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Spot-shadowing deployment for mitigating damage-growth of optics in high-power lasers based on a programmable spatial beam-shaping system

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ABSTRACT

Damage growth in optical components is a bottleneck problem of large solid state laser, which limits the system operating energy, interrupts the use and increases the maintenance cost dramatically. A spot-shadowing technique aimed to obscure damage pits in downstream optics in high-power laser is investigated in this work, whose goal is decreasing local fluence to mitigate damage growth upon subsequent laser shots exposure by shadowing small, isolated flaws on downstream optical components. The method to determine the quantity, geometrical shape, size, and spatial location of blockers is discussed in detail, which is applicable to other large solid lasers in principle. We also find that the local fluence around flaw sites decreases dramatically from ~5.87 J/cm^2 to ~1.10 J/cm^2 (far below laser-induced damage growth threshold ~4.50 J/cm^2) after spot-shadowing is deployed, which proves the feasibility of spot-shadowing for mitigating damage growth.

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1. Introduction

High-power lasers are crucial to numerous applications in industry, inertial confinement fusion (ICF) and other scientific fields [1]. Some large solid-state laser facility, such as NIF [2], operates at high fluence to optimize energy extraction from the amplifiers, thus operating near the damage threshold of optics, especially near the output of the laser system. Moreover, every optical component for a large-aperture laser system contains a number of imperfections or impurities from the manufacturing process [3], or defects generated as a result of the environmental [4], or excitation [5,6] conditions during its operation, all of which can lead to damage initiation due to excessive local absorption of laser pulse propagating through the optics. As a result, there is always a risk of initiating laser-induced damage in optics, and this problem is especially severe for UV optics due to the more efficient interaction of high-energy photons with optical materials, although some advancements in the manufacturing and processing of high damage resistant optics have been achieved [7,8].

The detriments of laser-induced damage are as follows. The presence of laser-induced damage in optical components is responsible for enhanced beam obscuration [9] of laser light arising from increased scattering or absorption which is due to macroscopic changes in the material integrity. In addition, beam modulation [10] that is due to the presence of damage pits can result in additional damage to optics downstream. The problem of enhanced beam obscuration and beam modulation can be addressed by avoiding damage initiation, such as increasing the damage resistance of optics, which is partially realized by optimizing the manufacturing and processing of optics [7,8].

Laser damage events generally consist of damage initiation by a single pulse irradiance and damage growth due to successive laser pulses exposure, and the appearance of a few small damage pits does not appreciably affect optic performance due to the density of defect in modern optics is very low, so damage growth which decreases the operational lifetime of optics and therefore increases operational and maintenance costs significantly is a crucial issue for large-aperture laser systems, such as the National Ignition Facility (NIF) [11].Damage growth can be dramatically mitigated or even be halted by three methods. From the perspective of optics manufacture/treatment, there are two main approaches to resolve the problem of damage growth [12].The first approach is the reducing/eliminating the damage initiation on the surface of the optics by producing a surface free of defects [7]. The second one involves post-treatment of the damage sites to reduce the growth rate, where the most successful method currently is damage sites under CO_2 laser beam exposure [13,14]. From the perspective of

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laser operating, lowering down local laser beam fluence around the flaw sites [15] during large-aperture laser operation is another optional approach.

Although the damage density of sites on fused silica optics at ~10 J/cm^2 (3ω) was reduced by 4 orders of magnitude during the years from 1997 to 2010 due to improved finishing [16], it may not be cost-effective to eliminate every isolated flaw susceptible to laser-induced damage growth. The method of localized CO_2 laser processing has demonstrated its ability to mitigate damage growth of fuse silica, but the downstream intensification [17], generation of re-deposition material [18], and thermal stress [19,20] are accompanied by the CO_2 laser mitigation process, largely limiting the development of laser mitigation technology. Shadowing the flaw sites is an appealing approach, which enhances operational flexibility and reliability by enabling uninterrupted the use of the laser facility.

A general method of shadowing the damage sites in large solid-state laser is introducing programmable obscurations at low fluence, image-relay plane located in infrared region of the laser upstream of the main amplifier chain [21–24]. The previous work [15,21] presents initial results of spot shadowing, and Awwal et al. demonstrates the feasibility of spot shadowing [23,24], while Bahk et al. shows that edge diffraction coupled with Kerr nonlinear effect limit the diameter of the blocker [22]. The above mentioned work only shows initial results of spot shadowing. However, an algorithm for spot shadowing has not been reported in detail for a high-power laser. In this paper, a general method for spot shadowing deployment in large solid-state lasers is demonstrated in detail, and then the feasibility of spot shadowing for mitigating damage growth is presented, which is primarily suited for various high-energy density science experiments, such as the study of laser-induced damage of optics, SRS (stimulated Raman scattering) and SBS (stimulated Brillouin scattering).

2. Experimental

2.1. MODSS (Multipurpose Optical Damage Science System)

The spot shadowing experiment was carried out on MODSS (Multipurpose Optical Damage Science System) facility constructed in 2011. MODSS is a medium aperture tripled Nd:glass laser which has an approximate output energy of ~100 J and ~40 J at 1053 nm (1ω) and 351 nm (3ω), respectively. As shown in Fig. 1, the laser pulse train generated in the front-end with all-fiber scheme gets high gain in the preamplifier constituted with two Nd:YLF rod amplifiers pumped by a single flash lamp, and then enters into spatial light modulator for pre-compensation of gain non-uniformity[25,26]. The spatial light modulator is constituted with a twisted-nematic LC-SLM (LC2002, Holoeye, Germany) where about 10 μm nematic liquid crystal is sandwiched between two layers of transparent electrode plates and a pair of polarizers that enables the polarization modulation to be manifested as an amplitude modulation. After spatial shaping, the main amplifier which consists of two Nd:YLF rod amplifiers and six Nd:glass rod amplifiers pumped by flash lamps further amplifies the laser pulse and delivers the output energy of ~100 J at 1053 nm (1ω), and then the 1ω beam is frequency-tripled using a type I/type II scheme with KDP crystals.

The transmission of each pixel of LC-SLM can be adjusted, which is designed for the compensation of the spatial beam non-uniformity resulting from the gain inhomogeneity of the laser amplifiers [25,26]. Apart from beam shaping, the spatial light modulator can also be used for spot shadowing [15,21–24]. As seen in Fig. 1, spatial light modulator, charge coupled device (CCD) and Optics Inspection (OI) system work together to deploy spot shadowing. Some key details are discussed as follows.

2.2. Spatial registering

Flaw sites were specified in the OI system coordinate, as a result they were required to be transformed into the LC-SLM coordinates prior to rendering. The picture captured by OI system was relayed from LC-SLM, therefore it's easy to determine the spatial transformation between these two image planes.

As illustrated in Fig. 2(a), test pattern at low fluence, image-relay plane (i.e., LC-SLM in Fig. 1) consisted of three blockers, and these three blockers which were arranged in right triangle were different in size and spatial separation between any two blockers. Fig. 2(b) captured by OI system was the result of test pattern. As illustrated in Fig. 2(c), the spatial relationship between Fig. 2(b) and (a) could be expressed as

$$\begin{bmatrix} x_i \\ y_i \end{bmatrix} = \begin{bmatrix} a & b \\ c & d \end{bmatrix} \begin{bmatrix} x_i \\ y_i \end{bmatrix} + \begin{bmatrix} e \\ f \end{bmatrix} \equiv T_1 \begin{bmatrix} x_i \\ y_i \end{bmatrix} + T_2 \qquad (1)$$

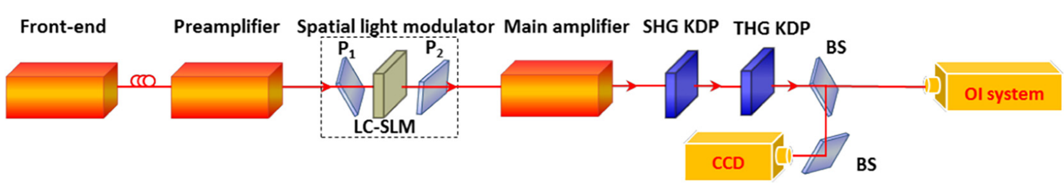

Fig. 1. The schematic setup for spot-shadowing deployment carried out in MODSS laser facility (P_1 and P_2, Polarizer; BS, Beam Splitter; OI system, Optics Inspection system; CCD, Charge Coupled Device), and more details are presented in text.

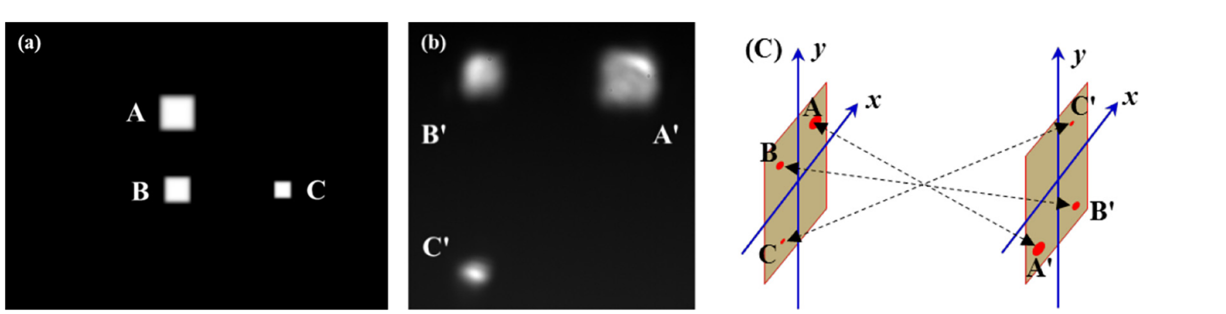

Fig. 2. (a) Test pattern located at LC-SLM image-relay plane for determining spatial transformation, (b) the figure captured by OI system was resulted from the (a), and (c) the schematic illustration of determining spatial transformation.

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