Method for studying laser-induced damage from sparse defects
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ABSTRACT
Laser damage testing is widely utilized by laser and laser system builders to ensure the reliability of their products. When damage is due primarily to sparse defects, the relatively limited data sets acquired under typical testing protocols tend to imply that laser damage probabilities go to zero below some reported damage threshold. However, this is rarely an accurate picture of the actual damage characteristics of the sample set. This study attempts to establish a correlation between observed coating defects and laser damage (from a 1064 nm laser in the nanosecond regime), utilizing a large sample size from a single coating run, together with the actual fluence levels present at the defect sites. This correlation is then used to predict damage for optics coated under different circumstances. Results indicate that it might be possible to develop an alternate methodology for determining damage characteristics, based on observed defects, which is both more reliable and less time-consuming than traditional laser damage testing.

Keywords: Laser damage threshold, LDT, HLDT, damage testing, surface quality, SAD, inspection

1. INTRODUCTION
Q-switched solid state lasers with pulsewidths in the nanosecond regime are commonly employed in industrial and military applications. The high fluences routinely achieved by these sources make laser-induced damage in optics a serious concern. In turn, laser and laser system builders attempt to minimize the potential for damage in their products by specifying a laser damage threshold for optics, and then performing damage testing to verify compliance with these specifications. Typically, this testing consists of irradiating a relatively small number of sites on a few sample components at several different fluence levels. The final test results may report the highest fluence at which no damage occurred. Based on this type of test protocol, it’s not uncommon for users to believe that if this tested “damage threshold” of their optics is, say, twice the peak fluence that is actually encountered in the normal operation of their product, then their system will never experience damage events. Unfortunately, this approach often drives up the cost of optics unnecessarily, and yet still doesn’t guarantee that damage will not occur under actual use conditions.

Part of the problem is a widespread misunderstanding of the actual meaning of laser damage testing results. Specifically, the testing reports the probability that damage will occur at a given fluence level, not an absolute “threshold” below which damage will essentially never occur. But, there’s also a problem with the testing itself. Traditional damage testing protocols sample too small an area of the optical surface to have a significant percentage chance of hitting the relatively sparse defects found on a typical high quality coating. Damage often occurs at these defects, whether due to electric field enhancement, local absorption from contamination, or mechanical weakness. In this connection, it’s important to note that the study reported here targets the kind of damage events most commonly experienced with pulsed, solid state lasers operating in the nanosecond regime (and sometimes, even CW solid state lasers). These damage events are usually associated with “macroscopic” defects (in the micron to tens of microns size range). In contrast, the damage events experienced with shorter pulsewidth (ultrafast) lasers or very small spot sizes are often caused by intrinsic characteristics of the coating or bulk material, including very small (nanometer) defects, or lattice defects, such as oxygen deficiencies.

This study attempts to address the limitations of traditional damage testing protocols by determining whether there is a correlation between the likelihood of laser damage and the presence of a given defect in a coated optic. If this connection can be established, then an automated surface quality inspection system could be used to more rapidly map a much larger area of an optical surface than can be assessed using traditional laser damage testing. The result of this non-destructive testing would be both reduced testing costs and higher confidence level results.

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2. EXPERIMENT DESIGN

The experiment was executed in two phases. In the first phase, a set of substrates was coated in a chamber that was past its usual preventive maintenance (PM) limits, in order to produce a comparatively large number of defects. The optics were then tested with a novel protocol. In this protocol, test sites on the optics were first imaged using an automated surface quality inspection microscope system that is integral to the damage testing setup. Then each test site was irradiated with a single fluence, before being imaged again by the microscope system. Defects in the “before” images were automatically identified with image processing software tools, and damage events in the “after” images were manually identified. The damage events were correlated with the observed defects based on their positions, and the local fluence at those defects was calculated using knowledge of the beam shape and position. In this manner the damage probability of a given defect as a function of local fluence was obtained. This probability then was used as an input to model the damage characteristics of the optics in a more standard protocol where the peak fluence is varied. A second set of optics, prepared in exactly the same way, was then tested with that standard protocol to assess the accuracy of the prediction.

In the second phase of the study, a third set of substrates were coated, but this time in a different chamber that was operated within its usual PM limits designed to produce high-quality laser optics. These optics were then subjected to the same surface quality inspection process and damage testing as the second set. The results of the inspection, together with the same model employed in the first phase of the study, were then used to predict the damage characteristics of these optics. The results were compared with that prediction.

2.1 Samples

Three sets of optics were used in this experiment. In all cases, these were one-inch diameter, fused silica substrates. They were coated in an ion beam sputtering (IBS) chamber with a quarter wave stack of HfO₂ and SiO₂ to achieve R>99.9% at 1064 nm. The substrates had surface quality equal to or better than 20-10 as judged by MIL-PRF-13830B, and were polished and cleaned with methods typically employed for high laser damage threshold components. Table 1 summarizes the salient facts about each set of optics.

Table 1. Summary of test optics characteristics.

<table>
<thead>
<tr>
<th>Set #</th>
<th>Part Count</th>
<th>Coating run</th>
<th>Chamber status</th>
<th>Defect Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9</td>
<td>S2-2709</td>
<td>Operated past usual PM limits to generate higher density of defects</td>
<td>35 defects/test site</td>
</tr>
<tr>
<td>2</td>
<td>14</td>
<td>S2-2709</td>
<td>Operated past usual PM limits to generate higher density of defects</td>
<td>35 defects/test site</td>
</tr>
<tr>
<td>3</td>
<td>30</td>
<td>I-4508</td>
<td>Operated within usual PM limits for minimal defect, high LDT applications</td>
<td>2.2 defects/test site</td>
</tr>
</tbody>
</table>

2.2 Testing instrumentation

REO’s automated instrument used for both defect identification and damage testing has been described in previous publications.3,4 “Before” and “after” images in this study were acquired with an 8-bit camera via a microscope with the sample under dark field illumination. The samples are irradiated with a Q-switched, Nd:YAG laser operating at 1064 nm, and a pulsewidth of 25 ns. The size of the elliptical, focused spot at the surface of the device under test is 1.1 mm x 0.9 mm (at the 1/e² points). This system incorporates an energy sensor, temporal profiling photodetector, and spatial profiling camera that measures the two dimensional energy distribution of the laser beam. A precise knowledge of beam profile then enables determination of the local fluence at a particular location (e.g. defect). A motorized XYZ stage shifts samples between the microscope inspection and laser irradiation parts of the instrument with ±5 μm repeatability.

2.3 Testing protocol

A hexagonal grid of test sites with center-to-center separation of 1.5 mm was defined on a sample, and images were acquired at these sites. Note that there was negligible beam overlap between test sites. Each site had a field size of 1.65 mm x 1.65 mm (2.72 mm² total). The exposure time of each image was set at 1 second as a compromise between
achieving sensitivity to small defects and avoiding camera blooming effects from large defects. The smallest defects visible with this exposure are about 1.5 μm.

Next, damage testing was performed with the incident laser beam centered at each of the sites. The fluence at the sample was set to 30 J/cm² with a motor-controlled variable attenuator, and each site irradiated with 20 pulses. This relatively low fluence was desirable both as a way to explore low-probability events, and also to avoid the occurrence of catastrophic damage that covers a large fraction of the test site, thus making it difficult to unambiguously identify the original coating defect source of the damage event.

Figure 1. The progression of data analysis starting with A) the “before” image of one test site, to B) the “after” image of the same site, to C) the schematic showing the locations of the defects and damage events as well as an overlay of a two dimensional Gaussian fit of the measured, average beam profile of the laser. The sizes of the circles represent the sizes of the defects and damage events. The local fluence at the defect that caused the largest of the three damage events was calculated to be 23.7 J/cm².

Peak fluence 30 J/cm²
Local fluence at this defect 23.7 J/cm²

Three distinct damage events
After laser irradiation, a sample was translated back to the microscope, and images acquired at the test sites. For these “after” images, the effective exposure time was reduced to 125 ms to avoid pixel saturation which washes out the internal structure that is characteristic of damage events. The “before” images were analyzed with a program that automatically identified sizes (defined in this study as the square root of the area of the defect) and locations of defects. Then, a human operator used software to identify damage events in the “after” images. For each damage event, the operator indicated what he considered to be the center and edge of the damage feature, and the computer then automatically determined the size (again the square root of the area) and location of the damaged area. A defect was considered to have caused the damage event if its center was within the diameter defined by the size of the damage event. The computer then used the location data, together with average beam profile data to calculate the local fluence at each causal defect. In the very rare cases where more than one defect was encompassed within a damage event, the causal defect was deemed to be the one at larger local fluence. This progression is summarized in Figure 1.

3. RESULTS

3.1 Data reduction of first phase results

The data from the defect identification and laser damage testing of Set #1 (nine components coated so as to produce a high density of defects) is summarized in the next two histograms. Figure 2 shows all the defects identified by the microscope system, binned by the local fluence to which they were subsequently exposed during damage testing. A total of 30,619 defects were located at 879 different test sites. The Gaussian falloff of laser beam intensity means that most of the surface area of a 1.65 mm x 1.65 mm test site is exposed only to a small local fluence; 75% of all defects fall in the 0-5 J/cm² local fluence bin.

Figure 2. Raw data of the total number of defects identified by the microscope system, binned by the local fluence to which they were exposed.

Figure 3 shows the same distribution over local fluence for only the 527 defects (of the 30,619 total) that caused damage events. There were an additional 28 damage events (making a total of 555) that did not appear to have a defect precursor. However, subsequent examination of the “before” images virtually always showed that some defect feature was there; however, these fell below the predefined threshold set in the image processing software used for automated defect identification.
Figure 3. A summary of all defects associated with damage events, binned by local fluence.

Dividing the values in Figure 3 by those in Figure 2 for each fluence bin yields the damage probability per defect as a function of local fluence. For example, for the 25-30 J/cm² bin, 184 causal defects/812 total defects = 0.22 probability of damage per defect. The results of performing this operation are plotted in the next chart. The uncertainty in each bin is calculated by dividing the square root of the number of causal defects by the number of total defects.

Figure 4. Damage probability per defect as a function of local fluence, derived from Set #1.

Note that Figure 4 gives the probability that a given defect will cause a damage event solely as a function of local fluence. If we expand this distribution to include the size of the causal defects as well, we end up with the two-dimensional probability plot shown in Figure 5. The 527 events with causal defects are separated into five bins along each axis, and the results within a bin are interpolated for display.
The probability of a given defect causing damage is seen to increase with both local fluence and size. While using the dependence of damage probability on size would in principle be useful for the analysis that follows, there aren’t enough events from the Set #1 testing to be able to do so. Instead we have integrated over defect size to maximize predictive power at any given local fluence.

### 3.2 Predicting damage in standard testing

One goal was to use the data obtained from testing Set #1 to predict the number of damage events that will occur in a typical threshold test where the fluence is varied. This prediction was to be applied to the other two sets of optics under test. This prediction assumes that all sets of test optics have similar defects in terms of size, shape, and possible contaminants – but not necessarily similar defect densities.

A test site irradiated with a test fluence $F$ will have defects binned by local fluences up to and including $F$. Defining the following:

- $p_i$ = probability that a defect in the $i$th local fluence bin will lead to damage,
- $f_i$ = fraction of the test site area in the $i$th local fluence bin,
- $\bar{\rho}$ = average number of defects per test site,
- $n(F)$ = the index of the test fluence bin,

then the predicted number of damage events per test site, $N_d$, at test fluence, $F$, is given by:

$$N_d(F) = \bar{\rho} \sum_{i=1}^{n(F)} p_i f_i .$$

A graph of the results of this calculation for coating run S2-2709 is shown in Figure 6. The stars represent predictions at each of the test fluence bins, and a smoothed curve (third-order polynomial, though this has no physical motivation) that fits these values has been included. The statistical range of the prediction comes directly from the uncertainties shown in Figure 4.
4. MEASURING PREDICTION ACCURACY

The next step in the experiment was to see how well this model predicted the damage characteristics of the Set #2 and Set #3.

4.1 Testing optics with similar characteristics

The optics from Set #2 were then tested using the same methodology as those in Set #1, with the exception that the test sites were subjected to a range of fluences from 5-30 J/cm² as opposed to just 30 J/cm². Set #2 in fact comprised just another 14 parts taken from the same coating run (S2-2709) as the Set #1 parts that were used to calculate the damage probability per defect. Figure 7 shows the actual damage results on Set #2 (circles with error bars) along with the prediction (solid curve). There is good agreement between the damage characteristics of Set #1, which was analyzed via
local fluence at individual defects, and Set #2 which only counted how many damage events were at each test site with no appeal to local fluence at all. Note that there is still a subtle difference between Figure 7 and a standard damage probability plot. Figure 7 plots number of damage events per test site, which can in fact be greater than one, even on average (recall that Figure 1 illustrated a specific test site with 3 damage events).

4.2 Testing optics with dissimilar characteristics

Set #3 was coated under different circumstances than the first two sets, leading to a substantially lower defect density. To get some idea of the comparison, Figure 8 shows two representative test sites: one from Set #1 (in fact the same site from Figure 1) and one from Set #3.

Figure 8. Images acquired with the defect identification microscope show the difference in defect density for optics in Set #1 (left) and Set #2 (right).

Set #3 (I-4508)
average 2.2 defects/test site

Figure 9. Actual damage test statistics from Set #3, shown with the prediction curve derived from Set #1.

Set #3 was tested in similar fashion to Set #2 – with a range of fluences from 5-30 J/cm². In Figure 9 the circles with error bars are the actual damage testing results for Set #3 and the solid curve is the prediction derived from Set #1. The
only thing that has changed between prediction for Set #2 and Set #3 is \( \bar{\rho} \), the average number of defects/test site; but it has changed quite significantly (note the \(~20x\) reduction in the y-axis scale on Figure 9 compared with Figure 7). Again, this is a plot of the number of damage events per test site, though in this very sparse defect limit it corresponds quite well to a damage probability.

The results of Set #3 agree qualitatively with the prediction. However, even with the 2,377 test sites on Set #3, the sparseness of the defects still leads to substantial statistical uncertainties in the measured number of damage events, so the ability to trace out the shape of the predicted curve is limited. Also, while the measured size distribution of the defects on Set #3 is similar to that of Set #1, we have not explored how those small differences will affect the prediction. Finally, there may be something fundamentally different in the nature of the defects between Set #1 and #3 because they were produced in two different coating chambers at different points in their normal preventive maintenance schedules. Possible differences of chemical composition and morphology could affect their damage characteristics, and have not been addressed at all here. Further study will be needed to identify and quantify these factors.

Figure 9 also demonstrates the motivation for studying this low-fluence regime of damage. A standard test on one of these optics using 10 sites per fluence over a range of, say 10-80 J/cm² would probably have indicated a damage threshold greater than 50 J/cm². In reality, this test shows a nonzero (albeit small) chance of damage down to 15 J/cm².

### 5. CONCLUSION

The ultimate goal of this work is to establish the basis for a method that will enable reliable prediction of laser damage of thin films based solely on automated, non-destructive surface inspection. It is hoped that this approach will be more accurate, faster and less costly than current laser damage testing protocols, which rely on a destructive methodology.

The results presented in this study justify the following conclusions:

- There is a strong association of damage events with pre-existing defects (>95% have visible precursors), and this leads to the ability to predict damage probability with defect information obtained from the “before” images of the darkfield, surface quality microscope system.
- Damage probability at a defect increases with both local fluence and defect size.
- Within a coating run, we can predict the results of a standard threshold laser damage test based on measurements at a single fluence and knowledge of defect density.
- We can extend this prediction to a significantly “cleaner” coating run with some success.

The reasonably good agreement between the prediction model derived in this study and actual laser damage test results is encouraging, and certainly merits further development.

### REFERENCES


