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Experimental and numerical investigations on cooling performance of chemical-vapor-deposited SiC deformable mirror for adaptive optics system in high-power laser radiation environments

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ABSTRACT

In an adaptive optics system combined with a high-power laser radiation (HPLR) system, the thermal deformation of a deformable mirror (DM), which is induced by high-energy irradiation, is a significant factor influencing the optical performance of the system. In particular, the thermal deformation of the DM with a large diameter of more than a few hundred millimeters should be controlled to be on the order of 1 μm in various HPLR environments. To satisfy these challenging criteria, we experimentally and numerically investigated the cooling performance of a large-diameter water-cooled DM (WDM) with U-shaped cooling microchannels (U-WDM) made of chemical-vapor-deposited SiC, which was designed first in our previous research. The fluid-thermal-structural coupling characteristics of the U-WDM were verified and analyzed through the verification process. In addition, the fluid-thermal-structural coupling characteristics of the DM and U-WDM were compared and analyzed by applying four different HPLR conditions: annular, circular, holed-square, and square beams. Under all the HPLR conditions, the comparative study demonstrated that the U-WDM had dramatic cooling performance, reducing the thermal deformation by more than 85% compared to that of the DM and achieving submicron-scale thermal displacement, which was lower than the targeted actuator deformation limit of 1.3 μm.

1. Introduction

Adaptive optics (AO) systems, which were initially developed for use in the military and astronomy fields, are now applied extensively in various fields, such as ophthalmology, microscopy, and underwater imaging [1–3]. Although AO systems differ methodologically according to the application field, they all deal with the issue of manipulating the optical wavefront and focusing the beam on the target. As another application, AO systems combined with a high-power laser radiation (HPLR) system are applied in the laser processing–by adjusting the beam profile [4–6], and in the military fields–by imaging artificial systems, such as satellites, debris, and high-altitude high-speed targets or by delivering high-energy beams to them [7–9]. This system typically consists of four basic components: an actively deformable mirror (DM), a wavefront sensor, a high-power laser, and a control unit and usually has a power of more than a few tens of kilowatts. The DM is a key component for precisely controlling the wavefront measured by the wavefront sensor by deforming its reflective surface structure using many push–pull actuators connected to its back surface. However, it is structurally vulnerable because of its exposure to an extremely high thermal load. Even if the DM is made of a high-reflectivity material (over 99%), its thermal deformation is inevitable owing to the absorbed laser energy. Moreover, when the amount of thermal deformation in the DM during the working time exceeds the actuator operating limits (early in the single-micrometer range), it is impossible to control the wavefront. This situation leads to detrimental results on the remote transmission of high-power laser beams, such as irradiance reduction, beam shape corruption, defocusing, and focus deformation. Hence, for a high-power laser beam, it is essential to have a sufficient thermal damage threshold and to minimize the thermal deformation of the reflective surface of the DM.

Efforts have been made to resolve the thermal problems induced by HPLR in a mirror by suitably choosing the mirror material, greatly increasing the coating quality of the reflective surface, and optimally

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