Simulations and experiments on optical inner-channel thermal deformation for high-power laser system

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Abstract: In order to research the influence on the beam quality due to cumulative effect of the inner channel thermal deformation in the high energy laser system, the theoretical simulation and experimental study were performed. Firstly, three typical laser power 10 kW, 50 kW and 100 kW with the unstable resonator were selected to analyze thermal deformation of mirror through the finite element analyze of thermodynamics instantaneous method. Then the wave front aberration could be calculated by ray-tracing theory. Finally, Strehl ratio, β parameter of far-filed beam can be calculated and comparably analyzed by Fresnel diffraction integration. The simulation results show that due to the effect of inner channel thermal deformation, eccentric phenomenon and astigmatism of far-filed beam emerge, and peak power and the focused ability decrease. With the increasing of reflection times, Strehl ratio decreases and β parameter increases, and tilt, astigmatism and coma of x direction gradually increase, which become the main aberration. Comparing with above theoretical simulation study, the thermal deformation experimental platform was built to measure the single copper mirror of 99% reflectivity with the 10 kW TEA CO_2 laser. Through the equivalent scale rule, the experimental results can also represent the 50 kW and 100kW power level. The measurement precision of thermal deformation of mirror is smaller than $\lambda/15$ and agree well with the simulation results. The results show that the thermal deformation of mirror cannot be neglected when the laser power great than 10 kW and has a great influence on the far-field transmission properties with the power increasing and reflection times. These results can also provide the reference to the thermal aberration analyze for high power laser system and can be applied to the field of laser nuclear fusion and laser weapon etc.

Key words: high-power laser; unstable resonator; optical beam quality; Strehl ratio
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高功率激光系统中内光路热变形的仿真及实验研究

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摘 要:为了研究高功率激光系统中的内光路热变形累积效应对光束质量的影响,开展了理论和实验

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研究。首先,选择三种非稳腔输出的典型高功率激光,激光功率分别为10 kW、50 kW 和 100 kW,通过热动力学瞬态方法的有限元分析对激光照射的反射镜进行热变形分析。然后,利用光线追迹理论得到激光的波前像差。最终,激光远场光束质量中的 Strehl 比,β 因子可以通过 Fresnel 衍射积分进行计算和对比分析。仿真结果表明,由于内光路反射镜的热变形,远场光束将出现偏心和像散的现象,其中心光强及会聚能力均会下降。随着内光路反射镜的增加,Strehl 比减少而 β 因子增加,远场光斑 x 方向的倾斜、像散及彗差也会逐渐增加,将成为系统的主要像差。为了和上述理论仿真结果进行对比,建立了一个测量反射镜热变形实验平台,实验中采用 10 kW 的 TEA CO_2 激光器照射 99%反射率的铜反射镜,通过等效放大原理,实验结果可以部分代替 50 kW 和 100 kW 功率水平。镜面热变形的测量精度小于 λ/15,并和仿真结果吻合得较好。结果表明,反射镜的热变形在激光功率超过 10 kW 时不能被忽略,且随着激光功率及反射次数的增加,这种热畸变将变得越发严重。所得结果将对高功率激光系统的热畸变分析过程提供指导,并可应用于激光核聚变及激光武器系统等的设计分析中。

关键词:高功率激光器; 非稳腔; 光束质量; Strehl 比

0 Introduction

After more than half century development of laser, there have been many high-power laser systems and this area is always the frontier field for international investigation[1-2]. The high-power laser often indicates that the laser output power is greater than 10 kW. When the beam passes through in the inner-channel, the optical beam quality will be influenced by the thermal distortion of the mirrors.

At present, many research groups have paid great attention for the heat distortion of mirror irradiated by high-power laser[3-6]. However, there rarely reports about the heat distortion of mirror influencing the far-field optical beam quality. The researchers mostly focus on the heat distortion of single mirror or output window of laser cavity, not including multiple mirrors which built up the real inner-channel of laser system. At the same time, the optical intensity distribution of high-power laser beam is usually generated by the unstable resonator which is hollow in center and asymmetry[7-9]. Therefore, it is necessary to investigate the thermal distortion of inner-channel for high-power laser system, especially the influence of far-field optical beam quality. At the same time, there rarely reports about the experimental results because it is difficult to obtain the high-power laser more than 10 kW.

In this article, the thermal distortion of inner-channel including several mirrors is analyzed through finite element method. Then the far-field optical intensity distribution of high-power laser beam is simulated by the diffraction integral and using the optical beam quality parameters Strehl ratio and β parameter to evaluate the effect of the inner-channel thermal distortion. At last, the equivalent experiment is performed to validate the simulation results.

1 Theoretical models

1.1 Thermal distortion theory

When the high-power laser irradiate the mirror, there must be a small part of laser power is absorbed by the mirror. The temperature of mirror will increase and the mirror begins thermal distortion and this distortion will influence the wavefront of high-power laser beam. Because inside the mirror, no heat source exists, so the temperature field distribution can be expressed by the differential equation of heat exchange[10]:

$$\frac{\partial}{\partial x}\left[k(T)\frac{\partial T}{\partial x}\right]+\frac{\partial}{\partial y}\left[k(T)\frac{\partial T}{\partial y}\right]+\frac{\partial}{\partial z}\left[k(T)\frac{\partial T}{\partial z}\right]=\rho c\frac{\partial T}{\partial t} \tag{1}$$

Where T is the temperature in the location (x,y,z) at time t, k is the coefficient of heat conduction of mirror, ρ is the density of mirror, c is the specific heat. Besides the heat absorbed in the surface of mirror, there also exists convection to exchange heat. Therefore, the boundary condition can be written as

$$\begin{cases} k\dfrac{\partial T}{\partial n}|_{\Sigma}=-[(1-\varepsilon)I(r,\phi)/S-h_c(T_s-T_c)] \\ k\dfrac{\partial T}{\partial n}|_{\Sigma}=h_c(T_s-T_c) \end{cases} \tag{2}$$

Where T_c is ambient temperature, T_s is the surface temperature of mirror, h_c is the convection exchange heat coefficient, ε is reflectivity, $I(x,y)$ is the laser beam intensity, S is the irradiation area, Σ is the irradiation region, Σ_1 is the region of heat convection load. Solving the equation (1), the temperature distribution of mirror will be obtained for the high-power laser beam irradiation.

The influence of the coating stress-strain field can be neglected due to the thickness of the coating is far smaller than the thickness of the substrate. The thermal distortion of roundness mirror can be expressed by the heat-elastic equation as

$$\begin{cases} \nabla^2 u_r-\dfrac{u_r}{r^2}+\dfrac{1}{1-2v}\dfrac{\partial e}{\partial r}-\alpha_t\dfrac{\partial T}{\partial r}=0 \\ \nabla^2 u_r+\dfrac{1}{1-2v}\dfrac{\partial e}{\partial z}-\dfrac{2(1+v)}{1-2v}\alpha_t\dfrac{\partial T}{\partial r}=0 \end{cases} \tag{3}$$

Where u_r and u_z are the radial and axial thermal distortion of mirror, e is the thermal body strain of mirror and α_t is the coefficient of heat expanding for the substrate material and v is the Poisson's ratio.

When the laser beam reflects from the mirror with the thermal distortion, there will add an additional phase $\varphi(x,y)$. This additional phase can be obtained by the fit of Zernike polynomial to radial thermal distortion and the ray tracking theory[11]:

$$j(x,y)=2k\Sigma\cos q u_z(x,y) \tag{4}$$

Where k is the wave number, θ is the incident angle. The far-field optical intensity distribution can be solved through the Fresnel diffraction integral. After n reflected times, the far-field intensity distribution can be written as,

$$I_F=\mathrm{IFFT}\{\mathrm{FFT}\{U_n\exp(-2jk\cos q u_z(x,y))\}\exp(jkz\sqrt{1(lf_x)^2-(lf_y)^2})\}^2 \tag{5}$$

Where U_n the field distribution before n mirror, z is the distance of beam transmission, f_x and f_y is the coordinate of frequency region, λ is the laser wavelength.

1.2 Simulation parameters

We choose the wavelength of laser is 10.6 μm and the spot size is 0.1 m×0.1 m. The block ration is 1/3. The asymmetry of beam will increase with the output power of laser. Because the intensity distribution of optical beam along the flow field direction of the gain medium is inhomogeneous, the asymmetry of beam will increase with the increasing output power of laser. Therefore the expression of optical intensity distribution of unstable resonator can be simply expressed as[12]:

$$U(x,y)=U_0(x,y)\left(1-\frac{x}{s}\right) \tag{6}$$

Where s is the intercept of x direction. It can describe the degree of asymmetry, which take $s=0.1$ in our simulation work.

In this paper, one 220 mm diameter silicon mirror is chosen with thickness 15 mm and 99% reflectivity. The other material parameters are listed in the Tab.1. The initial surface temperature and ambient temperature are both 20 ℃ and the convection exchange heat coefficient h_c is 60 W/(m²·℃).

Tab.1 Parameters of material silicon

Density /kg·m^{-3}	Specific heat /J·kg^{-1}·℃$^{-1}$	Heat conductivity coefficient /W·m^{-1}·K	Line expand coefficient /℃	Poisson's ratio	Elastic module /N·m^{-2}
2 329	695	153	4.68×10^{-6}	0.26	1.9×10^{11}

Supposed the inner-channel including 5 mirrors and each mirror can make the laser beam tilt 90° and 1 m between each mirror. The simulation model is as shown in Fig.1.

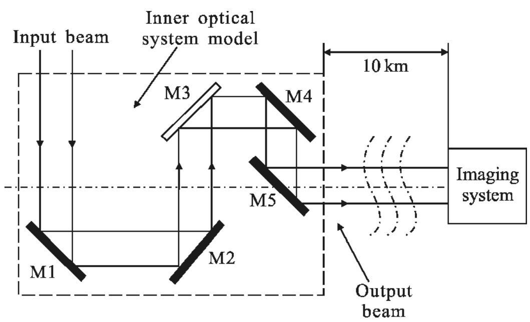

Fig.1 Simulation model of thermal deformation

2 Simulation results and discussion

2.1 Single mirror thermal distortion

The irradiation time is 10 s and the laser power is 10 kW, 50 kW and 100 kW respectively. The thermal distortion of the mirror is shown as Fig.2.

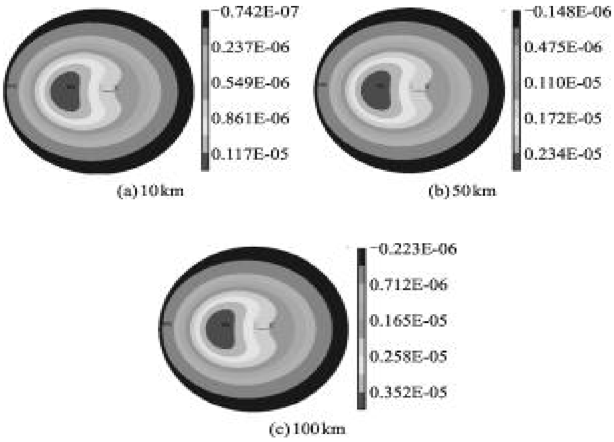

Fig.2 Thermal distortion of mirror with increasing of laser power

With the increasing laser power, the thermal distortion increases also and the maxium distortion is about 3.98 μm, which equal to $\lambda/3(\lambda@10.6\ \mu m)$. This thermal distortion cannot be neglected because the typical RMS of a mirror is less than $\lambda/10$. If we take the Nd:YAG laser with the wavelength 1.06 μm as the light source, the other condition is fixed. The thermal distortion is same as the TEA CO_2 laser, but the diffraction effect is much smaller because the shorter wavelength.

2.2 Far-field optical beam quality

The physical scientists often think the 100 kW is the least laser power for the laser weapon. Therefore, we choose the 100 kW as example to investigate how the reflective times influence the far-field optical beam quality. The far-field optical intensity distribution of the non-uniformity laser beam with the inner-channel thermal distortion is shown as Fig.3.

With the increasing reflective times, the offset from the center increases dramatically and at the same time there appears several peak intensity points. In the real applications, this phenomena will make the main laser power cannot reach the appoint location of target. To get the quantitative optical beam quality, the Strehl ratio (SR) and β parameter are chose as shown in Tab.2.

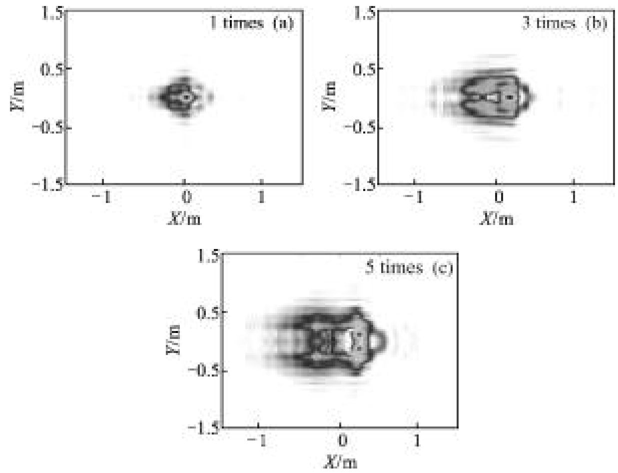

Fig.3 Intensity distributions of non-uniform laser with thermal aberration

Tab.2 Far-field beam quality with different reflection times

Reflective times	1	2	3	4	5
S_R	0.49	0.28	0.16	0.09	0.07
β	1.23	1.52	1.79	2.10	2.40

From Tab.2, with the increasing reflective times, the SR begins to decrease. After 5 times reflective times, the peak power in center will lose more than 90%. The β means that the laser beam will enlarge with the increasing reflective times and comparing with ideal beam, the size of laser spot in distance of 10 km increases more than 2 times.

3 Experiment and results

The experimental setup is shown as Fig.4. This measurement method is the equivalent net absorbed power density, which means that using small laser power and higher absorptivity and suitable spot size to simulate the thermal distortion of the real high-power laser transmission in the inner-channel. This method will achieve the same effect as the high-power laser system.

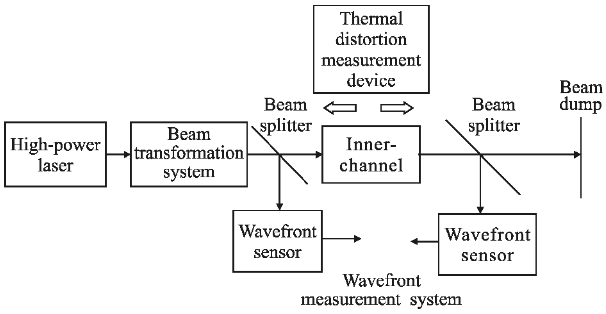

Fig.4 Experimental setup for thermal distortion measurement

In Fig.4, the high-power laser is the 10 kW TEA CO_2 laser. The beam transformation system can change the spot size and collimate the beam into the inner-channel. The wavefront sensor can measure the wavefront before and after the inner-channel. The Thermal distortion measurement device is the dynamic interferometer, which can measure the thermal distortion of single mirror in the inner-channel.

Using above method, the thermal distortion of single mirror for the 10 kW, 50kW and 100 kW laser power are shown as Fig.5.

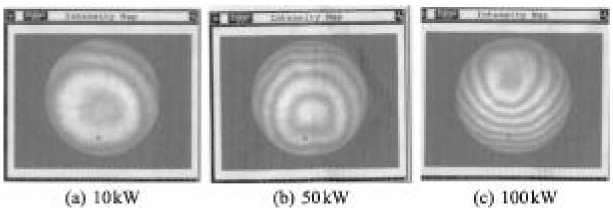

Fig.5 Thermal distortion of single copper mirror

In Fig.5, with the increasing the laser power, the thermal distortion increasing, and the interference fringes have a great change at the area of laser irradiation. The initial interference image is shown as Fig.6.

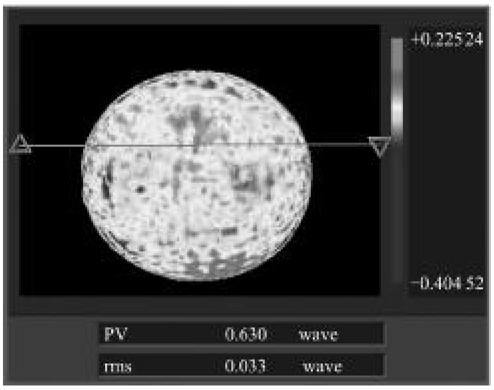

Fig.6 Initial interference image

Comparing Fig.5 with Fig.6, we can find the maximum thermal distortion for 100 kW about 3 μm, which agree well with the simulation results. The discrepancy is come from the vibration of laser operation and the ambient temperature variety.

4 Conclusions

In summary, the inner-channel thermal deformation is theoretically analyzed. The simulation results show that the laser power and the reflection times are the key factors to influence the far-field optical beam quality when the material and the boundary are determined. At the same laser power, the Strehl ratio decreases and the β parameter of the far-field optical beam quality increases with the reflective times increasing, which means that the peak power and the focus ability descend. Therefore the cooling system and the beam shaping system are needed in the high-power laser system and the β parameter astigmatism and the tilting phenomenon will become the main effect to decrease the far-field optical beam quality with the increasing laser power and reflective times. There will exist a special inflexion reflective time, which more than that time will need the control techniques to restrain this thermal distortion. The results will provide the reference for the optical beam control of entire path of the high-power laser system. Although the intensity distribution of high-power laser and the structure of inner-channel are more complex in the real system, the investigate method of simulation and experiment are also suitable and the conclusions for the rule of thermal distortion are also qualitatively correct. This will provide the reference for the control of optical beam quality in the transmission path for the high-power laser system, like laser nuclear fusion and laser weapon etc.

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