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Full Length Article

Temporal scaling law and intrinsic characteristic of laser induced damage on the dielectric coating

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ABSTRACT

High power laser is essential for optical manipulation and fabrication. When the laser travels through optics and to the target finally, irreversible damage on the dielectric coating is always accompanied without knowing the law and principle of laser induced damage. Here, an experimental study of laser induced damage threshold (LIDT) F_{th} of the dielectric coating under different pulse duration t is implemented. We observe that the temporal scaling law of square pulse for high-reflectivity (HR) coating and anti-reflectivity (AR) coating are $F_{th} = 9.53t^{0.47}$ and $F_{th} = 6.43t^{0.28}$ at 1064 nm, respectively. Moreover, the intrinsic LIDT of HR coating is 62.7 J/cm^2 where the coating is just 100% damaged by gradually increasing the fluence densities of a 5ns-duration pulse, which is much higher than the actual LIDT of 18.6 J/cm^2. Thus, a more robust and reliable high power laser system will be a reality, even working at very high fluence, if measures are taken to improve the actual LIDT to a considerable level near the intrinsic value.

1. Introduction

High power laser has a wide range of applications, such as precision welding, cutting and marking, and is also useful for research in high-energy-density science, particularly at short pulse duration, e.g. National Ignition Facility [1] and Laser Mégajoule [2]. Since we are in pursuit of high power, a serious problem of laser induced damage emerges on the optical devices, especially on the surfaces, where are coated with dielectric films for high-reflectivity (HR) and anti-reflectivity (AR) [3]. Consequently, the laser induced damage thresholds (LIDTs) of the coatings directly limit the available power or fluence for safely and reliably operating a laser system. Theoretically, the LIDTs are determined by the bandgaps of coated materials [4–6] and high thresholds can be achieved by using the materials with wide bandgap like SiO_2 and HfO_2. However, the threshold on the surface is always much lower than predicted value since the stochastic presence of defects caused by imperfect procedure of polishing and cleaning [7,8]. It is generally accepted that the defect act as an absorber and large amount heat deposition around it finally damage the coating [9–12].

Detailed analysis of the mechanism of aforementioned damage is beneficial for predicting the lifetime of optical elements [13], thus the security and stability of the laser system can be guaranteed. Since the defects randomly distribute on the surface of dielectric coating components, damage events are probabilistic [14,15], which are exposed by damage tests. So, a series of approaches are introduced to implement the test of 1/1, S/1, R/1 and N/1 and find the basic law of LIDT. Lamaignere et al. [16] apply a raster scan procedure with small beam to measure the damage density of sample and extrapolate the LIDT of large optics. Employing the contrast of a large beam, damage density can also be achieved by matching fluence and damage maps for just a single shot [17,18]. Laser induced damage of optics depends on pulse width and the duration dependencies of LIDT are different for different materials [19]. Carr et al. [20–22] have studied the influences of pulse duration on damages in DKDP and SiO_2. For the dielectric coating, Mackenzie et al. [4,23,24] have done a lot of work on the scaling law of laser pulse duration in the picosecond to femtosecond regime. But the temporal scaling law for dielectric coating is still obscure and more work is needed in the nanosecond regime.

Here we first apply the raster scan procedure to make tests on HR coating and AR coating. HfO_2 and SiO_2 are chosen as high (H) and low (L) refractive-index materials for both HR coating and AR coating, which are deposited by e-beam on the fused silica substrate. The multilayer structure of HR and AR coating are Sub/4L(HL)^{11}H4L/air and Sub/2L0.5H1.25L/air respectively, with

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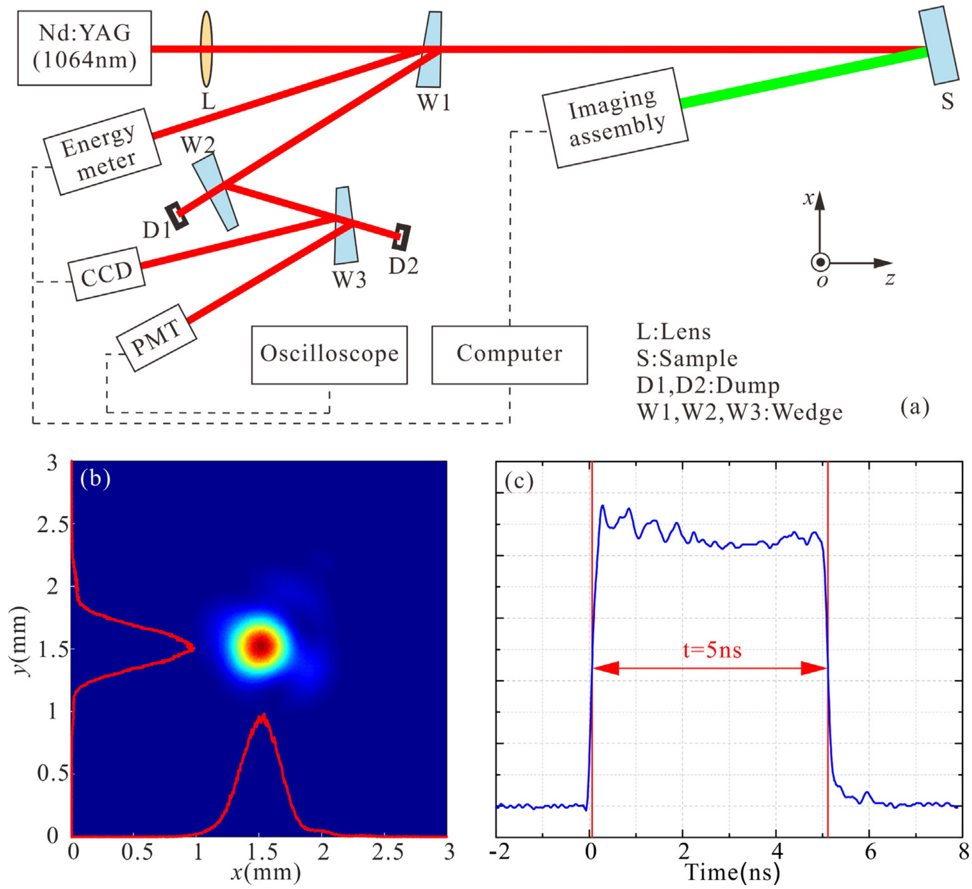

Fig. 1. Laser induced damage test. (a) Experimental setup; (b) spatial profile; (c) temporal profile (@5 ns).

an optical thickness of λ/4 @1053 nm for H and L. The refractive indexes of HfO_2 and SiO_2 are 1.97 and 1.45 at 1053 nm, respectively. Then the LIDTs of the two coatings are extrapolated, and further fitted with pulse duration to obtain the pulse scaling laws. Besides, we make a comparison on the LIDTs of the same sample using different test methods. The intrinsic damage of the two are also discussed for well understanding the nature of laser induced damage.

2. Laser induced damage threshold test

2.1. Experimental setup

The experimental setup, as shown in Fig. 1(a), used for laser induced damage test is equipped with the Nd:YAG laser system developed by our group [25], of which the wavelength is 1064 nm (1ω). The pulse is single longitudinal mode, with the highest energy of 100 mJ (RMS = 0.72%), repetition range of 0 ~ 100 Hz and pulse duration available from 100 ps to 10 ns under arbitrary waveform. Adding another Xenon lamp rod amplifier, the output could reach 1J while repetition should narrow down to 0 ~ 5 Hz for leaving the rod cool enough. The near field of the output beam is almost flattop with an aperture of Φ10 mm. During the test, the beam is focused at the sample to achieve high fluence. Energy, spatial and temporal profile on the sample are recorded by energy meter, CCD and oscilloscope in real time, respectively. The CCD is positioned at a location optically equivalent to that of the sample. The actual incident of the test beam is 12° deviating from the normal during the procedure. A small angle tilt of the sample could protect the optics of the experimental setup and the imaging assembly from the reflected laser via the test surface and avoid the back and forth reflection of the test beam affecting the test results, which may lead to an inaccurate damage threshold. The focus spot is Gaussian distribution with diameter of 490 μm (1/e), as shown in Fig. 1(b). Fluence on the sample is calculated from energy and spatial profile of laser pulse, and also the deviate factor of cos12° is taken into consideration. The pulse duration used in the experiment here ranges 1 ns to 10 ns with a shape of square and Fig. 1 (c) shows the temporal profile of 5 ns. The sample is mounted on a 3-axis stage for raster scan. New damage site on the test area is detected from the imaging assembly and displayed on the screen. As illustrated in Fig. 2, it demonstrates the damage sites on HR coating at different fluence with a pulse width of 5 ns during the LIDT test. It can be seen that an initial damage site appearing at a low fluence, 16J/cm^2 for example, is always a small one with a size of ~15 μm. It is found that the number of damage sites and damage sizes increased with the increasing fluence. The damage size is as large as ~50 μm at 36J/cm^2, as shown in Fig. 2(c).

2.2. Test method and data treatment

The raster scan procedure [16] for damage density tests proves to be reproducible [26] and representative [27]. Beam overlap is a key parameter during the small beam raster scan damage test procedure. The test area is 1cm × 1 cm and the interval between two successive shots is 250 μm to make sure every corner is under tested. The measurement begins with a low fluence that no damage occurs and step up 2J/cm^2 to scan the area over again until a certain damage density (~10% damage sites) detected on the test area. Damage density increases with fluence since that if damage takes