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Laser-Induced Damage Threshold and Certification Procedures for Optical Materials

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1. Introduction

1.1. Purpose

This document provides instructions for performing laser-induced-damage-threshold tests and pass-fail certification tests on optical materials used in pulsed-laser systems. The optical materials to which these procedures apply include coated and uncoated optical substrates, laser crystals, Q-switches, polarizers, and other optical components employed in pulsed-laser systems.

1.2. Scope

This document provides guidelines for performing one-on-one, laser-induced-damage-threshold tests and pass-fail certification tests for optical components. The procedures described herein are applicable to the testing of optical materials intended for use in pulsed-laser systems and in electro-optical systems that use lasers. The test procedures are performed by using a pulsed-laser system with the optic under evaluation positioned normal to the incident laser source. Reports of test results must include the wavelength, pulse length, polarization, and Gaussian distribution of the laser source.

2. Definitions

Beam diameter (ω_0) — Distance across the center of a laser beam for which the energy (E_0) equals $1/e^2$ of the maximum fluence, assuming operation in the TEM_{00} mode.

Certification test — Pass-fail test performed to ensure that an optic possesses a damage threshold greater than a minimum specified value. This test is performed by exposing five test sites within the clear aperture of an optic to a predetermined fluence level. If no damage is observed on the test optic, the optic has successfully met the certification criteria.

Clear aperture — Also known as the free aperture or objective aperture; the opening in the mount of an optical system or its components that restricts the extent of the bundle of rays incident on the given surface. This aperture is usually circular and specified by its diameter.

Damage threshold — Maximum applied laser energy density (or fluence) below which no damage to an optical material is observed. This value is determined by using the techniques outlined in section 3.6 of this document.

Damage-threshold test — Destructive test procedure that determines the maximum applied laser energy density (or fluence) below which no damage to an optical material is observed.

Fluence — Ratio of the applied laser energy to the cross-sectional area of the incident laser beam. The fluence of an individual laser pulse is calculated by using the relation (ref. 1)

$$F = \frac{8E_0}{\pi\omega_0^2} \quad (1)$$

where F is the calculated applied laser fluence (J/cm^2), ω_0 is the Gaussian beam diameter at $1/e^2$ (cm) at the optic being tested, and E_0 is energy of the incident beam (J).

Gaussian beam — Laser beam with an energy cross section that follows the equation of a Gaussian distribution

$$E(r) = E_0 e^{-2(r/\omega_0)^2} \quad (2)$$

where E_0 is the energy, r is the distance from the center of the beam, and ω_0 is the beam diameter at the $1/e^2$ point.

Optical coating — Material deposited in single or multiple layers onto an optical substrate that is designed to alter the reflective or transmissive properties of the optic.

Optical damage — Permanent physical change in an optical material that results from interaction with a laser beam.

Optical substrate — Material with physical characteristics that allow the alteration or transportation of a specific electromagnetic frequency band.

Polarization — Orientation of the electric field. For the purposes of these tests, a rectangular representation will be used. That is, the electric field could have two components, nominally in the plane of incidence and perpendicular to the plane of incidence.

Pulse width	Time duration of a single laser pulse at 50 percent of the maximum intensity, assuming a Gaussian temporal distribution.
Transverse modes	In a transverse electromagnetic mode (TEM), both the electric and magnetic field vectors are normal to the propagation direction. Transverse modes are designated by TEM_{mn} using Cartesian coordinates. The integers m and n represent the number of nodes of zeros of intensity transverse to the beam axis in the vertical and horizontal directions. The lowest order mode is the TEM_{00} mode, which has a Gaussian-like intensity profile with its maximum on the beam axis.
Wavelength	Minimum distance over which a wave repeats itself.

3. Specifications

3.1. Equipment and Test Configuration

The experimental procedure described in this document involves the use of high-energy lasers. Therefore, the safety guidelines set forth in references 2 and 3 should be observed to ensure the safety of the operator and others.

Laser-induced-damage-threshold tests are performed by using a pulsed laser of known wavelength, pulse length, polarization, and TEM. In this procedure, the laser is located on a stabilized optical table with the beam directed toward a test optic, as shown in figure 1. A helium-neon (He-Ne) laser also may be placed on the optical table for use with the alignment of optics; however, this second laser is not employed in the performance of the tests.

Near the end of the optical path, a portion of the incident laser beam is directed toward the beam diagnostics with a beam splitter. The beam diagnostics requirements for performing damage-threshold and certification tests include instruments capable of determining the energy, Gaussian distribution, pulse width, polarization, and diameter of the incident laser beam. Each of these beam diagnostic devices should be accurate to within ±5 percent.

During testing, the optic under evaluation is placed on an *x-y* translation stage normal to the incident laser beam at the end of the optical path, as shown in figure 1. The translation stage mechanism provides a means to

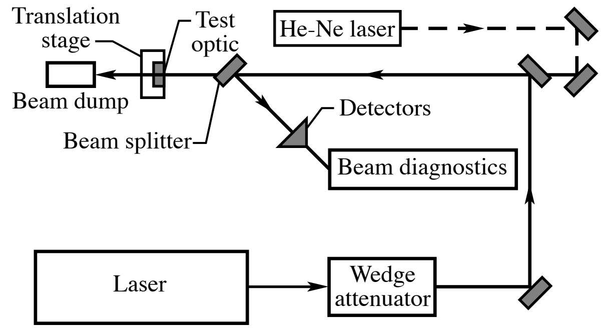

Figure 1. Layout of laser and diagnostic instrumentation for damage-threshold testing of optical materials.

obtain uniform spacings between the exposure sites on the optic under evaluation. To prevent reflection of laser light back into the laser source, this procedure may be carried out with the incident beam 1 to 2° off axis from the normal.

After passing through (or reflecting from) the test optic, the laser beam is directed to a nonreflective surface that terminates the laser beam (i.e., a beam dump). The test configuration illustrated in figure 1 describes the testing of an optic with an antireflective (AR) coating. If a mirror is to be tested, the beam dump should be positioned on the optical table so that the incident beam terminates after interacting with the reflective optic.

3.2. Pretest Evaluation, Cleaning, and Handling of Optics

Prior to damage testing, inspect the optical components with optical and/or Nomarski microscopy at a magnification of at least 100x. This evaluation identifies any preexisting flaws in the optical surface that would otherwise be included in the posttest damage assessment. The pretest optical evaluation also provides a means of assessing the cleanliness of the optical surface prior to testing. If particulate matter is present on the surface of the optic, these particulates may be removed with compressed dry nitrogen gas. If the optic requires further cleaning, use a drag-wipe cleaning procedure. With this procedure, clean the optical surface with a lint-free cloth and spectroscopic grade methanol and/or acetone. After cleaning, perform another microscopic evaluation of the test specimen to ensure complete removal of all foreign matter from the optical surface.

At all times during this test procedure, handle the optics under evaluation by the edges to prevent accidental damage to the optical surface. Additionally, laboratory personnel must wear finger cots or latex gloves to prevent accumulation of oils on the test specimens. Prior to testing, store the optical materials in a desiccator maintained at a relative humidity of less than 50 percent. These handling and storage measures ensure that the test specimen has not been influenced by the laboratory environment so that an unbiased estimate of the damage threshold is obtained.

3.3. Damage-Threshold Test Procedure

3.3.1. Damage-threshold approximation. If the approximate value of the laser-induced damage threshold of an optic is unknown at the beginning of a test, an approximation procedure may be employed to determine an appropriate fluence level at which to begin the procedure described in the preceding paragraphs. In this approximation procedure, one test site per fluence level and incremental fluence steps of 2 to 5 J/cm^2 should be employed. This procedure is employed only to identify a range of fluence values to use during testing, and these results should not be used in the damage-threshold determination procedure described in section 3.6.

3.3.2. Damage-threshold test procedure. When the experimental arrangement described in section 3.1 is used, at least five sites on the optical surface under evaluation are exposed to single laser pulses at a known fluence level. After the exposure sites are subjected to the known laser fluence level, the applied fluence level is increased or decreased by an increment of 0.025 J, ±0.005 J, and another set of five test sites is exposed to the incident laser pulses. This procedure is repeated until the data set includes two consecutive fluence levels that induce no damage (0 percent failures) and at least one applied fluence level at which at least 60 percent of the sites are damaged.

A spacing of at least three times the diameter of the incident beam must separate each exposure site on the surface of the optic in any direction to ensure that the test results are not influenced by adjacent test sites. Additionally, each test site should lie within the clear aperture of the optic to ensure the results provide an accurate representation of the optic as it will be employed. An illustration showing the array of exposure sites for a laser-induced-damage-threshold test with five applied fluence levels, five test sites per fluence level, and a spacing of three times the diameter of the incident beam (ω_0) is provided in figure 2.

For this test, the incident beam should possess a beam diameter of 1.0 to 1.25 mm and a Gaussian distribution of at least 90 percent. The use of laser beams with diameters of less than 1.0 mm artificially increases the damage-threshold value obtained with this procedure (refs. 4–6). This increase in the damage threshold obtained through the use of smaller spot sizes is related to the portion of the optic sampled by the incident laser

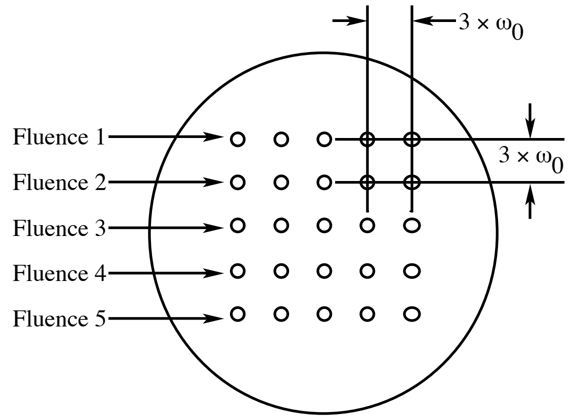

Figure 2. Test pattern for performance of damage-threshold test.

beam. As the diameter of the incident beam decreases, a smaller, less representative portion of the optic is sampled, and the data obtained are not necessarily indicative of the performance of the entire optical surface.

3.4. Damage Assessment

The presence of laser-induced damage to an optic is assessed with optical and/or Nomarski microscopy techniques. In some instances, the presence of optical damage may be obvious under low magnifications (i.e., ±10x); however, the tested optic should be examined with magnifications of at least 100x to ensure that damage to the optic does not go undetected. Damage is defined as a permanent change (e.g., pitting or coating delamination) in the optical surface as a result of interaction with an incident laser beam.

3.5. Damage-Threshold Determination

3.5.1. Case 1: At least five test sites per fluence. Once all of the planned exposures have been performed and the damage to each site assessed, a plot of the percentage of sites damaged as a function of applied fluence level is prepared. The damage threshold is then determined by linear regression analysis. In this procedure, the regression line is obtained by using the data points between the highest nondamaging fluence and the first fluence level at which at least 60 percent of the test sites are damaged. The damage threshold is then defined as the *x*-intercept of the regression line (ref. 7). An illustrative example showing a regression line fit to a plot of the percentage of damaged sites versus the applied laser fluence level is provided in figure 3.

3.5.2. Case 2: Fewer than five test sites per fluence. When optics with limited available testing areas are damage-threshold tested, at least two test sites per fluence level may be used. In this case, however, the use of

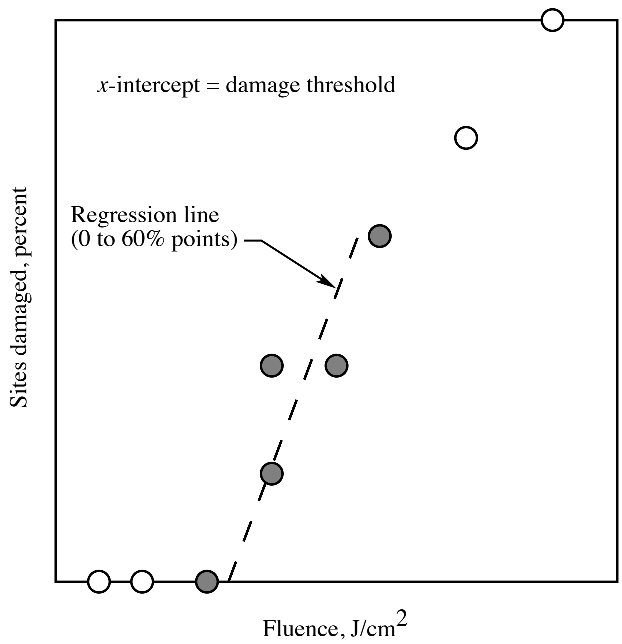

Figure 3. Graph of relationship between percentage of damaged test sites and applied fluence level. Dashed line represents regression line fit to data points between highest nondamaging fluence and fluence at which 60 percent of the test sites were damaged.

linear regression analyses to determine the damage threshold may yield less accurate results. To avoid errors, the damage threshold is defined as the highest non-damaging fluence. An example of a test performed with this technique appears in the appendix.

3.6. Certification Testing

In addition to the destructive evaluations described in section 3.4, an optical material may also be certified to a specified level by exposing the optic to a predetermined fluence level. The test configuration for performing a pass-fail certification test is the same as that described for damage-threshold tests.

In this procedure, five test sites, with site-to-site spacing of at least three times the beam diameter, are each exposed to a single laser pulse of known fluence. The incident laser beam should possess a minimum beam diameter of 1.0 to 1.25 mm and a Gaussian fit of greater than 90 percent and operate in a TEM_{00} mode. If no damage is observed on any of the five certification test sites, the optical component is said to have passed the certification test at the specified level.

4. Reporting and Documentation

The documentation of damage-threshold and certification tests should include the procurement specifications of the optic under evaluation, the laser parameters used in the performance of the test, and the damage-threshold and certification test results. Specifically, the procurement information to be maintained must include but not be limited to

- Name of optical component
- Manufacturer's name
- Manufacturer's trademark and identification number
- Manufacturer's lot number
- Purchase order number
- Dimensions of optic
- Coating specifications
- Substrate specifications

Additionally, the laser-induced-damage-threshold test parameters and results to be maintained must include but not be limited to

- Test wavelength
- Test pulse length
- Gaussian fit of beam employed in testing
- Polarization state of laser employed in testing
- TEM mode
- Plot of the percent of sites damaged versus applied fluence
- Damage threshold, J/cm^2
- Certification test level
- Certification test results (pass-fail)

If damage threshold test data are to be used as acceptance testing criteria, the data should be kept in control chart format. Techniques for implementing statistical process control procedures for procured materials are described in references 8 and 9.

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Appendix

Laser-Induced-Damage-Threshold Test Example

Laser-induced-damage-threshold tests were performed on eight uncoated, fused silica windows. The tests were performed using monochromatic laser light with a wavelength of 532 nm generated by a frequency doubled Nd:YAG laser. The laser, laser diagnostics, and test optics were oriented on an optical table in a similar configuration to the one shown in figure 1. The laser, which possessed a pulse length of 7.5 nsec, Gaussian distribution of 95 percent, and linear polarization, operated in a TEM_{00} mode.

In this example, the uncoated optics were tested at two test sites per applied fluence. A beam diameter of 1.0 mm and spacing of 3 mm between test sites were used. After all of the planned exposures were performed, the optics were evaluated with both optical and Nomarski microscopy.

Figure A1 shows the plot of the percentage of sites damaged at each fluence for one of the eight optics under evaluation. The highest nondamaging fluence observed in this trial, the damage threshold, was 43 J/cm^2. The horizontal error bars seen in figure A2 represent the measurement error in the fluence calculation attributable to the beam diagnostics employed in testing (±3 percent). Because of the probabilistic nature of this test procedure

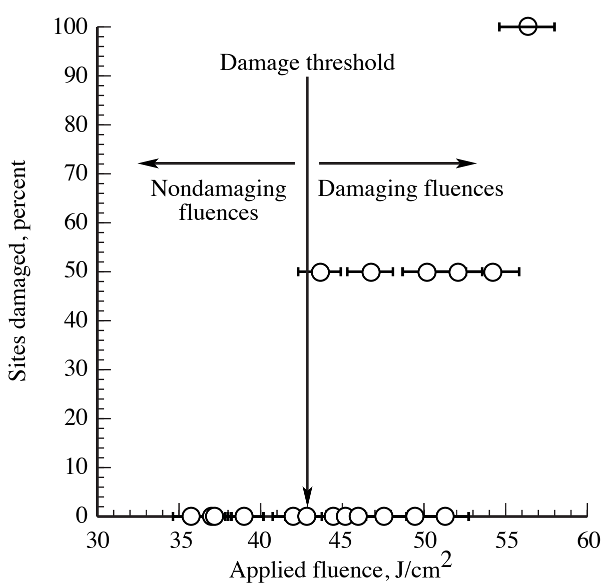

Figure A1. Damage-threshold data for uncoated fused silica. Damage threshold = 43 J/cm^2.

(i.e., the results are based on the percentage of sites that damage at each fluence), some fluences show no damage (0 percent failures) even above the damage-threshold value. However, no damage to the optic was observed at any fluence below the damage threshold. An example of laser-induced damage to the optic under evaluation as a result of exposure to a damaging fluence is shown in figure A3.

Once the damage threshold for each of the eight uncoated optics was obtained, the damage-threshold data

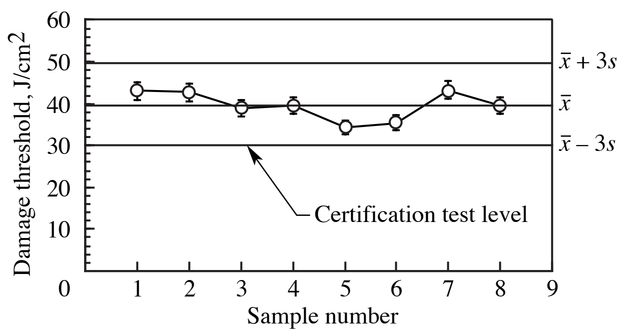

Figure A2. Laser-induced damage threshold for eight uncoated, fused-silica specimens.

Figure A3. Nomarski image of laser-induced damage to uncoated, fused silica specimen. Magnification = 75x.

were used in control charts to provide a useful means of displaying the variability among procured optics and for establishing certification test criteria for other similar optics. In this instance, the average damage threshold for the eight optics was 39.6 J/cm^2, and the standard deviation among the test specimens was 3.4 J/cm^2. Figure A2 shows the damage threshold data, the mean value, and the 6σ upper and lower control limits (i.e., $\bar{x} \pm 3s$) for this optical material. In this figure, $\bar{x}$ represents the sample mean value, and s is the sample standard deviation. The vertical error bars seen in figure A2 represent the measurement error attributable to the beam diagnostic tools employed in the performance of the damage-threshold test.

Once the upper and lower control limits for the optical component were established, the lower control limit was employed as the certification test exposure level. This value represents the minimum damaging fluence that a similar optic can possess and still meet the acceptance criteria. In this case, similar optics may be subjected to a pass-fail certification test at a test fluence of 30 J/cm^2, as described in section 3.6. If an optic from this family successfully passes an exposure at this level, the optic is accepted and may be inserted into the laser system with the assurance that its damage threshold is above the minimum acceptance level.

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