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Characteristics of thermal distortions of the laser mirror substrates filled with phase-change materials

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Abstract

Under irradiating of the laser power of 2 kW, the thermal deformations of the silicon mirror substrates with phase change materials are experimentally measured and numerically analyzed by using finite element methods, respectively. The experimental results show that when the absorbed laser power is 120 W and the laser irradiating time gets to three seconds, the thermal distortion of the silicon mirror substrates with paraffin/carbon powder is 0.25 μm, that of the paraffin/aluminum powder 0.33 μm, and that of the paraffin/copper powder 0.37 μm. The numerical calculation coincides with the experimental results.

Keywords: Mirrors; Thermal distortion; High-power lasers; Phase-change material

1. Introduction

Some applications of high-power lasers, which currently are being developed at a rapid rate, are limited by the lack of suitable optical component materials. Since laser mirrors (or windows) are normally exposed to direct radiation of high power laser light, the thermal distortions of the mirrors will be generated due to the absorption of laser light, which will result in the degradation of the beam quality of output laser. In order to reduce the thermal distortion and the thermal damage of the laser mirrors, the substrates of the mirrors are generally forced to cool down by using the appropriate methods.

In 1983, Palmer [1] demonstrated continuous wave laser damage on optical components and analyzed thermal properties of fluid cooled mirrors. Curzon et al [2] experimentally investigated a water-cooled mirror, which endured illumination levels approaching $1\,MW\,m^{-2}$. Sun et al. [3] experimentally measured the thermal deformations of the silicon mirror substrate cooled by the paraffin waxes as a phase change material (PCM). The research results show that the thermal deformation on reflecting surface of the PCM cooled mirror can be effectively minimized.

The motivation for using PCM is their high-energy storage density and their ability to provide heat at a constant temperature [4]. The various PCMs are generally divided into two groups: organic and inorganic compounds. Inorganic compounds show a volumetric latent thermal energy storage capacity twice that of organic compounds. Nevertheless, organic substances present several advantages including their ability to melt congruently, their self-nucleation and their non-corrosive behaviors. Alkanes and paraffin waxes belong to this category. Their properties as PCM have been extensively studied by Himran et al. [5]. Although paraffin waxes exhibit desirable properties as PCMs, they present a low thermal conductivity ($0.24\,W\,m^{-1}\,K^{-1}$). In order to offset the low thermal conductivity of an alkane-based PCM, the thermal conductivity enhancement techniques were examined by many researchers [6–9]. For example, Py et al. [9] have

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used paraffin/graphite composite as a high and constant power thermal storage material.

In the present study, the thermal conductivities of the paraffin/graphite powder, paraffin/graphite powder and paraffin/graphite powder composites have been measured, and the thermal deformations of the silicon mirror substrates with phase change materials are experimentally measured and numerically analyzed by using finite element methods.

2. Substrate model

2.1. Mirror substrate structure

High-power lasers are required for nuclear fusion applications whereas more-modest power levels are required for laser machining, laser chemistry, and material processing applications. However, the resonator of a real laser oscillator may be perturbed by mirror distortions and mirror misalignment. All these perturbations will have a great influence on the laser mode properties [10,11]. If the amount of distortion of mirror surfaces in optical resonators that are produced by the thermal deformations of mirrors owing to direct irradiation of high-power laser light and absorption of laser power is in the range $\lambda/10$–$\lambda/4$, the beam quality of the output lasers will become rather poor, and the output laser energy within small angle ranges will obviously decrease.

For high power lasers, silicon are usually used as the materials of the mirror substrates as a result of its high thermal conductivity, low thermal expansion coefficient and absorption coefficient near the wavelength of 1.5 μm. The designs of the mirror substrates are various for different purposes.

The structure diagram of the mirror substrate cooled by the PCMs is shown in Fig. 1a. The thickness W_d of the mirror substrate is chosen as 1.6 cm, and the diameter $D = 8.0$ cm. At the backside of the substrate there are a lot of honeycombed holes for containing the PCMs. The depth W_t of the small containers is about 1.4 cm, and their diameter D_t 0.8 cm as shown in Fig. 1b. The interspaces between the centers of the holes along the horizontal or vertical are about 1.0 cm.

2.2. PCM preparation

The organic compounds as PCMs present several advantages including their ability to melt congruently, their self-nucleation and their non-corrosive behavior. Whereas paraffin waxes as PCMs exhibit the property of a low thermal conductivity (0.24 W m^{-1} K^{-1}). This property reduces the rate of heat storage and extraction during melting and solidification cycles. It will result in poor cooling efficiency for the mirror substrate. Therefore, the thermal conductivity enhancement techniques are necessarily examined. For conveniences, paraffin/copper powder and paraffin/ carbon powder composites as PCMs to cool mirror substrates are utilized in our experiments.

The thermal conductivity enhancement of the PCMs with thermal conductivity promoters, copper, aluminum and carbon powders, is shown in Fig. 2. k_{eff} and k_{p} are the efficient thermal conductivity of the PCMs with and without promoters, respectively. X_{f} is the weight fractions of the thermal conductivity promoters of the PCM composites. From Fig. 2 it is found that the thermal conductivities of paraffin waxes including the thermal conductivity promoter can be obviously improved. While the weight fractions of the thermal conductivity promoters of the PCM composites X_{f} are identical, the efficient thermal conductivity of the paraffin/carbon powder composite is largest among the three kinds of composites. And the efficient thermal conductivity of the paraffin/aluminum powder composite is larger than that of the paraffin/copper powder composite.

3. Finite element analyses

The finite element code ANSYS (Revision 5.6) provides a convenient means of numerically modeling

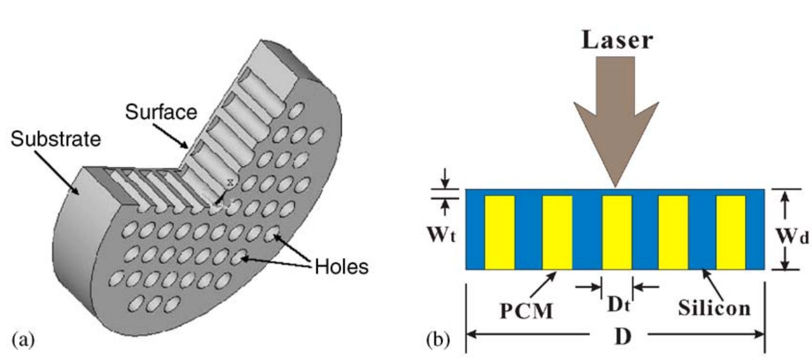

Fig. 1. A typical geometry of the honeycombed mirror substrate.