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Trans-reflection thermal driven deformable mirror with flexible bonding in high energy laser system

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ABSTRACT

Deformable mirrors used in high energy laser system suffer from problems like the stress from adhesive solidification or the relatively expensive unit price of piezoceramic actuator. The thermal driven deformable mirror (TDDM) investigated here provided a promising prospect to solve these problems. Four scenarios of TDDM were studied and compared. Results showed that the trans-reflection TDDM with flexible bonding best met the requirement in practical use. The flexible bonding excluded the stress problem in the solidification of adhesives, trans-reflection brought about enough correction range, and the choice of thermo-electric cooler as actuator could greatly bring down the cost of adaptive optics apparatus as well.

1. Introduction

In high energy laser system, adaptive optics is an essential part to guarantee the performance of focal spot. Particularly, in the inertial confinement fusion (ICF) oriented mighty laser systems, such as National Ignition Facility (NIF) in the USA [1,2], Laser Mégajoule (LMJ) in France [3,4], or ShenGuang -III (SG-III) in China [5,6], tens or hundreds beamlets would be focused within one small spot to create the extreme physical condition. Normally, the deformable mirror was set in the path of each beamlet to correct the wavefront aberration before the focusing. There are plenty of different deformable mirrors available on the menu; however, the comparatively large size (400 mm^2) of deformable mirrors used in the high energy laser system asks for powerful driven mechanism, which excludes the applications like electrostatic force or electromagnetic force [7,8]. Since the piezoceramics could provide thousands newton push force, more than 100 μm displacement and quick dynamic response [9], deformable mirror driven by piezoceramic actuators usually became the first choice in large adaptive systems [1,5]. In spite of those advantages of piezoceramics, there are still concerns that should be taken into consideration. At the technology level, the creep and hysteresis effects of piezoceramics were an intrinsic obstacle in the wavefront correction procedure [10,11]. Besides, the surface shape of deformable mirror would be affected by the stress generated in the solidification of adhesives between the mirror and actuators [12]. Although the bonding position could be optimized, the stress, normally, still accounts for a difference around 1 μm in the initial surface shape. In addition, when the multi-beam laser system is activated, the deformable mirrors would be put into mass production, the relatively expensive unit price of piezoceramics would become a great expense [9].

Based on concerns above, application of thermal driven deformable mirror (TDDM) was proposed in this paper, which could become a substitution in the adaptive optics system of ICF laser system, for example in the SG-III. Since the single laser pulse shot in SG-III was performed every 3 to 4 h, it created the foundation of application for TDDM by providing sufficient time to reach the heat balance, where time for the thermal field to reach a balance was normally within 60 s [13]. The study of TDDM was mainly developed in the response function, correction range, system linearity and optimal thickness.

2. The configuration of TDDM

The idea of taking thermo-optical effect as the driven force has been put forward in [14]. The driven actuator could be external pump beam [15], radioactive heater [16], or resistive heater [17], which were applied in the interferometer gravitational wave detector as no mechanical contacts were needed. In this paper, the thermo-electric cooler (TEC) was chosen as the actuator, which was an electrically driven heat exchanger that pumped heat in a

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direction depending on the polarity of the applied voltage. In that way, both cooling and heating conditions could be applied; thus both forward and backward wavefront correction could be achieved.

As shown in Fig. 1, the TECs were directly attached to the downside surface of mirror. One copper heat sink was set below the TECs and provided thermal dissipation. The heating or cooling condition applied on the mirror would bring about temperature gradient; as a consequence, the refractive index of mirror would change and both surfaces would deform according to the thermal expansion.

There were two options of the coating film on the mirror: High reflection (HR) coating on the upside surface; anti-reflection (AR) coating on the upside surface and HR coating on the downside surface. In the first case, the incident wavefront was reflected on the upside surface; thus thermal deformation of the upside surface provided all the phase correction in the “surf-reflection model”. In the latter case, which could be named as “trans-reflection model”, incident wavefront penetrated the mirror and was reflected on the downside surface; consequently, the deformation of both surfaces and the change of refractive index all contributed to the total phase correction.

The bonding between the mirror and TECs could be rigid or flexible. The conductive structural adhesives could provide rigid bonding, where a fixed constraint over the downside surface of the mirror was applied along the thickness. In the flexible bonding condition, the adhesives could be chosen as conductive grease, where the mirror could be seen as in free expansion since the pressure applied on the mirror by the grease was small enough to be neglected. We summarized the four scenarios of TDDM mentioned above in Table 1.

3. The analysis and comparison of TDDM

The model of a TDDM with seven actuators was established as in Fig. 2; the TEC actuators were hexagonal distributed, which could keep the distance between actuators identical. The X and Y axis were along the length and width of the mirror, and Z axis was along the thickness. The wavelength of input laser was 351 nm, material of the mirror was BK_7 glass; parameters used in the analysis are listed in Table 2.

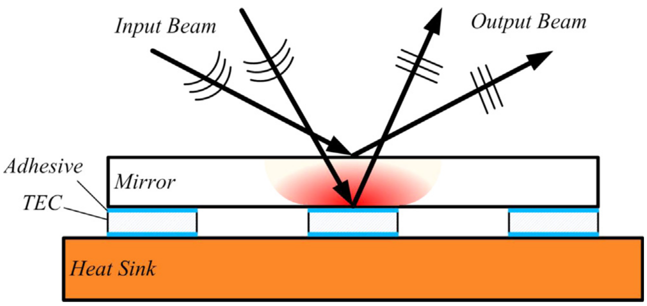

Fig. 1. Configuration of TDDM.

Table 1
Analysis scenarios.

Scenario	Bonding	Reflection
1	Rigid	Surf-reflection
2	Flexible	Surf-reflection
3	Rigid	Trans-reflection
4	Flexible	Trans-reflection

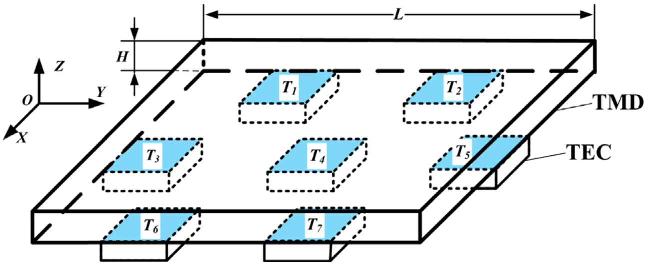

Fig. 2. Model of TDDM with hexagonal distributed TEC actuators.

Table 2
Parameters of the mirror and the TECs.

Mirror (BK_7)	Convection coefficient of air	$5\ \mathrm{Wm^{-2}\,K^{-1}}$
	Dimensions	$100 \times 100 \times 10\ \mathrm{mm^3}$
	Young's modulus	82 GPa
	Poisson ratio	0.2
	Thermal conduction coefficient	$0.74\ \mathrm{Wm^{-1}\,k^{-1}}$
	Thermal expansion coefficient	$7.1 \times 10^{-6}\ \mathrm{K^{-1}}$
	Thermal coefficient of refractive index	$2.5–3.9 \times 10^{-6}\ \mathrm{K^{-1}}$ [18]
	Refractive index	1.539
TECs	Dimensions	$20 \times 20 \times 4\ \mathrm{mm^3}$
	Applicable temperature	0–80 °C

3.1. *Response function of a single actuator*

The response function of single actuator was investigated at first. In consideration of practical use, temperature applied on Actuator-4 was set between 0 °C to 80 °C, where steady and precise temperature control was available. The room temperature T_0 was set to be 20 °C. In the “surf-reflection” model, obviously, the deformation of upside surface was the only contribution to the optical path difference (OPD). The response function can be written as

$$\mathrm{OPD}_{surf}(x,y) = -2S_{up}(x,y) \tag{1}$$

where $S_{up}(x,y)$ is thermal induced deformation of the upside surface. While in the “trans-reflection” model, both the refraction change and the surface deformation dominated the response function

$$\mathrm{OPD}_{trans}(x,y) = 2\left[\int_0^H \Delta n(x,y)dz + \int_0^{\Delta H(x,y)} n_0 dz\right] \tag{2}$$

where n_0 was the refraction index of BK_7 glass at room temperature, $\Delta n(x,y)$ was the refraction index change caused by the temperature gradient, $\Delta H(x,y)$ was the total deformation of both surfaces. To be specific, $\Delta n(x,y)$ and $\Delta H(x,y)$ can be written as

$$\Delta n(x,y) = \frac{dn}{dT}[T(x,y) - T_0] \tag{3}$$

$$\Delta H(x,y) = S_{up}(x,y) - S_{down}(x,y) \tag{4}$$

where dn/dT is the thermal coefficient of refractive index, $S_{up}(x,y)$ and $S_{down}(x,y)$ are the upside and downside surface deformation respectively. Thus the total OPD in trans-reflection model can be divided into three items

$$\mathrm{OPD}_{trans}(x,y) = 2\left[\int_0^H \frac{dn}{dT}[T(x,y) - T_0]dz + \int_0^{S_{up}(x,y)} n_0 dz - \int_0^{S_{down}(x,y)} n_0 dz\right] \tag{5}$$

Based on finite element analysis (FEA), the amplitudes of OPD in the four scenarios are shown in Fig. 3. The amplitude of OPD kept good linearity in all the four scenarios. Compared with the