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高功率激光反射镜热畸变补偿结构设计与仿真

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摘要: 为了研究激光反射镜热畸变补偿结构的设计,在分析激光腔镜热变形行为的基础上,采用优化镜体结构,提出了一种减少入射激光光斑区域镜面热畸变的途径——热畸变自补偿激光反射镜,并与普通硅镜的热变形情况进行了比较。结果表明,当反射镜反射率为98%、入射激光功率为7kW、激光照射时间分别为2s、4s和10s时,普通硅镜镜面中心与光斑边缘处的热变形之差分别为0.167μm、0.174μm和0.172μm;而热畸变自补偿激光反射镜镜面中心与光斑边缘处的热变形之差分别为0.092μm、0.052μm和0.027μm。该研究结果对提高高能激光腔镜热效应稳定性、改善高能激光光束质量具有一定参考价值。

关键词: 光学器件; 激光反射镜; 热畸变; 自补偿; 高能激光

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Simulation and structure design of a high power laser mirror with self-compensation of thermal distortion

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Abstract: A high-power laser mirror with self-compensation for thermal distortion was presented and numerically simulated on the basis of its thermal deformation behavior after optimizing its substrate structure. When 7kW laser was input in 17cm diameter, and the reflectivity of the mirror was 98%, the difference between central maximum thermal distortion and boundary thermal distortion within laser radiation region on the mirror surface for the general silicon substrate (peak valley values) was 0.167μm, 0.174μm and 0.172μm respectively, under the radiation time of 2s, 4s and 10s. However, the thermal distortion difference (peak valley values) of the laser mirror with self-compensation of thermal distortions was 0.092μm, 0.052μm, 0.027μm, respectively. The study results are useful for improving the heat-effective stability and beam quality.

Key words: optical devices; laser mirrors; thermal distortion; self-compensation; high-power laser

引言

光学元件在强激光作用下的热吸收变形是难以避免的客观现实,而且随着激光功率的增加将日趋严重,最终成为强激光输出功率和光束质量的制约条件^[1-6]。目前,减少激光腔镜热变形的技术途径主要有两种:一种方法是镜体强迫冷却^[7-8],另一种方法是提高激光腔镜的反射率。其中,超高反射率的激光腔镜可以大大

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缓解热变形问题,但由于镀膜工艺和薄膜材料的限制,镜面反射率很难满足实际需要。而在一定镜面反射率下,对镜体进行强迫冷却,是不得已而为之、且行之有效的一种减少热变形方法,但镜体内嵌沟槽流体压力容易引起镜面附加畸变,另外,由于热传导速率的限制,镜面初始瞬态热畸变较为严重。

作者在研究激光腔镜热变形行为的基础上,通过优化镜体结构,提出一种减少入射激光光斑区域镜面热畸变的途径——热畸变自补偿激光反射镜,即让光斑区域镜面发生微小热平移,而不引起整体光束相位热畸变。镜体沟槽不含流体,不会存在镜面附加流体压力畸变;另外,热畸变自补偿激光反射镜基于镜体的自身结构热行为,可以有效减少镜面初始瞬态热畸变,尤其适用于激光器出光初始阶段光束质量要求比较高

的情况。

1 理论基础

图1所示为热传导问题结构简图。激光束沿 z 轴方向入射，腔镜 M_1 的厚度为 d ，半径为 b 。整个谐振腔由 M_1 和 M_2 组成。假定激光束在镜体内部传输时，其光束半径保持不变。由于有限厚介质(腔镜基片)部分吸收激光能量，从而引起腔镜基片的热变形和温度的升高。

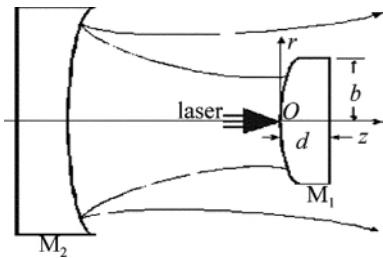


Fig. 1 Diagram of heat conduction analyses

若介质的热扩散系数为 α ，热导率 κ ，则介质内的温度分布由热传导方程表示如下^[9]：

$$\frac{\partial^2 T(r, z, t)}{\partial r^2} + \frac{1}{r} \frac{\partial T(r, z, t)}{\partial r} + \frac{\partial^2 T(r, z, t)}{\partial z^2} + \frac{1}{\kappa} g(r, z) = \frac{1}{\alpha} \frac{\partial T(r, z, t)}{\partial t},$$

$$(0 \leq r < b, 0 < z < d, t > 0)$$

(1)

初始条件和边界条件可以写为：

$$[D]^{-1} = \begin{pmatrix} 1/E_x & -\nu_{xy}/E_x & -v_{xz}/E_x & 0 & 0 & 0 \\ -\nu_{yx}/E_y & 1/E_y & -\nu_{yz}/E_y & 0 & 0 & 0 \\ -\nu_{zx}/E_z & -\nu_{zy}/E_z & 1/E_z & 0 & 0 & 0 \\ 0 & 0 & 0 & 1/G_{xy} & 0 & 0 \\ 0 & 0 & 0 & 0 & 1/G_{yz} & 0 \\ 0 & 0 & 0 & 0 & 0 & 1/G_{xz} \end{pmatrix}$$

$$(8)$$

式中 E 为杨氏模量， ν 是泊松比， G 表示剪切模量。

2 镜体结构设计

如图2所示，反射镜基体材料为单晶硅，镜体直径为80mm，厚度为15mm。在反射镜的背面，内环诸多小孔中心位于半径为10mm圆周上，小孔直径为5mm，深度为13mm；外环诸多小孔中心位于半径为20mm圆

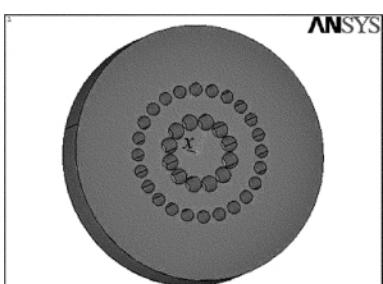


Fig. 2 Laser mirror substrate with self-compensation of thermal distortions

$$\frac{\partial T}{\partial r} + H(T - T_\infty) = 0 \quad (r=b, t>0) \quad (2)$$

$$\frac{\partial T}{\partial z} + H(T - T_{in}) = 0 \quad (z=0, t>0) \quad (3)$$

$$\frac{\partial T}{\partial z} + H(T - T_\infty) = 0 \quad (z=d, t>0) \quad (4)$$

$$T = T_\infty \quad (t=0 \text{ 区域内}) \quad (5)$$

式中 $\alpha = \kappa / (\rho c_p)$ ， κ 为热导率， ρ 表示介质密度， c_p 是比定压热容， T_∞ 是环境温度和初始温度， T_{in} 是激光器腔内温度， $g(r, z)$ 为内热源强度， H 为对流系数($H = h/\kappa$)， h 为表面传热系数。

(1)式的解依赖于边界条件(2)式~(4)式和初始条件(5)式。求解方法多种多样，例如数值方法包括有限差分法、有限元法以及快速傅里叶变换法等，本文中采用有限元法。

耦合热弹性本构方程可表示为^[10]：

$$\{\varepsilon\} = [D]^{-1}\{\sigma\} + \{\alpha\} \Delta T \quad (6)$$

$$S = \{\alpha\}^T \{\sigma\} + \frac{\rho c_p}{T_0} \Delta T \quad (7)$$

式中 S 表示熵密度， $[D]$ 是弹性刚度矩阵。 $\Delta T = T - T_{ref}$ ， T 为当前温度， T_{ref} 为参考温度； $\{\varepsilon\}$ 是总应变矩阵矢量， $\{\varepsilon\} = [\varepsilon_x \varepsilon_y \varepsilon_z \varepsilon_{xy} \varepsilon_{yz} \varepsilon_{xz}]^T$ ； $\{\sigma\}$ 为应力矩阵矢量， $\{\sigma\} = [\sigma_x \sigma_y \sigma_z \sigma_{xy} \sigma_{yz} \sigma_{xz}]^T$ ； $\{\alpha\}$ 为热膨胀系数矩阵矢量， $\{\alpha\} = [\alpha_x \alpha_y \alpha_z 0 0 0]^T$ 。

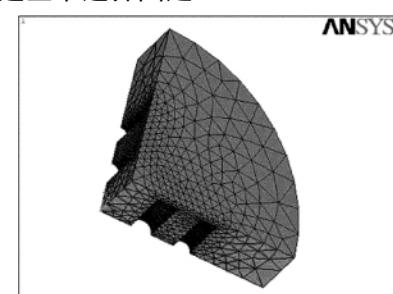


Fig. 3 Structure model for finite element analyses

3 结果与分析

为方便起见，采用ANSYS有限元分析软件进行数值仿真。当入射激光光斑直径为17mm，镜面反射

率为98% ,镜面吸收激光功率为140W(相当于入射激光功率为7kW) ,利用上述给定的边界条件以及有关数据 ,可以得到反射镜的温升分布以及镜面热变形情况。

图4所示为镜面吸收激光功率为140W、光照时间为10s时镜面温度场等高分布云图。图5中给出了光照时间分别为2s, 4s和10s时的镜面温升径向分布情况。

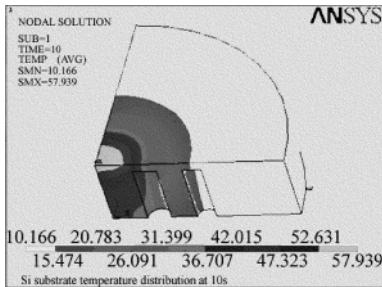


Fig. 4 Contour plot of temperature on the mirror substrate

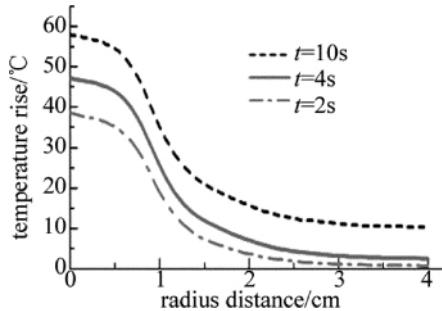


Fig. 5 Radial profiles of temperature on the mirror surface

图6表示普通硅镜在激光照射时间分别为2s, 4s和10s时的镜面热变形径向分布情况。当反射镜吸收功率为140W、激光照射时间分别为2s, 4s和10s时 ,镜面中心与光斑边缘处的热变形之差(PV 值) 分别为0.167μm, 0.174μm 和0.172μm。

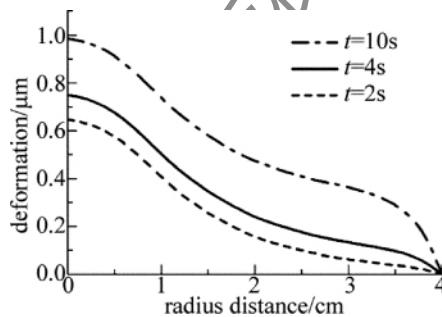


Fig. 6 Radial profiles of thermal deformation on the general silicon substrate

图7所示为热自补偿硅镜镜面吸收激光功率为140W、光照时间分别为2s, 4s, 6s和10s时的镜面热变形径向分布情况。在镜面中心光斑区域(光斑半径为8.5mm)面形畸变量峰谷值(peak valley , PV)如表1所示。由表1可以看出 ,光照时间从2s至10s时 ,光照区域面形畸变量PV值始终小于化学氧碘激光器输出波长(1.315μm)λ/10 但光照区域面形平移随着光照时间的增加而不断增加 ,10s时镜面中心平移量为1.33μm。

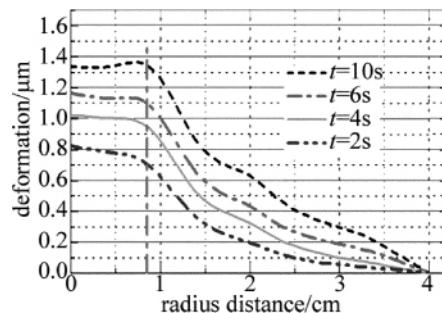


Fig. 7 Radial profiles of thermal deformation on self-compensated silicon substrate

Table 1 The thermal distortion PV values within the laser radiation region

radiation time/s	0	2	4	6	10
thermal distortion PV values/μm	0	0.095	0.052	0.046	0.027
central deformation/μm	0	0.82	1.02	1.16	1.33

图8为普通硅镜、热自补偿硅镜在激光照射时间为4s时不同激光功率下的镜面热变形径向分布情况。当普通硅镜反射镜吸收功率P分别为100W和140W时 ,镜面中心与光斑边缘处的热变形之差(PV 值) 分别为0.124μm 和0.174μm ,而热自补偿硅镜吸收功率P' 分别为100W 和140W 时 ,镜面中心光斑区域(光斑半径为8.5mm)面形畸变量 PV 值分别为0.074μm 和0.052μm。

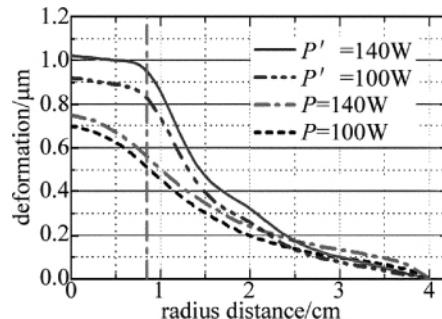


Fig. 8 Radial profiles of thermal deformation on the general and self-compensated silicon substrates

4 结论

在高能激光器中 ,镜面面形至关重要 ,尤其是光照区域的镜面热畸变直接影响着激光传输光束质量^[11-12]。传统减少镜面热畸变的方法是通过某种手段尽量减少镜体温度 ,从而实现减少镜面热变形的目的。而本文中提出的镜体新型结构是巧妙利用镜体热变形 ,来实现特定区域无畸变的目的。需要说明的是 ,对于不同的入射激光光斑尺寸 ,相应的镜体结构也不一样 ,其热变形特性也不尽相同。在实际应用中 ,应根据给定的激光参量及其指标 ,来设计具体的镜体结构。

参考文献

- [1] PENG Y F , CHENG Z H , ZHANG Y N , et al. Temperature distribu-

- tions and thermal deformations of mirror substrates in laser resonators [J]. *Applied Optics*, 2001, 40(27): 4824-4830.
- [2] PENG Y F, CUI J L, CHENG Z H, et al. Characteristics of thermal distortions of the laser mirror substrates filled with phase-change materials [J]. *Optics & Laser Technology*, 2006, 38(8): 594-598.
- [3] LI X F, ZHANG B L, LIN M, et al. Numerical analysis of thermal distortion of the mirror in space to ground laser communication links [J]. *Optoelectronics Letters*, 2005, 1(3): 0209-0212.
- [4] REVESZ P, KAZIMIROV A, BAZAROV I. Optical measurement of thermal deformation of multilayer optics under synchrotron radiation [J]. *Nuclear Instruments and Methods in Physics Research*, 2007, A582(1): 142-145.
- [5] APOLLONOV V V, BYSTROV P I, BROVAL' SKIÝ Y A, et al. Feasibility of using liquid-metal heat carriers to cool power optics components made of porous structures [J]. *Soviet Journal of Quantum Electronics*, 1981, 11(6): 796-798.
- [6] YU D L, SANG F T, JIN Y Q, et al. Finite element analysis of the mirror in high-energy density laser resonator [J]. *High Power Laser and Particle Beams*, 2001, 13(2): 129-132 (in Chinese).
- [7] YUEN W W, FLEISHMAN R V. Parametric study of mesh enhanced forced convection heat transfer for the cooling of high power density mirrors [J]. *Proceedings of SPIE*, 1989, 1047: 43-45.
- [8] ZHANG Y N, PENG Y F, CHENG Z H, et al. Research of complex structure of mirror cooled by phase change [J]. *High Power Laser and Particle Beams*, 2000, 12(s1): 77-79 (in Chinese).
- [9] ÖZISIK M N. Heat conduction [M]. New York: Wiley, 1980: 1-21.
- [10] NOWINSKI J L. Theory of thermoelasticity with applications [M]. Netherlands: Sijhoff & Noordhoff International Publishers, 1978: 261-270.
- [11] FENG Z Q, BAI L, ZHANG Z B, et al. Thermal deformation compensation of high-energy laser mirrors [J]. *Optics and Precision Engineering*, 2010, 18(8): 1781-1786 (in Chinese).
- [12] YANG Zh Q, CHEN H Q, WANG L, et al. Investigation of laser aberration compensation using an intracavity deformable mirror [J]. *Laser Technology*, 2007, 31(5): 449-451 (in Chinese).

(上接第119页)

散射情况,完成了该检测装置的光学系统设计。

参 考 文 献

- [1] EISON J M. Theory of light scattering from a rough surface with an inhomogenous dielectric permittivity [J]. *Physics Review*, 1984, B30(3): 5460-5480.
- [2] EISON J M, BENNETT H E, BENNETT J M. Scattering from optical surfaces in applied optics engineering [M]. New York: Academic Press, 1979: 191-220.
- [3] WANG S H, QUAN C, TAY C J, et al. Surface roughness measurement in the submicrometer range using laser scattering [J]. *Optics Engineering*, 2000, 39(6): 1597-1601.
- [4] DONG L, XIANG Y, WANG A, et al. The study of surface roughness measuring by laser optical fiber sensor [J]. *SPIE*, 2005, 5634: 524-532.
- [5] ZENG Y, LI R H, DENG H Q. Measurement of surface horizontal profile parameters using laser scattering distribution of solid angle [J]. *Infrared and Laser Engineering*, 2010, 39(1): 156-159 (in Chinese).
- [6] TSANG L, KONG J A, DING K H. Scattering of electromagnetic waves: theories and applications [M]. Ottawa, Canada: John Wiley & Sons Inc, 2000: 389-417.
- [7] HAN X G, WU Zh S, ZHANG X P. Experiments study of laser scattering from very rough surfaces [J]. *Laser Technology*, 1997, 21(3): 151-155 (in Chinese).
- [8] YANG J, WU F. Experimental research on visible light scattering characteristics of rough surfaces [J]. *China Measurement*, 2009, 35(2): 125-128 (in Chinese).
- [9] NICHOLSON M. ZEMAX detailed instructions for use [M]. New York: ZEMAX Development Corporation Press, 2008: 385-390.