensor at the exit of the inner optical system. Based on the results of sensor, the controller generates signals to the corrector which applies the phase conjugate on the laser entering the optical system.

To reduce the amounts of material, time and expense, the simulation and laboratory experiment of wavefront pre-compensation is necessary and the result can be studied to design the phase correction system. Firstly, the thermal deformations of a Si mirror and correlative phase shift in a simple case have been simulated. Secondly, based on the numerical computation of phase shift, the complex amplitude distribution of the outgoing laser is calculated with the space ray method of geometrical optics and the light diffraction theory. Finally, the laboratory experiment is designed to model the propagation of a high power laser beam on simple condition that the beam control system just has one reflector.

2. Calculation of phase shift

In the case that the transverse intensity distribution $I(r, \theta)$ of a laser beam irradiating on a Si mirror of radius r_0 and thickness d, and considering the heat convection between the environment and the mirror, the temperature distribution $T(r, \theta, z; t)$ is given by the following axisymmetric thermal conduction equation [5]:

$$\nabla^2 T(r,\theta,z;t) + \frac{\dot{q}}{\kappa} = \frac{1}{\alpha}\frac{\partial T(r,\theta,z;t)}{\partial t} \quad (1)$$

The boundary conditions and initial condition are [5]

$$\frac{\partial T(r,\theta,z;t)}{\partial r}|_{r=r_0} = \frac{h}{\kappa}(T - T_\infty) \quad (2)$$

$$\frac{\partial T(r,\theta,z;t)}{\partial z}|_{z=0} = \frac{h}{\kappa}(T - T_\infty) \quad (3)$$

$$\frac{\partial T(r,\theta,z;t)}{\partial z}|_{z=d} = \eta I(r,\theta,d;t) \quad (4)$$

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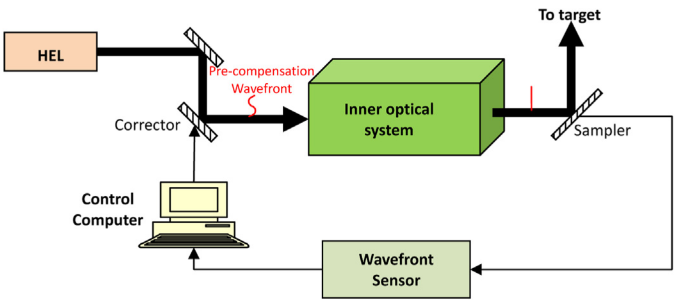

Fig. 1. Schematic diagram of wavefront pre-compensation for an inner optical system.

$$T(r,\theta,z;t)|_{t=0} = T_\infty \tag{5}$$

where, $\alpha=\kappa/\rho C$ is the thermal diffusivity, κ is the thermal conductivity, ρ is the density of the medium, C is the special heat, $\dot{q}$ is the heat generation rate per unit volume, h is the heat transfer coefficient, $T_\infty = 293\,\text{K}$ is the ambient temperature. Assuming that all the energy of laser absorbed by the thin coatings changes to heat energy, the heat flux load on the surface ($z=d$) is considered as the only heat source and the heat generation inside $\dot{q}$ is ignored, η is the absorptivity of coatings.

When the continuous wave laser irradiates on a Si mirror with high-reflectivity coatings, because the thickness of coatings ($\sim\lambda$) is far smaller than that of substrate, the deformations of coatings can be ignored. The thermal deformations of a high reflectivity circle mirror can be calculated by thermo-elastic equations of the substrate material [4],

$$\nabla^2 u_r - \frac{u_r}{r^2} + \frac{1}{1-2\nu}\frac{\partial\varepsilon}{\partial r} - \frac{2(1+\nu)}{1-2\nu}\alpha_l\frac{\partial T}{\partial r} = 0 \tag{6}$$

$$\nabla^2 u_z + \frac{1}{1-2\nu}\frac{\partial\varepsilon}{\partial z} - \frac{2(1+\nu)}{1-2\nu}\alpha_l\frac{\partial T}{\partial z} = 0 \tag{7}$$

When the side of a mirror is constrained, the boundary condition is

$$u_r|_{r=r_0} = u_z|_{r=r_0} = 0 \tag{8}$$

where, u_r, u_z is the radial and axial thermal deformations, respectively, ν is the Poisson's ratio, α_l is the linear thermal expansion coefficient, ε is the thermal strain.

After reflection from a mirror, because of the thermal deformation the phase distribution of laser beam changes to (shown in Fig. 2)

$$\Delta\phi = k\cdot 2u_z\cdot\cos\,\theta \tag{9}$$

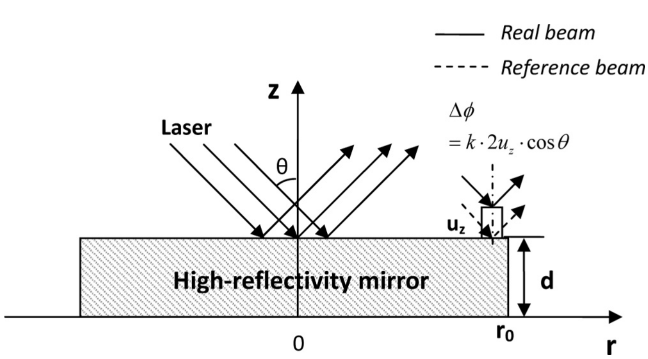

Fig. 2. Illustration of a high-reflectivity mirror irradiated by laser and the calculation of phase shifts $\Delta\phi$ caused by thermal deformations. u_z is the axial thermal deformations on the surface, and θ is the angle between the incident ray and normal line.

where, $\Delta\phi$ is the phase shift. So the complex amplitude distribution of reflecting laser $\tilde{U}^r(x,y)$ is

$$\tilde{U}^r(x,y) = \tilde{U}^i(x,y)\exp(-i\Delta\phi) \tag{10}$$

where, $k=2\pi/\lambda$, λ is the wavelength, u_z is the axial thermal deformations on the surface, θ is the angle between the incident ray and normal line, $\tilde{U}^i(x,y)$ is the complex amplitude distribution of incident laser.

3. Beam propagation in the inner optical system

As mentioned in Section 1, for the purpose of minimize the phase aberrations, we place the conjugation wavefront compensation on the incident laser beam. Then the complex amplitude distribution of incident laser $\tilde{U}_0'(x,y)$ become to

$$\tilde{U}_0'(x,y) = \tilde{U}_0(x,y)e^{-i\varphi'(x,y)} \tag{11}$$

where, $\varphi'(x,y)$ is the phase aberrations, $\tilde{U}_0(x,y)$ is the amplitude distribution of original incident laser beam. After the conjugation wavefront pre-compensation the incident laser is not a plane wave again, so the characteristic of outgoing laser is changed. Otherwise, the difference of laser field distribution on each reflector is considered, so the phase aberrations of the emitted laser $\varphi'(x,y)$ must be calculated by using both the space ray method of geometrical optics and light diffraction theory [6,7] connected with the calculation of thermal deformations.

The laser field distribution on the reflector can be calculated with the Fresnel diffraction integral by FFT (Fast Fourier Transform) method. The Fresnel diffraction integral is [7]

$$\tilde{U}(x,y) = \iint_\Sigma \tilde{U}_0(x_0,y_0)\frac{\exp(ikd)}{i\lambda d}\exp\left(\frac{ik}{2d}[(x_0-x)^2+(y_0-y)^2]\right)$$
$$dx_0dy_0 = \iint_\Sigma \tilde{U}_0(x_0,y_0)h(x_0-x,y_0-y)dx_0dy_0 \tag{12}$$

Direct integrating as a convolution form:

$$\tilde{U}(x,y) = \tilde{U}_0(x,y) * h(x,y)$$
$$h(x,y) = \frac{\exp(ikd)}{i\lambda d}\exp\left(\frac{ik}{2d}[x^2+y^2]\right) \tag{13}$$

where, d is the distance of beam propagation.

Introducing the Fourier transform and inverse Fourier transform into Eq. (13) yields the following solution:

$$\tilde{U}(x,y) = F^{-1}\{F\{\tilde{U}_0(x,y)\}H_F(f_x,f_y)\} \tag{14}$$

where, $f_k=(k/\lambda d)(i=x,y)$, and $H_F(f_x,f_y)$ is the Fresnel diffraction transfer function [7]

$$H_F(f_x,f_y) = F\{h(x,y)\} = \exp\left\{ikd\left[1-\frac{\lambda^2}{2}(f^2+f^2)\right]\right\} \tag{15}$$

Beam propagation between adjacent mirrors in a optical system can be calculated by Eqs. (14) and (15) (d_n is the distance between nth mirror and ($n+1$)th mirror):

$$\tilde{U}_{n+1}^i(x,y) = F^{-1}\left\{F\{\tilde{U}_n^r(x,y)\}\exp\left[i\kappa d_n\left[1-\frac{\lambda^2}{2}(f^2+f^2)\right]\right]\right\}$$
$$= F^{-1}\left\{F\{\tilde{U}_n^i(x,y)\exp(i\Delta\phi_n)\}\exp\left[i\kappa d_n\left[1-\frac{\lambda^2}{2}(f^2+f^2)\right]\right]\right\} \tag{16}$$

In a beam control system with many reflectors the complex amplitude distribution of emitted laser can be described as

$$\tilde{U}_e(x,y) = U_e(x,y)e^{i\varphi'(x,y)} \tag{17}$$