Analysis of Damage Thresholds of Laser Scanning Mirrors using Ultrashort Laser Pulses

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Abstract

A series of laser induced damage threshold experiments are carried out at various wavelengths and angle of incidences (AOI) with a $t_p = 10$ ps laser. Various fused silica laser scanhead mirrors are tested according to the conditions of its intended use. Damage is initiated by a focused beam so that a safe operating value of fluence can be derived. Results indicate that the threshold is dependent on the AOI which is caused by the limitations of the coating design. An increase in AOI results in a higher percentage of laser energy being coupled rather than reflected.

Keywords: dielectric mirror; damage threshold; scanhead; ultrashort pulses; picosecond

1. Motivation / State of the Art

The pursuit of research and demands of industry have led to the advent and significant improvement of pulsed ultrashort laser systems. For instance, commercial picosecond and femtosecond laser systems can reach pulse energies of up to 250 mJ [1] and 1 mJ [2] respectively. The limiting factor in achieving higher energies is that of the optical elements, in particular, mirrors. In a laser system, it is that of the resonator mirrors, but the focus of this paper is targeted towards dielectric mirrors within a laser scanhead system. In particular, scanhead mirrors are dynamically active optical components and are designed with tremendous limitations causing it to be characterized as an extremely sensitive optical component. Therefore, it is the motivation of industry and research institutions alike to determine the damage threshold of these mirrors so that safe deflection of the laser beam can be carried out. An associated damage threshold of an optical component in the ultrashort pulse regime is typically rated in the order

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of 10-20 ns. This causes the user of such a component to use scaling laws if operating in the picosecond pulse regime. The SPIE Boulder Damage Symposium documents very well the research conducted in this area every year and ISO 11254 documents how a damage threshold test is performed.

Extensive testing has been carried out in the subnanosecond up to continuous time regimes over a wide range of wavelengths [3]. However, the damage mechanisms in these regimes are different compared to nanosecond pulses since below 20 picosecond pulse duration, the damage in dielectric materials changes from thermally dominated melting and vaporizing to one dominated by plasma formation and ablation [4,5]. In addition, damage threshold becomes a deterministic rather than a statistical value at shorter pulse durations resulting in more defined values for threshold [6]. The manner in which free electrons are excited initiates an electron avalanche. Beyond a certain density build-up of free electrons on the surface due to laser beam irradiation, surface state, defects, etc., an electron avalanche is sustained leading to damage of the material. For picosecond and femtosecond pulse regimes, damage is associated with avalanche ionization and multi-phonon ionization respectively, and sometimes a combination of both [3]. Damage threshold topics range from using novel coating materials [7], determining damage thresholds in the femtosecond pulse regime [8], introduction of damage resistant features onto coatings [9], change in damage threshold due to coating technique [10], and investigations into pulse duration scaling laws [11] among others. In the study of laser induced damage of dielectric mirrors, irradiation is almost always directed normal to the specimen and sometimes at an AOI of 45° according to ISO 11254. This is inappropriate for a mirror coating that is designed for AOI outside these angles. Optical component dependence on the AOI has been investigated for example in [12,13], but specific investigation on damage thresholds of galvanometer driven, dielectric scanhead mirrors in the picosecond pulse regime does not exist. In this paper, we present a series of laser induced damage threshold experiments which are carried out at various wavelengths and AOI with a \( \tau_p = 10 \) ps laser.

2. Experimental setup

An idealized structure of a dielectric coated mirror is shown in Figure 1 (a), which consists of a substrate (\( n_{\text{sub}} \)), a high-low refractive index coating material pair (\( n_2, n_3 \)), in which thickness is a multiple (typically either \( \lambda/2 \) or \( \lambda/4 \)) of the wavelength, and an even number of layered pairs. Laser beam propagation is characterized by the AOI and transmission (\( \theta_{\text{air}} \) and \( \theta_{\text{sub}} \)) respectively. Figure 1 (b) shows a scanning electron microscopy (SEM) image of a cut and polished cross section of a commercially available 1064 nm dielectric mirror. In addition to the shown layered structures of the idealized structure as shown in Figure 1 (a), there is a protective layer at the front surface of the mirror. Subsequently, there is an antireflection coating designed for a specific wavelength. Following the reflective layered pairs of alternating refractive indices, there is another section which exhibits a similar layered paired structure, but the coating thickness is reduced. This region is designed to mitigate any further radiation which could propagate into the substrate layer of the material.

Figure 1. (a) Layered dielectric coated mirror and propagation of laser radiation. (b) Scanning electron microscopy image of a polished cross section of a dielectric 1064 nm coated mirror specimen: (1) Embedding material, (2) Front mirror surface, (3) Protective layer, (4) Antireflection coating, (5) reflection layered coating pairs, (6) Radiation stop layered pairs, (7) Mirror substrate.
Figure 2. Experimental setup: (1) laser system, (2) tilt mirrors, (3) periscope, (4) iris diaphragms, (5) data acquisition unit, (6) plano-convex lens, (7) incident beam, (8) online camera, (9) specimen, (10) reflected beam, (11) power meters, (12) specimen fixture with z- and AOI-translation, (13) transmitted beam, (14) x,y- motorized translation stage.

The experimental setup depicted in Figure 2 has been designed as to closely follow the layout as designated by ISO 11254 but modified to adapt to the intended purpose of a scanhead mirror. The laser source used is a Nd:YVO₄ laser generating linearly polarized laser radiation at fundamental (p-polarized wave), double (s-polarized wave) and triple (p-polarized wave) harmonics. The pulse duration is $\tau_p = 10$ ps, average power is controlled via a polarization optic and irradiation periods do not exceed 60 seconds. The setup is contained within a temperature and humidity controlled environment and focusing occurs with a 100 mm plano convex lens. Orthogonal focal spot diameters are 12.5, 18.7 and 37.5 $\mu$m for 355, 532 and 1064 nm wavelengths respectively. A power meter is used for the laser induced damage threshold experiments to measure the reflected beam, which reflects off the specimen surface while the coating is undamaged. The change in reflectivity, if damage occurs, can be recorded online using this technique. In general, scanhead mirrors are designed with coatings for a limited AOI bandwidth. Hence, the initial idle position of a x- and y- mirror is 45° and 38° respectively with a range of oscillation of ±12°. A y- direction mirror was tested only at an AOI of 38, 44 and 50° since such values are equal to that when the AOI is 38, 32 and 26°. The specimen is able to translate using nanometer scale motorized stages about the x- and y- axis so that the focal plane can be accurately determined. Using micrometer scale manual stages, the specimen is able to translate about the z-axis as well as about the AOI- direction so that easy movement to each subsequent test site is accomplished. Additionally, it is fixed upon a rotary stage about the z-axis to adjust for different AOI. Constraints on the mirror such as uninhibited thermal expansion are facilitated by only holding the mirror at two points. The above description outlines the experimental setup to determine the damage threshold of the scanhead mirror. The subsequent experiment necessary to determine absorption, requires two power meters to measure both the reflected and the transmitted beam. The power meter which measures the transmitted beam has a 55 mm aperture which is sufficiently large to detect scattered transmitted radiation. The fixture also holds the mirror at two points but this time the rear face is uninhibited to allow for transmission measurements.

3. Results and Discussion

Experiments are carried out on mirrors supported by a fused silica substrate with wavelength dependent coating, which are 1064, 532 and 355 nm. All three wavelength studies follow a certain structure and produce similar results. Therefore, all following studies and results are shown for a 532 nm mirror such that damage is defined according to ISO 11254. The damage threshold of the above described mirrors is determined using the multiple laser pulse per site method (denoted as S-on 1 by ISO 11254). Damage is any permanent laser induced change of the surface characteristics of the specimen which can be observed by an inspection method as explained in the following. Pre-damage detection is carried out by the use of a power meter measuring reflected radiation and an optical camera. In case of damage, the reflected power level reduces significantly until the coating layers are completely damaged.
This results in a change in contrast as detected by the optical camera. Post-damage detection is verified by white light interferometry and optical microscopy. Some examples of damage detection methods results are shown in Figure 3 and Figure 4. In order to detect damage, the reflected radiation from the mirror’s surface is measured using a power meter and plotted versus time as shown in Figure 3 (a). Measurements are recorded without irradiation for eight seconds, and then the laser shutter is opened to initiate irradiation onto the surface of the specimen. The reflected power rises to the predefined power level. Depending on the intensity of the irradiation, the coating withstands or fails irradiation. If the intensity level is high enough to damage the coating, it still withstands irradiation for a short period of time, then there is a drop in reflected power which converges to zero. The damage threshold is determined accordingly for each AOI and plotted as shown in Figure 3 (b). Generally it can be observed, that entrance damage is elliptical, smaller in diameter and relatively cleanly ablated as shown in Figure 4 (a). After radiation has travelled to the exit face of the mirror substrate, the exit damage on the other side presents itself as always circular. A diameter change occurs and the exit damage is larger than on the entrance face due to the self focusing effect caused by reflection of the incident beam from the sides of formed cavities. This side also shows higher thermal effects, as shown in Figure 4 (b) due to higher local power density. One might initially expect that given the fact that the spot size increases for larger AOI, then this would result in a drop in fluence and accordingly a higher damage threshold. This is not the case and the contrary occurs as depicted in Figure 5 (a). Therefore, measures to prevent damage through beam expansion are not always effective and the design specifications of the optical element must be checked. To better understand this concept, experiments are performed to measure reflection and transmission properties over a period of time, at maximum available average laser power $P_{avg} = 5.19$ W at $f_p = 200$ kHz and a beam diameter of 4.8 mm over a range of AOIs. As a result, the absorbed power can be computed. The result of absorbed power, for which transmitted power follows a similar trend can be seen in Figure 5 (b). Since the majority of commercial dielectric coatings are unable to effectively provide a high degree of reflectance over a wide range of AOIs, it tends to absorb and transmit a high portion of laser radiation. When measuring using two power meters, as indicated in the experimental setup as shown in Figure 2, reflection decreases and accordingly transmission increases at higher AOI. This corresponds to a rise in absorption or more coupled laser radiation at higher AOI, which is the reason why damage occurs sooner. An explanation is that because dielectric coatings are periodic multilayered structures, strong reflections occur only at certain AOI corresponding to photonic band gaps or stop bands [14]. A photonic band gap is a frequency band in which electromagnetic waves cannot propagate through. Within this band gap region, optical modes, spontaneous emission and zero point fluctuations are not present allowing one to control these noted parameters by means of the band gap’s characteristics [15]. This band gap is shown in Figure 6 (a) as the region of high reflectance approximately between 460 and 540 nm when AOI = 0°.
To further understand this concept, the matrix method according to [16] is employed to analyze the optical transmission through an array of dielectric multilayers. The following is based on the assumption of an arbitrary dielectric coating based on the schematic of Figure 1 (a). Laser radiation propagates from air ($n_{\text{air}} = 1.0003$) into a coated pair of dielectric material ($n_2 = 1.90$, $n_3 = 1.38$) which is supported by a substrate material ($n_{\text{sub}} = 1.52$). Eleven layer pairs are present and the designated wavelength for ideal reflection is $\lambda = 500$ nm for orthogonal laser
propagation. Three effects occur with greater AOI. Firstly, the photonic band gap shifts away from the designed wavelength if independent of polarization as shown in Figure 6 (a). Secondly, since experiments were performed with different polarization states, given s-polarization (532 nm), the band gap increases in bandwidth with increasing AOI while with p-polarization (355 and 1064 nm), the band gap decreases [17,18]. Thirdly, the penetration depth into the dielectric layers decreases for s-polarization and increases for p-polarization with greater AOI [19]. As a result, the reason for a reduction in the damage threshold at high AOI is attributed to the limitations of the dielectric coating. In terms of the 355 and 1064 nm mirrors, the band gap shifts away from the designed wavelength and the band gap bandwidth gets narrower. This explains the large difference in damage threshold from 38 to 50°, $\Delta$1064$^{\text{threshold}}$ = 0.962 J/cm$^2$ and $\Delta$355$^{\text{threshold}}$ = 1.61 J/cm$^2$. In terms of the 532 nm mirror, the difference is $\Delta$532$^{\text{threshold}}$ = 0.157 J/cm$^2$, such that the increase in bandwidth tends to compensate the shift of the band gap resulting in a smaller difference in threshold. The change in reflective properties is shown in Figure 6 (b). Through direct measurement and theoretical explanation of the behavior of the photonic band gap in terms of AOI, emphasis is put on the fact that for mirrors employed for scanheads, it can be deduced that the damage threshold depends on the oscillation range of the galvometrically driven dielectric mirror.

4. Conclusions / Outlook

The values for damage threshold and degree of reflectivity of three dielectric mirrors varying in coating composition are determined. To quantify, the damage threshold for the 355, 532 and 1064 nm mirrors is 2.7, 0.96, 2.4 J/cm$^2$ respectively when the AOI = 50°. The reflectivity of the 532 nm mirror is 97, 96.28, 96.04% when the AOI equals 38, 44, 50° respectively. As long as these values are not reached, then the safe use of current picosecond laser pulses on dielectric scanhead mirrors is feasible. Accordingly, the pulse duration, the fluence and especially the angular offset from the designed AOI needs to be observed carefully, since absorption rises due to the limitations of the mirror, namely a change in the photonic band gap characteristics. Furthermore, both reflectivity and thus the damage threshold decreases at greater AOI. Further investigations into mirror deformation properties with respect to long term irradiation as well as dynamical behavior of deflection mirrors are currently being carried out.

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