Plasma Optik Techne System — Qualification for High Fluence Optical Applications

Executive Summary

Thin film optics lifetime under exposure to high laser fluence levels benefit from having both high laser damage threshold and low optical absorption. Plasma Process Group has developed the Techne Ion Beam Sputtering deposition tool for manufacturing these challenging coatings. Plasma Optik has optimized Techne process parameters to both maximize laser damage threshold and minimize absorption. This paper explains 1-on-1, S-on-1 and LLNL-TR-740296 (used for National Ignition Facility applications) laser damage testing methodologies. Also discussed are details of photothermal common path interferometry (PCI) used for optical absorption testing. Techne system laser damage performance data generated with the LLNL-TR-740296 testing procedure on 1064nm and 532nm high reflector mirrors made with the Techne system is given along with PCI data from similar optics. Finally, comparison is made between laser damage values from Mil-Spec 10-5 and super-polished substrates with similar high-reflector coatings.

High fluence laser optics are a manufacturing challenge. Applications for high power laser optics range from a window on a laser welder, to an industrial laser component all the way to an optic to guide light for laser fusion experiments. These different applications have different requirements for laser wavelength, pulse duration and repetition rate. Despite the many differences, there are common wavelengths that can be considered standards for the purposes of talking about laser-initiated damage. One such common laser standard is the 1064nm laser.

1064nm lasers are based on the Neodymium -Yag (Nd: YAG) lasing medium. Nd: YAG material lases very efficiently at 1064nm when pumped with 808nm input power. Part of the popularity of Nd: YAG lasers arises from the ability of laser manufacturers to frequency double, triple or quadruple the 1064nm output. The Nd: YAG lasing medium therefore acts as the basis for lasers at 1064nm, 532nm, 355nm and 266nm. For many high-power applications, the 1064nm laser continues to be the wavelength of choice.

The mechanisms leading to laser damage vary depending on the properties of laser used for testing. The variables of laser light are wavelength, pulse duration and pulse repetition rate. Wavelength will often be either the fundamental frequency or one of the harmonics of 1064nm. Pulse

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duration can go from continuous wave (CW) all the way to limits of technology, currently in the attosecond pulse width regime. Laser repetition rate is how many pulses a non-CW laser will provide per second in Hz. Considered here is laser light at 1064nm, with a pulse duration of 3 nanoseconds and a rep rate of 5-10 hertz for LDT. 1064nm and 532nm CW laser light is used for absorption measurements.

In the nanosecond pulse regime, we can usually consider the mechanism leading to laser damage to be defect driven.[1] In this case, the laser beam meets a small particle or defect in the coating or on the substrate and the laser power vaporizes the particle. The force of the vaporization often damages the otherwise extremely durable ion beam sputtered (Plasma Optik only uses ion beam sputtering) dielectric structure. The need to standardize testing of optical surfaces has led to several standards being written on the measurement of optical resistance to laser damage. ISO 21254 is one standard describing a testing process used to determine laser damage threshold.

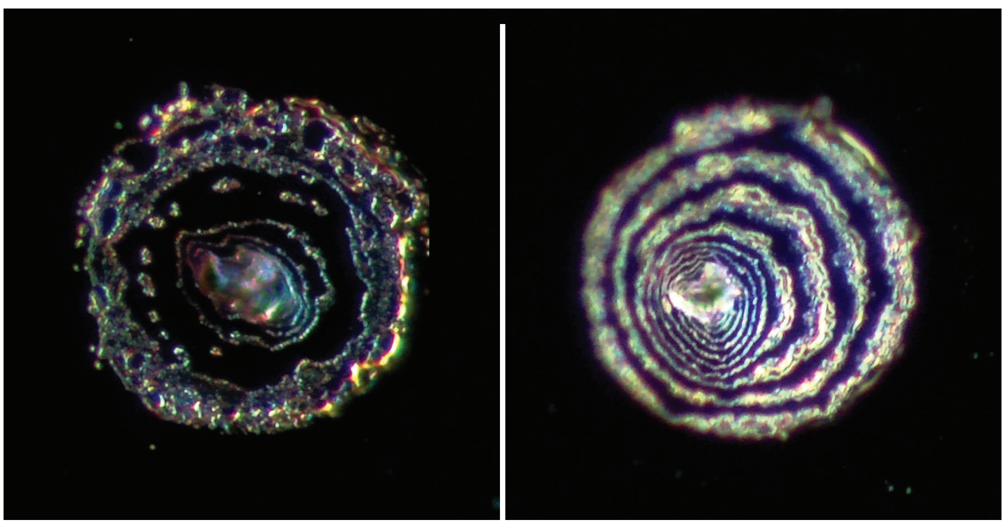

Figure 1. Differential Interference Contrast Images of Laser Damage on Plasma Optik Tested Optics. The left image appears to be a failure near the coated surface and the right appears to have revealed a defect at or near substrate level. Note that these failures occurred at very high fluence levels!

ISO 21254 – "Test methods for laser induced damage threshold"[2] contains general information on test methods for laser damage testing. Typical laser damage testing irradiates laser optics with increasingly intense laser shots until damage is visible under darkfield microscope examination. The most common testing methodology is called 1-on-1 testing. The typical number of laser shots for 1-on-1testing might be around ten. This is a

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cost-effective way to estimate the laser damage of batches of parts. Due to the statistical nature of the mostly defect driven laser damage failure mechanism in the nanosecond pulse width regime, however, this method of testing can give falsely high values for laser damage resistance.[3]

A more thorough investigation of laser damage failure uses the S-on-1 procedure. S-on-1 testing replaces the single shot used in 1-on-1 testing with a series of laser pulses. The "S" represents some number of laser shots at common fluence level, typically in the hundreds or thousands. The "Small Optics Laser Damage Testing Procedure" or LLNL-TR-740296 was released in 2005 by Lawrence Livermore National Labs (LLNL) and updated in 2017.[4] LLNL released this document to aid in the successful manufacturing of optics supporting the National Ignition Facility. Testing procedures developed for LLNL-TR-740296 are based on a S-on-1 process and dramatically improve the statistical variation in laser damage values arising from distributed defects as compared to 1-on-1 testing.

The LLNL-TR-740296 process removes much of the uncertainty involved in laser damage testing by illuminating many sites while rastering around the substrate clear aperture in a pattern with increasing laser fluence. At the same time as the laser illumination progresses, the substrate surface is continually inspected for evidence of damage. The increased number of laser shots reduce the chance that laser testing will miss small, distributed defects in the thin film structure. LLNL-TR-740296 clearly defines the beam specifications for the test laser and the specifics of the testing method. Due to the increased confidence level in results based on this type of laser damage testing, this method was chosen by Plasma Optik for validating Techne manufactured optics.

Scaling of laser damage results from one wavelength, pulse width or beam diameter to another is possible. For example, although a pulse width of 3ns is specified in the LLNL-TR-740296 document, another common pulse width for laser damage testing at 1064nm is 10ns. One way to accomplish the scaling from 3ns to 10ns is with the following formula[5]:

$$LIDT(\lambda 2, , \tau 2, \theta 2) = LIDT(\lambda 1, , \tau 1, \theta 1) * \left(\frac{\lambda 2}{\lambda 1}\right) * \sqrt[2]{\frac{\tau 2}{\tau 1}} * \left(\frac{\theta 2}{\theta 1}\right) \wedge 2$$

Where: $\lambda = wavelength, , \tau = pulse\ duration\ and\ \theta\ is\ beam\ diameter$

Plasma Optik prepared and coated multiple fused silica substrates with a MIL-SPEC 10-5 surface quality. Note that although the surface quality is good on these optics, they are not the best available. These 10-5 parts were laser damage tested with a 1064nm laser with 3ns pulses and a 1.01mm beam diameter by Spica Technologies. Below are the results from laser

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damage testing performed at 3ns alongwith the 10ns values calculated with the formula above.

Sample	Tested Wave-length (nm)	AOI	Polar-ization	Pulse Duration Desired (ns)	Pulse Duration Tested (ns)	Beam Diameter Desired (mm)	Laser Damage Failure Level (joules/cm²)
1	1064	Normal	Linear	10	3	1.01	56.6
1	1064	Normal	Linear	3	3	1.01	31
2	1064	Normal	Linear	10	3	1.01	40.2
2	1064	Normal	Linear	3	3	1.01	22

Table 1. Plasma Optik HR Laser Damage results obtained with 10-5 substrates and tested according to NIF 5008633 Protocol at 1064nm and 0° AOI.

More recently, similar testing has been performed with super-polished 2" optics. For these super-polished substrates, the thin film coating design was also modified so that laser damage could be performed at 45° AOI. Other than these two differences, these parts were coated in an identical manner to those above. Testing included both S and P polarizations and results are shown below.

Sample	Tested Wave-length (nm)	Pulse Duration Desired (ns)	Pulse Duration Tested (ns)	Pol	AOI°	Beam Diameter Desired (mm)	Laser Damage Failure Level (joules/cm²)
1	1064	10	3	S	45	1.03	63.9*
1	1064	3	3	S	45	1.03	35*
2	1064	10	3	P	45	1.03	49.3
2	1064	3	3	P	45	1.03	27

Table 2. Plasma Optik HR Laser Damage obtained with super-polished substrates tested according to NIF 5008633 Protocol at 1064nm and 45° AOI.

Note that in the case of the first sample tested above, the coating did not fail. The maximum output from the laser was reached at 35 joules at 3ns without any visible defect growth. *Our testing indicates that super-polished substrates do improve laser damage threshold as compared to Mil-Spec 10-5 optics. These results highlight the ability of Plasma Optik ion beam sputtered coatings to resist extremely intense laser fluence.

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Another important parameter for optics used in high laser fluence applications is low optical absorption. Many variables affect absorption levels, including but not limited to, sub-stoichiometric oxides and OH absorption bands. A thermal transient occurs at absorption centers when exposed to high laser fluence. To precisely quantify optical absorption, sophisticated testing methods have been developed. The most precise method currently available to assess absorption in optical coatings is with photo-thermal common path interferometry (PCI).

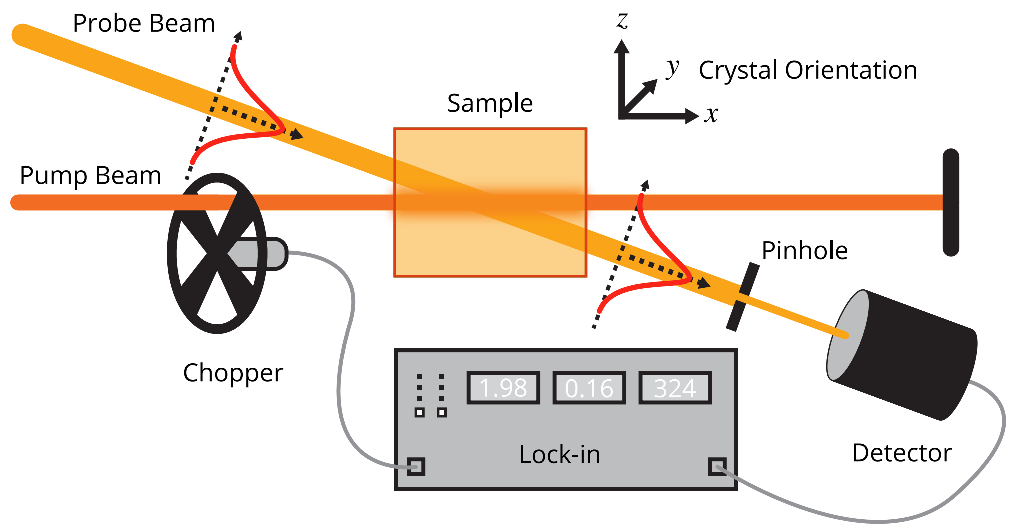

Figure 2. Photothermal Common Path Interferometer Diagram.[6]

PCI utilizes a high-power continuous beam laser, labeled pump beam above, to illuminate a sample. This high energy stimulates absorption centers in material being tested and causes a refractive index change. Changing the pump laser allows testing different wavelengths. Typically, pump lasers at 1064nm, 532nm or 355nm are used since the pump laser requires a large fluence for maximum absorptive resolution and these wavelengths tend to be available with quite robust specifications.

A 633nm laser is used for the probe beam laser since here beam quality is more important than power. The probe beam is crossed with the pump beam and aligned with a detector on the far side of the sample. The probe laser experiences a phase change proportional to the material absorption present from the interaction with the material heated by the pump laser. Increased phase change resolution is accomplished with the use of a lock-in amplifier. This phase change can thereby be measured with high accuracy and absorption derived from the data. The probe beam intensity variation is measured at the detector and absorption level is determined.[7]

Plasma Optik has had several parts evaluated at 532nm and 1064nm via

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PCI by Island Interferometry, working with Stanford Photothermal Solutions equipment. Note that in the data below, the absorption limit was reached with our sample at 532nm at 2ppm. There is some conversion inefficiency from the frequency doubling from 1064nm to 532nm. Reduced power is therefore available for testing at 532nm as compared to 1064nm. This 2ppm floor measurement at 532nm compares to a resolution of a fraction of a ppm from direct conversion of 808nm pump power to 1064nm laser power.

Design	Layers	Substrate	1064nm Absorption (ppm)	532nm Absorption (ppm)	Test Angle
532nm HR	32	Fused Silica		< 2	0°
1064nm HR	32	Fused Silica	0.9		0°
1064nm HR	32	Fused Silica	3.3		45°

Table 3. Sample absorption data taken by Photo-Thermal Common Path Interferometry

The values generated above are competitive with some of the best values available with other ion beam sputtering platforms. The Techne platform is fully capable of manufacturing very low absorption optics.

Plasma Optik has manufactured and tested laser optics per Lawrence Livermore National Laboratory standard process LLNL-TR-740296 written for qualification of NIF optics. Similar parts have been evaluated with Photothermal Common Path Interferometry. Results from this combination of testing indicates that Plasma Optik manufactured optics are fully competitive with thin film industry state of the art. Plasma Optik manufactured optics can withstand very high laser fluence when coated on the Techne coating platform and have also been shown to have very low absorption values. Although Plasma Opitk currently has limited coating capacity, we do have the ability to expand operations cost-effectively. Plasma Optik does currently possess capacity for small batch, R&D coatings and would like to speak with you if you have needs in this area.

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Plasma Optik manufactures bandpass filters, notch filters, edge filters, polarizing beam splitters, non-polarizing beam splitters, mirrors and anti-reflective coatings. Our optical monitoring capability combined with ion beam sputtering technology allows us to manufacture precision optical coatings from the ultra-violet to near infrared wavelength ranges. Plasma Optik is always happy to talk about high laser damage threshold optics with low absorption.

Contact Plasma Optik for further information and find out how we can help you to optimize performance for your application's thin film optics.