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Repair of a mirror coating on a large optic for high laser damage applications using ion milling and over-coating methods

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Abstract. When an optical coating is damaged, deposited incorrectly, or is otherwise unsuitable, the conventional method to restore the optic often entails repolishing the optic surface, which can incur a large cost and long lead time. We propose three alternative options to repolishing, including (i) burying the unsuitable coating under another optical coating, (ii) using ion milling to etch the unsuitable coating completely from the optic surface and then recoating the optic, and (iii) using ion milling to etch through a number of unsuitable layers, leaving the rest of the coating intact, and then recoating the layers that were etched. Repairs were made on test optics with dielectric mirror coatings according to the above three options. The mirror coatings to be repaired were quarter wave stacks of HfO₂ and SiO₂ layers for high reflection at 1054 nm at 45 deg incidence in P-polarization. One of the coating layers was purposely deposited incorrectly as Hf metal instead of HfO₂ to evaluate the ability of each repair method to restore the coating's high laser-induced damage threshold (LIDT) of 64.0 J/cm². The repaired coating with the highest resistance to laser-induced damage was achieved using repair method (ii) with an LIDT of 49.0 to 61.0 J/cm². © The Authors. Published by SPIE under a Creative Commons Attribution 3.0 Unported License. Distribution or reproduction of this work in whole or in part requires full attribution of the original publication, including its DOI. [DOI: [10.1117/1.OE.56.1.011002](https://doi.org/10.1117/1.OE.56.1.011002)]

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1 Introduction

Optical coatings that provide high laser-induced damage threshold (LIDT) are a vital aspect of the meter-class optics in the Z-Backlighter laser system at Sandia National Laboratories.¹ The Z-Backlighter laser system is a kJ-class laser capable of pulse widths in the ns range for terawatt pulses and in the ps range for petawatt pulses. At Sandia's large optics coating facility, optical coatings are deposited via e-beam evaporation using Sandia's large optics coating system.² Our coatings achieve high LIDTs through the implementation of strict contamination controls such as operating in a class 100 clean room, using only vacuum-approved lubricants, and thoroughly cleaning the optics, tooling, and other equipment. We also utilize coating materials with high LIDTs such as HfO₂ and SiO₂. We deposit SiO₂ from the evaporation of SiO₂ granules, and we deposit HfO₂ from the evaporation of Hf metal in an oxygen environment. Because Hf is absorbing, it is imperative to ensure that it becomes fully oxidized in the oxygen environment to form coating layers that are, to the best of our ability, purely HfO₂.

Our motivation to repair optical coatings was inspired by a mirror coating that was deposited incorrectly on a 65-cm diameter BK7 substrate. The coating error was caused by a lack of oxygen pressure in the coating chamber, which resulted in the deposition of a layer of Hf metal instead of HfO₂ at layer 35 of a 42-layer quarter wave design for high reflection at 1054 nm at 45 deg in P-polarization (P-pol). For reference, layer 1 is the innermost layer and touches the substrate; layer 42 is the outermost layer, facing the ambient environment. Such a metal layer severely compromises

the coating's LIDT because of conduction band electrons of the metal that couple strongly to the incident laser radiation.

When an optical coating is not suitable, the conventional practice to salvage the optic is to remove the coating by first repolishing the optic, then recoating the optic with the proper coating. However, repolishing an optic is often costly, and even worse, the expected lead time of several months would have been overly disruptive to laser operations. Because of this unique circumstance, we therefore tested three coating repair methods to salvage the optic with a faster turnaround compared to repolishing. The repair methods are listed below:

- i. Over-coating: bury the unsuitable mirror coating under another mirror coating
- ii. Ion milling: etch the unsuitable coating completely from the optic surface with ion milling, then recoat the optic
- iii. Ion milling: etch through a number of unsuitable layers with ion milling, leaving the rest of the coating intact, then recoat the layers that were etched

The subsequent section discusses why each repair method was considered as a suitable alternative to repolishing. Sections 3 and 4 describe how each repair method was performed and then evaluated with LIDT testing. In the final sections, we share our results and conclusions on which repair method best restores the LIDT of the mirror coating.

2 Alternatives to Repolishing Optics

The introduction listed three different optical coating repair methods that were tested in this study as alternatives to

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repolishing. We elected to test these repair methods for the reasons described later.

2.1 Over-Coating: Bury the Unsuitable Mirror Coating Under Another Mirror Coating

The electric field magnitude in a high reflection coating quenches rapidly within the outermost coating layers, as shown in Fig. 1, which is an electric field model generated by OptiLayer software of the 42-layer quarter wave design. The reasoning behind repair method (i) is that the deposition of a correct mirror coating on top of an incorrect mirror coating would even further diminish the amount of light penetrating into the incorrect coating. Therefore, the incorrect coating may be prevented from greatly impacting the LIDT. This repair method is therefore most suitable for mirror coatings rather than high transmission coatings. The primary advantage of over-coating is that it is straightforward and faster than the ion milling approaches that we also tested. A disadvantage of this method concerns the possibility of delamination and crazing as a result of stress mismatch between the incorrect coating and the correct over-coating.

2.2 Ion Milling: Etch the Unsuitable Coating Completely from the Optic Surface with Ion Milling, and then Recoat the Optic

Ion milling is a physical etching process that involves the ionization of a gas (or combination of gases) that is accelerated by an ion source.³ The ion source is typically directed at the surface to be etched, and the bombardment of the ions against the surface removes particles from the surface.³ It is

possible to remove an optical coating from a substrate using ion milling, but mention of this practice is virtually absent from the literature. More common applications of ion milling for optical coatings include ion-assisted deposition,⁴ substrate cleaning,^{4,5} optical fabrication,⁶ *in situ* coating layer thickness control,⁷ and distributed phase plate manufacture.⁸

Although ion milling is slower compared with reactive ion etching and various chemical etching processes, it is promising for the removal of optical coatings because of its relative simplicity: it does not rely on maintaining complex chemical conditions with hazardous materials, and the mechanical force on the substrate due to the ion bombardment is negligible compared with polishing.⁶ However, ion milling can also increase the surface roughness of the substrate, and create an altered substrate layer as a result of preferential sputtering and decomposition.⁴ While these factors can degrade the performance of an optic, we tested ion milling anyway, considering that surface defects on the substrate may be less damaging to high reflection coatings compared with transmissive coatings. Coating systems that include an ion source for ion-assisted deposition are already equipped to perform ion milling. Following ion milling, the bare optical substrate can then be recoated with the correct optical coating.

2.3 Ion Milling: Etch Through a Number of Unsuitable Layers with Ion Milling, Leaving the Rest of the Coating Intact, and then Recoat the Layers that Were Etched

This process is the same as repair method (ii) except that it involves ion milling to only etch through undesired layers,

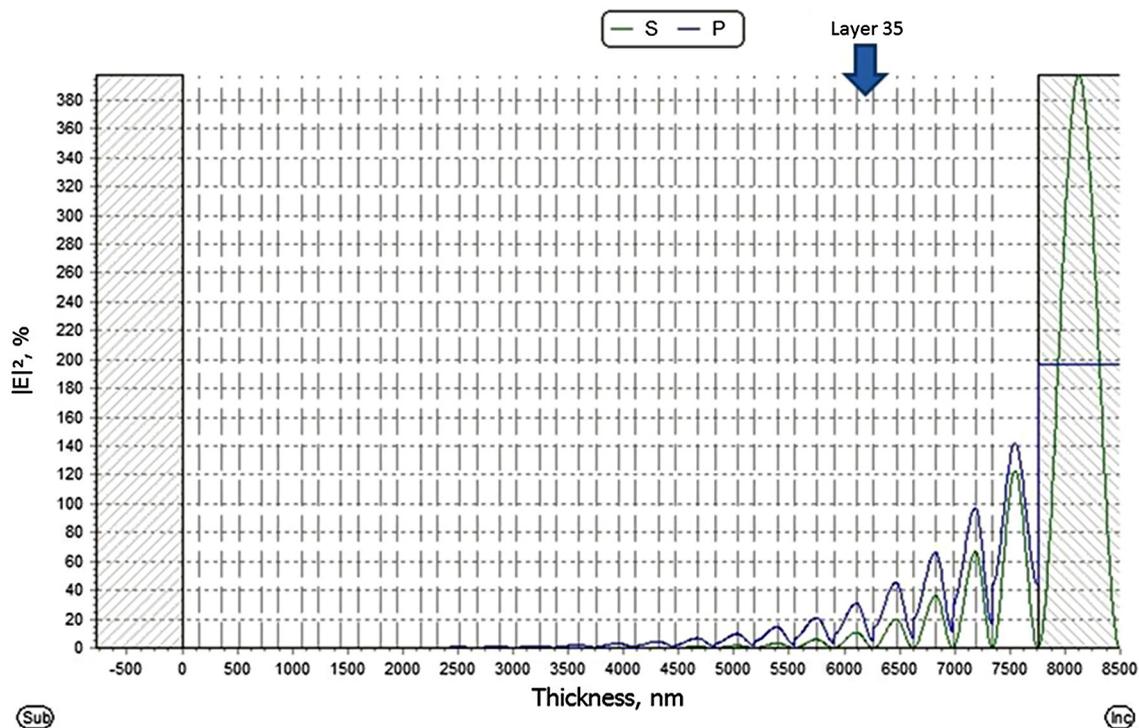


Fig. 1 Electric field magnitude model of the 42-layer $\text{HfO}_2/\text{SiO}_2$ quarter-wave type coating design, shown at 1054 nm, 45 deg in P-pol and S-pol. The vertical dashed lines denote layer boundaries. When this coating was deposited, a lack of oxygen resulted in the deposition of Hf metal instead of HfO_2 for layer 35. At the boundaries of layer 35, the electric field intensity, as a fraction of the incident intensity, is 30% at the start of the layer and 15% at the end of the layer.

then recoating those etched layers. This has the advantage of being faster than repair method (ii), which requires more time to accommodate the entire removal of the optical coating. In our case, we used this method to etch through all the layers leading up to and past the incorrect Hf metal layer (a total of 10 layers were etched). Then, we recoated those 10 layers.

3 Experimental Setup

In this section, the coating designs, substrate preparation, deposition processes, and etching processes are described. General information is provided first, followed by specific discussions of the processes that pertain to each optical coating repair method.

As noted in the Sec. 1, the coating that was deposited incorrectly was a 42-layer quarter wave type high reflector for 1054 nm at 45 deg in P-pol, on a large BK7 substrate (65-cm diameter, 8-cm thick). We conducted tests of each repair method with 50-mm diameter, 10-mm thick optically polished BK7 substrates. In addition, to save time and coating resources, the 42-layer incorrect coating was abbreviated to a 34-layer incorrect coating on the test substrates, which had an Hf metal layer intentionally placed at layer 27 to imitate the same error at layer 35 in the 42-layer coating. Layer 27 is an appropriate location to intentionally insert the Hf layer because the electric field magnitude at layer 27 in the 34-layer coating is nearly identical to the electric field magnitude at layer 35 in the 42-layer coating, based on an analysis of the coating designs with OptiLayer software. An additional feature of these coatings was the inclusion of a half-wave of SiO₂ as the outermost coating layer, which has been shown to improve the LIDT of high reflection coatings.⁹

The coating system, described in detail here,² measures 2.3 m × 2.3 m × 1.8 m, and can accommodate optics up to 120 cm × 80 cm. The coating system uses planetary rotation, masking to maintain coating uniformity, and quartz crystal monitoring with a single crystal for layer thickness control. Each of the test substrates was prepared according to our standard cleaning method¹⁰ immediately before they were loaded into the coating chamber. The coating chamber reached a base pressure of approximately 3e-6 Torr prior to deposition. The depositions took place at 200°C. SiO₂ was evaporated from SiO₂ granules, and HfO₂ was evaporated from Hf metal in an oxygen environment. The oxygen gas added to the chamber to react with the evaporated Hf metal raises the chamber pressure to 1.2e-4 Torr, as measured by a calibrated ion gauge (Granville-Phillips Stabil-Ion Gauge). For layers where the deposition of Hf metal was intentional, the oxygen backfill was shut off.

The following subsections describe how the test substrates were processed to evaluate the three different optical coating repair methods described earlier.

3.1 Over-Coating: Bury the Unsuitable Mirror Coating Under Another Mirror Coating

A test optic was prepared with the 34-layer mirror coating having the intentional Hf metal layer at layer 27. Following the deposition of this 34-layer coating, the test optic was removed from the coating chamber. While it would be prudent to allow the optic to remain in the coating chamber for the immediate deposition of the correct mirror

coating over the incorrect one, we opted to remove the test optic in order to mimic the conditions that our 65-cm diameter BK7 mirror had gone through. More specifically, when we learned that the coating on the 65-cm diameter optic was incorrect, we removed it from the coating chamber because we lacked experience in the repair of optical coatings and, therefore, needed to conduct tests to determine the best approach for repairs. After the 34-layer test optic was removed from the coating chamber, it was washed according to our protocol¹⁰ and returned to the coating chamber for the over-coating process. The over-coating was a 35-layer mirror coating that was equivalent to the 34-layer coating except (1) the coating did not contain any Hf metal layers, and (2) the first layer was a quarter wave of SiO₂ to maintain the quarter-wave stack characteristics of the coating, since the outermost layer of the incorrect 34-layer coating was a half-wave of SiO₂. What this over-coating method amounted to was essentially a 41-layer quarter-wave stack coating on top of an Hf metal layer. The 41-layer quarter wave stack begins with a SiO₂ quarter-wave (layer 28 of the incorrect 34-layer coating) and ends with a SiO₂ half-wave (layer 35 of the correct over-coating).

3.2 Ion Milling: Etch the Unsuitable Coating Completely from the Optic Surface with Ion Milling, and then Recoat the Optic

We performed ion milling using our 16-cm diameter RF ion source (manufactured by Veeco), which is normally used for ion-assisted deposition. As shown in Fig. 2, the ion beam is oriented diagonally to aim at the center of the rotating planet can when it is located on the opposite side of the chamber. We performed a preliminary ion milling test on a slab of float glass that was 94-cm diameter truncated to 44-cm wide in order to test different ion milling parameters and establish the settings to use for etching the large 65-cm diameter optic. The slab of float glass was prepared with the 34-layer test coating having the intentional Hf metal layer located at layer 27. We etched the float glass until layer 25 was removed. Several lessons were learned as a result of this initial ion milling test with float glass, which are summarized in the points later.

- Ion beam voltage and current: ion milling is a relatively slow process. We began the experiment using an ion beam voltage and current of 500 V and 500 mA, and increased these to 750 V and 750 mA to achieve



Fig. 2 The RF ion source.

a higher etch rate. The system can handle up to 1000 V and 1000 mA, but the performance of the system is more consistent at 750 V and 750 mA.

- Gas flows: oxygen 5 sccm, argon 35 sccm, argon neutralizer 7 sccm. Although ion milling is primarily achieved with the 35 sccm flow of argon, 5-sccm oxygen was later added to oxidize metallic buildup on the ion source grids.
- Etch rates: using the above parameters for gas flows and ion beam voltage and current, the etch rate of SiO_2 was, on average, close to 100 nm/h, and the etch rates of HfO_2 and Hf metal were both, on average close to 60 nm/h.
- Etch indicators: SiO_2 layers appear dark and HfO_2 /Hf layers appear white during the ion milling process. The lights in the coating lab had to be turned off in order to see these color differences between layers.
- Nonuniform etch rate: the etch rate was fastest at the center of the optic compared with the edges. This culminated in the appearance of a bull's eye pattern on the float glass, where several different layers were clearly visible simultaneously. This means that when ion milling completely removes the coating from the center of the optic and exposes the substrate, the substrate will continue to be exposed until the remaining outer layers are finally etched away. The substrate will therefore etch longer in the center compared to its edges, which could induce some substrate curvature.

The nonuniform etch rate of our ion milling process posed the most significant challenges, and we considered what effect this would have on the feasibility of repair method (iii) as we observed the removal of the Hf metal layer (layer 27) on the float glass. The float glass ion milling test was stopped after etching through layer 25, to help ensure that no remnants of Hf metal remained at the center of the optic. However, additional layers were exposed simultaneously in a bull's eye pattern due the etch rate being fastest at the center of the optic compared to the edges. Starting from the center of the float glass we observed layer 24, and in the bull's eye rings surrounding layer 24, we observed layer 25, 26, and 27. If we were to pursue repair method (iii) and recoat the layers that were removed, we would begin with recoating layer 25, but that means the final coating would only be correct over the center of the bull's eye area (~15-cm diameter) where layer 24 was exposed after ion milling. This partial correction of the coating would not adequately serve the function of the large optic that we were trying to repair. Therefore, repair method (iii) was no longer an option for large optics, but we tested it anyway at a later time because it may be suitable for small optics, which we describe in Sec. 3.3.

At this point, our investigation of repair method (i) was also complete and we learned that the LIDT of the repaired coating was too low to be appropriate for operation in the beam train.

By process of elimination, we could already appreciate that repair method (ii) was the best option for large optics, and this informed our decision to promptly utilize this method to repair the 65 cm diameter optic without further testing, especially because this optic was required urgently. A few unknowns that were not addressed were (1) what the

etch rate of the BK7 substrate was, (2) how much curvature would be etched into the substrate as a result of the nonuniform etch rate, and (3) how would the surface roughness of the substrate be affected by the long ion milling process.

In preparation to determine the etch rate of BK7, we measured the thickness of two uncoated BK7 test substrates in five locations each using a micrometer with 1- μm resolution. Then, one test substrate was placed at the center of a planet can in the coating chamber, and the other was placed 25 cm from the center of the planet can, allowing us to measure differences in etch uniformity at locations analogous to the center of a large optic and 25 cm from the center of the large optic (the 25-cm distance is based on an existing opening in the tooling plate that secures the test substrates in the chamber). These uncoated test substrates were then etched during the ion milling process that completely removed the 42-layer mirror coating from the 65-cm diameter BK7 optic.

We paused the etch process for the 65-cm diameter BK7 optic when layer 1 appeared (HfO_2). During the pause, we measured the diameter of each ring in the bull's eye pattern, which included layers 1 through 9. A model of the bull's eye pattern, based on the diameter measurements, is shown in Fig. 3, and a plot of the curvature of the etched layers is shown in Fig. 4. A radius of curvature of 32 km, also plotted in Fig. 4, was loosely fitted to the layer thickness data. However, because the substrate etches at a slower rate compared with the coating materials, it was practical to assume that the radius of curvature etched into the substrate would be even greater than 32 km. However, even if the substrate had a radius of curvature of 32 km, this would not have a significant effect on the performance of the mirror.

The entire ion milling process was spread over 10 days with few breaks. The substrate itself was etched for 52.5 h. In other words, after the substrate first appeared, it was exposed to the ion beam for 52.5 h while the coating layers between the center and edge of the substrate were finally etched away, due to the slower etch rate at the edges.

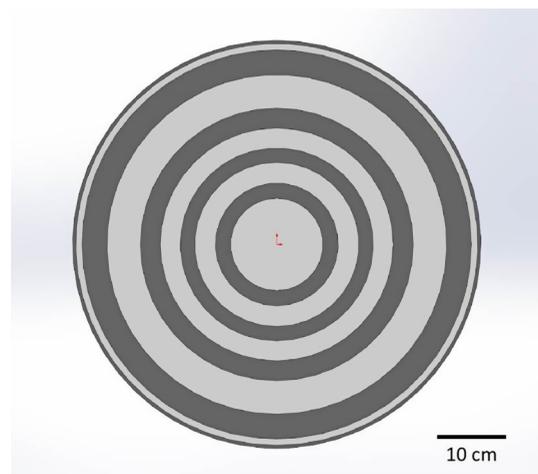


Fig. 3 Model of the etched coating layers in a bull's eye pattern on the 65-cm diameter substrate just after layer 1 (HfO_2) was exposed. Layer 1 is the central light circle, surrounded by layers 2 through 9. Light colored rings represent HfO_2 and dark colored rings represent SiO_2 . The outermost dark ring is the portion of the BK7 substrate that was masked by the tooling that holds the optic in the coating chamber.

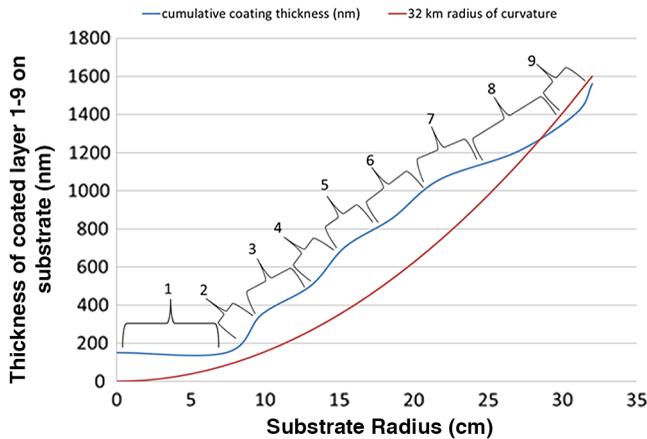


Fig. 4 The thicknesses of the layers present on the substrate with respect to substrate radius just after layer 1 was exposed during the ion milling process of the 65-cm diameter substrate. A radius of curvature of 32 km was loosely fitted to the data to give a conservative approximation of the curvature that would be etched into the substrate. The labeled brackets show the approximate span of each layer, starting with layer 1 and ending with layer 9.

After the ion milling process finally concluded, we visually inspected the surfaces of the 65-cm diameter substrate and test substrates. Every substrate was covered with small pits, and the 50-cm diameter test substrates were subsequently measured with a microscope to determine the pit sizes (microscope: Zeiss Axioskop 2 with Basler A631 fm camera). Also, the thicknesses of the 50-cm diameter test substrates were measured again to calculate the etch rate of BK7, but the amount of material removed was so small that no change in thickness was measured due to the limited resolution of the micrometer.

Following the surface inspection, the etched optics (two test substrates and the 65-cm diameter BK7 substrate) were cleaned using our standard protocol.¹⁰ The pitting did not hamper our ability to clean the substrates in any discernable way. Moreover, the surface tension of the substrates as we washed them indicated they were quite clean, which is a testament to the effectiveness of ion milling as an *in situ* cleaning process. The most characteristic evidence of this was how easily the deionized water sheeted off the substrates without beading up. In our experience, contamination on substrates causes water to bead up, and these beads can leave additional residue on the substrate. We did not experience this issue with any of the etched substrates.

After cleaning, the substrates were returned to the coating chamber. As before, one of the test substrates was located in the center of the planet can and the other was located 25 cm away from the center of the planet can. The correct 42-layer coating was then deposited.

3.3 Ion Milling: Etch through a Number of Unsuitable Layers with Ion Milling, Leaving the Rest of the Coating Intact, and then Recoat the Layers that were Etched

As explained above, repair method (iii) is not an appropriate method for large optics because the etch rate is uniform only within a central 15-cm diameter region. However, for small optics, repair method (iii) is applicable and faster than repair

method (ii). For this ion milling test, we prepared a single test substrate with the 34-layer test coating having the intentional Hf metal layer located at layer 27. Ion milling was then used to remove all layers through layer 25, in the same ion milling test that was used to etch layers from the float glass substrate reported above. Layers 25 through 34 (10 layers total) were then recoated at a later date. Test coatings of the recoated layers were conducted to obtain a spectral match between the recoated layers and the underlying layers. When an appropriate test coating was realized, it was then recoated onto the test substrate.

4 Laser Damage Testing Protocol

Following the conclusion of all repair methods conducted above, the LIDTs of the repaired coatings were measured at 1064 nm at 45 deg incidence in P-pol. The laser damage measurements were conducted by Spica Technologies, Inc.¹¹ using the NIF-MEL method.¹² In this protocol, the coated surface of the test optic first undergoes an alcohol drag-wipe cleaning step. Then, single transverse mode, multilongitudinal mode laser pulses of 3.5-ns duration and produced at a 5-Hz repetition rate in a 1-mm diameter collimated beam are incident one at a time per site in a raster scan composed of ~2500 sites over a 1-cm² area. In the raster scan, the laser spot overlaps itself from one site to the next at 90% of its peak intensity radius. The laser fluence typically starts at 1.0 J/cm² in the cross section of the laser beam. After testing the 2500 sites at 1 J/cm², the fluence is increased in a 3.0 J/cm² increment and the 2500 sites are tested again. This progression repeats until the damage threshold fluence is reached.

The NIF-MEL procedure is essentially an N-on-1 test at each of the 2500 sites. Laser damage is identified as some type of melt or crater that alters the coated surface, but in some cases the damage stabilizes as a damage site that does not propagate—i.e., grow in size—as the laser fluence increases. In other cases, the damage does propagate. According to the NIF-MEL damage criterion, the LIDT is reached at the fluence at which 1 or more propagating damage sites occurs, or the fluence at which the number of nonpropagating (NP) damage sites accumulates to at least 25, whichever fluence is the smaller. The 25 or more NP sites are 1% or more of the 2500 sites tested and constitute about 1% or more of the 1-cm² coating area tested. Our reasoning behind this LIDT criterion is the following. We know we cannot tolerate a propagating damage site in the laser beam train because it will quickly develop into catastrophic damage in the form of a large crater in the optic or worse; 25 or more NP damage sites per cm², while they are benign because they do not grow, are flaws in the coating that scatter about 1% or more of the laser light out of the beam, and that level of loss of laser intensity is unacceptable for us.

5 Results

The repaired coatings were evaluated according to their LIDTs and ability to meet spectral requirements. Figure 5 includes optical transmission data of the repaired and unrepaired coatings (transmission data was acquired with a Perkin Elmer Lambda 950 spectrophotometer). The LIDTs of the repaired and unrepaired coatings are presented in Fig. 6. As shown in Fig. 6, the LIDT is 1.0 J/cm² for the 34-layer incorrect coating with layer 27 intentionally

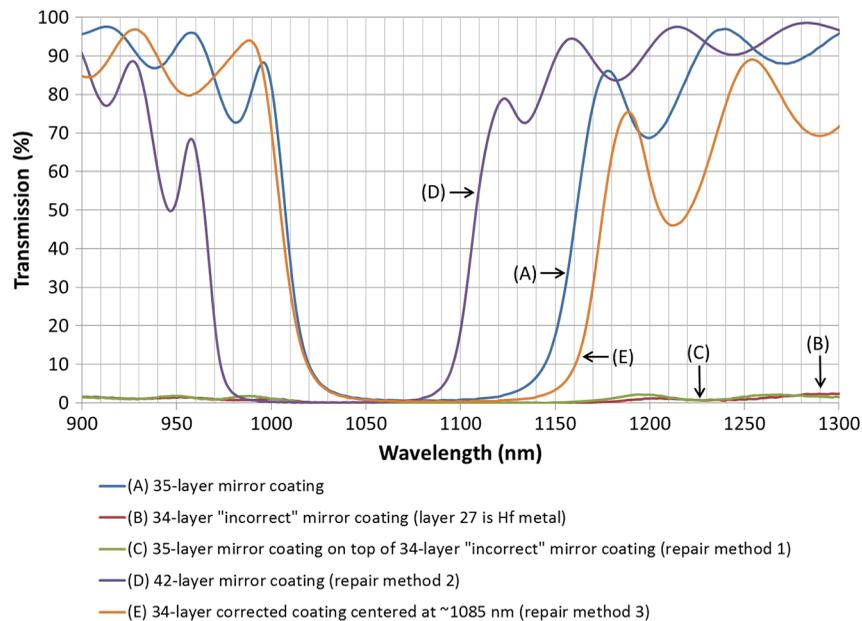
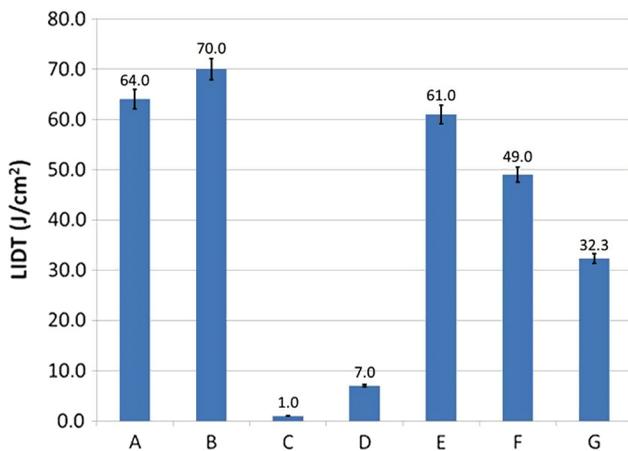


Fig. 5 Spectral scans of the repaired and unrepaired optical coatings, shown in P-pol for 45 deg AOI.



| | |
|---|---|
| A | 42-layer mirror coating |
| B | 35-layer mirror coating |
| C | 34-layer mirror coating (layer 27 is Hf metal) |
| D | 35-layer mirror coating on top of 34-layer mirror coating (repair method 1) |
| E | 42-layer mirror coating (repair method 2, located at center of planet can) |
| F | 42-layer mirror coating (repair method 2, located 25 cm from planet can center) |
| G | 34-layer mirror coating, centered at 1085nm (repair method 3) |

Fig. 6 LIDT measurements of the repaired and unrepaired optical coatings.

deposited as Hf metal. This LIDT, which is dramatically lower than the 64.0 J/cm² LIDT of the correct 42-layer coating, clearly confirms the high susceptibility to laser damage of the Hf metal layer. Our evaluation of each repair method is discussed below in accordance with how close the LIDT of the repaired coating improves to 64.0 J/cm². We also evaluate the optical transmission at the center wavelength of 1054 nm, and the 1064 nm wavelength that was used for LIDT testing. For operation in the laser beam train, the repaired coatings must have a transmission of less than 0.4% at 1054 nm.

5.1 Over-Coating: Bury the Unsuitable Mirror Coating under Another Mirror Coating

As shown in Fig. 6, the LIDT of the repair method (i) coating is just 7.0 J/cm². This repaired coating consists of the incorrect 34-layer coating and a correct 35-layer overcoat. The LIDT of just the 35-layer overcoat is 70.0 J/cm², which indicates that the low LIDT of the repaired coating may still be influenced by the Hf metal layer in the incorrect coating even though that layer is 42 layers deep in the coating. An electric field model of this coating could help us understand whether the deeply buried yet absorbing Hf metal layer may play a large role in reducing the LIDT of the coating. Unfortunately, there was not an adequate amount of refractive index or absorption data available for Hf metal to create an electric field model of this coating in our wavelengths of interest.

An alternative explanation of the poor LIDT of this coating is the possibility of high residual stress. Depositing 35 additional layers on top of an existing 34-layer coating more than doubles the thickness of the original coating and therefore increases its susceptibility to residual stress problems. Furthermore, the original coating was deposited at an earlier time compared with the additional 35 layers, which could lead to a stress mismatch between the original and recoated layers. Fortunately, we did not observe crazing, delamination, or any other obvious physical defects, but these problems could be more apparent on larger optics.

The optical transmission scans shown in Fig. 5 of both the repaired and unrepaired coatings are similar, owing to the broad reflectivity of the Hf metal layer in the incorrect coating. The coatings have low transmission, below 0.04% at both 1054 and 1064 nm. Even so, the low LIDT of the repaired coating indicates that enough light may still be reaching the incorrect Hf metal layer to induce damage. As a consequence of the low LIDT improvement from 1.0 J/cm² to 7.0 J/cm², repair method (i) is not adequate for our laser system.

5.2 Ion Milling: Etch the Unsuitable Coating Completely from the Optic Surface with Ion Milling, and then Recoat the Optic

The LIDTs of the repair method (ii) coatings are 61.0 J/cm^2 and 49.0 J/cm^2 , which are adequate for operation in our laser system. The difference between these coatings is that one substrate was located at the center of the planet can (achieving the LIDT of 61.0 J/cm^2), and the other was located 25 cm from the center of the planet can (achieving the LIDT of 49.0 J/cm^2), as explained in Sec. 3. Beyond this difference, the exact causes of the LIDT dissimilarity is not known, and could be due to a number of factors, including coating or etch nonuniformity on the coating plane, which warrant further investigation.

The repair method (ii) coating has a transmission of 0.10% at 1054 nm and 0.34% at 1064 nm, which is adequate for operation in the laser system, although these values could be improved with better centering of the high reflection band at 1054 nm at the time of LIDT testing. The repair method (ii) coating is actually centered at 1036 nm where transmission is 0.02%, but this was intentional because aging often allows our high reflective coatings of this type to shift 20 nm to higher wavelength. Also, because of the higher transmission at 1064 nm compared with 1054 nm, the LIDT at 1054 nm is likely greater than the 49.0 to 61.0 J/cm^2 values reported here.

While the repair method (ii) coating meets both the LIDT and spectral requirements for operation in the laser beam train, the presence of pits on the etched substrate is a concern. As mentioned in Sec. 3, small pits were scattered on all etched substrate surfaces, which included the two test substrates and the 65-cm diameter mirror substrate. The pits appeared to be scattered fairly evenly on these substrates, with slightly higher density in the center, and ranged in size from about 5 to $10 \mu\text{m}$, as captured by the microscope images in Fig. 7. A visual inspection revealed the density of pits to be $\sim 40 \text{ pits/cm}^2$ in the worst case at the center of the substrate.

Optical scattering is a problem associated with pits, but the effect has been negligible since the repaired mirror has been operating in the beam train since April 2014. In other words, the performance of the laser system did not change after the repaired mirror was introduced as a replacement for the original mirror. We suspect that high reflection coatings are more resilient in terms of their ability to perform well on an inferior substrate because only a small fraction of light actually transmits through to the substrate before being reflected back to the incident medium. Also, the relatively

large thickness of high reflection coatings may be better able to fill in defects on a substrate surface. On the other hand, the high density of substrate pits could be very harmful to the LIDT of transmissive coatings due to absorption at these defect sites, causing coating damage or removal. However, at a later time we used the same ion milling process to remove an 8-layer coating from a lens (1132-nm thick coating, versus 7758-nm thick for the 42-layer coating in this study) and observed that the density of pits was much lower: ~ 1 to $5/\text{cm}^2$. The presence of these imperfections on the lens is not ideal, but certainly more suitable for a transmissive coating compared with the mirror substrate analyzed in this study. Ultimately, our experiments demonstrate that etch time has a direct effect on the density of substrate pits. Future research could involve tuning the ion milling process to reduce pitting, perhaps by decreasing the ion energy once the substrate surface becomes visible, though this will increase the time to etch away the remainder of the coating.

5.3 Ion Milling: Etch Through a Number of Unsuitable Layers with Ion Milling, Leaving the Rest of the Coating Intact, and then Recoat the Layers that were Etched

The repair method (iii) coating has an LIDT of 32.3 J/cm^2 . This is a moderate improvement, but still not as satisfactory as the LIDT of the repair method (ii) coating. The LIDT of the repair method (iii) coating suffers because it was discovered that the 24-layer coating that remained on the substrate after the ion milling process was actually a high reflection coating centered at 1085 nm, rather than 1054 nm. We did not know this from the outset because the reflectance of the original incorrect coating was broad, due to the reflective Hf metal layer, as shown in Fig. 5. To maintain consistency among the coating layers, the 10 layers that were recoated to form the 34-layer repaired coating were also centered at 1085 nm. However, because LIDT testing took place at 1064 nm, the transmission of the repaired coating at this wavelength is 0.47%. For comparison, the repair method (ii) coating has a transmission of 0.34% at 1064 nm and achieved an LIDT that was nearly twice as high as the LIDT of the repair method (iii) coating. Moreover, the transmission of the repair method (iii) coating at 1054 nm is 0.71%, which is not adequate for operation in the laser beam train. Consequently, the spectral shift that is an effect of aging of the repair method (iii) coating will further increase the transmission at 1054 nm. It would therefore be interesting to repeat this experiment, starting with a

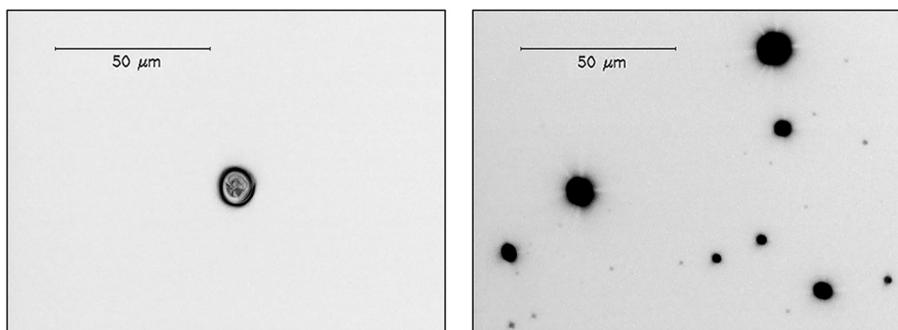


Fig. 7 Microscope images of the 5 to $10 \mu\text{m}$ pits that were scattered on the repair method (ii) substrates.

Table 1 Advantages and disadvantages of optical coating repair methods for mirrors.

| Method | Advantages | Disadvantages |
|---|---|---|
| (i) Over-coating: bury the unsuitable mirror coating under another mirror coating | <ul style="list-style-type: none"> • Shortest lead time | <ul style="list-style-type: none"> • Poor LIDT—negative impact of underlying metal layer still evident, and stress issues may be a factor • Delamination and crazing may be a concern with large optics |
| (ii) Ion milling: etch the unsuitable coating completely from the optic surface with ion milling, and then recoat the optic | <ul style="list-style-type: none"> • Achieves the highest LIDT compared to methods i and iii • Useful for both small and large optics | <ul style="list-style-type: none"> • ~1.5 weeks required to remove 42-layer quarter wave type coating for 1054 nm, 45 deg P-pol • Minor removal of material from center of substrate due to poor etch uniformity • Pits on substrate surface, may be especially detrimental to LIDT of transmissive coatings |
| (iii) Ion milling: etch through a number of unsuitable layers with ion milling, leaving the rest of the coating intact, and then recoat the layers that were etched | <ul style="list-style-type: none"> • Entire removal of coating not required | <ul style="list-style-type: none"> • Unsuitable for large optics (>15-cm diameter) because nonuniform etch simultaneously exposes multiple coating layers in bands • Difficulty with spectral mismatch between repaired and underlying layers; could compromise LIDT • Potential for issues with delamination, crazing, and residual stress |
| (iv) Repolishing | <ul style="list-style-type: none"> • Returns substrate surface to original condition | <ul style="list-style-type: none"> • Expensive • Potentially long lead time |

properly centered “incorrect” coating at 1054 nm, and determine whether the LIDT is still poor after the coating repair has taken place.

6 Discussion

The optical coating repair method that outshines the others in terms of maintaining spectral requirements and high LIDT is repair method (ii), i.e., the use of ion milling to completely remove the unsuitable coating from the optic and then recoat it. Repair method (iii), the removal of select layers with ion milling and recoating them, may be suitable for smaller optics, with the added challenge of obtaining a good spectral match between the original coating and the recoated layers. Regrettably, repair method (i), burying an incorrect mirror coating under a correct mirror coating, is not a viable repair method because very little improvement in LIDT was realized after the coating was repaired.

A summary of the various advantages and disadvantages of each optical coating repair method are highlighted in Table 1. Repolishing is also included in Table 1 because this is an effective, low-risk repair method that we still advocate in place of ion milling if time and budgets are permitting.

7 Conclusion

In this paper, we have presented the results of three different methods that may be used to repair or remove an unsuitable mirror coating. These methods can provide faster turnaround compared with repolishing an optic. The repair method that far surpassed the others in terms of upholding the spectral requirements and LIDT of the optical coating involved the use of ion milling to completely remove the unsuitable coating and then recoating the optic with the desired coating. The

disadvantages of ion milling include nonuniform etch rate (depending on your system) and the formation of pits and, hence, increased surface roughness and scattering. Lower ion energies may reduce the incidence of pitting, but this will also decrease the etch rate. Exploring these tradeoffs could be the subject of a future study. Fortunately, the surface imperfections that we observed on the large BK7 mirror that we repaired with ion milling have not been significant enough to cause the optic to not meet its performance requirements, perhaps because the low transmission of the mirror at its 1054 nm, 45 deg P-pol operating point allows little light to reach these surface defects. Nonetheless, the influence of ion milling on substrate modifications such as pitting, roughness, and curvature warrants further investigation. It is for this reason that we still favor optical repolishing, which reliably restores the substrate surface to its original condition. However, when fast turnaround is required, ion milling is an appropriate alternative to repolishing for high reflection coatings such as the ones presented in this study, which are better suited to avoid the performance degradation associated with substrate defects compared to antireflection coatings.

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