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Strategies for improving the laser-induced damage thresholds of dichroic coatings developed for high transmission at 527 nm and high reflection at 1054 nm

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ABSTRACT

We report on progress for increasing the laser-induced damage threshold of dichroic beam combiner coatings for high transmission at 527 nm and high reflection at 1054 nm (22.5° angle of incidence, S-polarization). The initial coating consisted of HfO_2 and SiO_2 layers deposited with electron beam evaporation, and the laser-induced damage threshold was 7 J/cm^2 at 532 nm with 3.5 ns pulses. This study introduces different coating strategies that were utilized to increase the laser damage threshold of this coating to 12.5 J/cm^2.

Keywords: Optical Coatings, Hafnia, Silica, Laser Damage, Dichroic

1. INTRODUCTION

Dichroic coatings have been developed for Sandia's Z-Backlighter Laser Facility [1] for high transmission at 527 nm and high reflection at 1054 nm (22.5° angle of incidence, S-polarization). The Z-Backlighter lasers are kJ-class systems that require optical coatings with high resistance to laser damage. The purpose of the present study is to improve the laser-induced damage threshold (LIDT) of our dichroic coatings. In previous studies, the highest LIDT achieved was 10 J/cm^2 (measured at 532 nm, 22.5° AOI, S-pol, 3.5 ns, NIF-MEL laser damage testing protocol [2]). The quality of the HfO_2 layers in those coatings are a suspected cause of poor LIDT. Therefore, the present study focuses on strategies to eliminate defects during the coatings process and produce higher quality HfO_2 layers. We used the same coating design as in previous studies [2,3], and adjustments to the coating process led to an improved LIDT of 12.5 J/cm^2.

2. DICHROIC COATING CHALLENGES

This dichroic coating must meet challenging spectral performance requirements while also having high resistance to laser damage. These demands are in competition with each other because strategies that improve spectral performance may be a detriment to laser damage resistance. The design tradeoffs are described below in more detail.

The spectral requirements of the dichroic coating are challenging because the standard type of coating for reflection at 1054 nm (e.g. quarter wave stack) does not provide high transmission at 527 nm. Likewise, the standard type of coating for transmission at 527 nm (e.g. half-wave stack) does not provide high reflection at 1054 nm. This is because the index of refraction of HfO_2 is higher at 527 nm compared to 1054 nm. Therefore, a quarter-wave stack at 1054 nm does not equate to a half-wave stack at 527 nm. Optilayer software was used to find a compromise between half-wave and quarter-wave designs that achieve the desired spectral performance at 527 nm and 1054 nm, and optimize the electric field characteristics of the coating at 527 nm for better laser damage resistance [3].

The portion of the dichroic coating that is most vulnerable to laser damage is the high transmission feature at 527 nm. In general, this is because photon energy is higher at lower wavelengths. However, the difficulty associated with this dichroic coating is that it is composed of 22 layers, and at 527 nm, the laser fluence is transmitting through all 22 layers. More layers to transmit through increases the potential for laser interactions with absorbing defects/contamination that lead to damage. The design was therefore optimized to contain the fewest number of layers possible while still meeting spectral requirements.

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During deposition, a quartz crystal monitoring system (QC-12 from Sensors Technology) was used for layer thickness control. Quartz crystal monitoring is not as accurate as optical monitoring methods and therefore layer thickness errors during deposition adversely affect the repeatability of a coating. Repeatability only worsens as the number of layers in a coating increases, hence it was in our best interest to create a dichroic coating with the fewest number of layers possible while still maintaining the desired spectral performance.

Coatings deposited with electron beam evaporation are porous. Consequently, such coatings are subject to a spectral shift to longer wavelength caused by aging and water absorption. Moreover, our dichroic coating design has a narrow high transmission bandwidth that is barely accommodating of spectral shifts. We are compensating for this by maintaining a constant level of humidity in the operating environment of the dichroic optic.

3. DICHROIC COATING STRATEGY

Our optimized dichroic design originally had a LIDT of 7 J/cm^2 and was produced from the e-beam evaporation of HfO_2 and SiO_2 with ion-assisted deposition [3]. We suspected that the low LIDT was due to the higher magnitude of the electric field in the outermost 2 HfO_2 layers [2]. Therefore, we decided to replace those outer 2 HfO_2 layers with a higher bandgap material (Al_2O_3) to better withstand the electric field. The LIDT of this dichroic coating with 2 Al_2O_3 layers was 10 J/cm^2 [2]. This is an improvement, though not as significant as we hoped for, which means that the lower bandgap HfO_2 layers may still play a large role in the poor laser damage resistance of the coating. Accordingly, we took a step back to focus on optimizing the deposition of HfO_2 before introducing another material like Al_2O_3 again.

To improve quality and reduce defects in our HfO_2 films, we tested 3 strategies:

1. Deposit 100 nm SiO_2 foundation layer on substrate→ improve nucleation of first HfO_2 layer
2. Slower HfO_2 deposition rate (from 3 Å/s to 2 Å/s) → minimize spitting from the hafnium source
3. No ion-assisted deposition → minimize roughness and defects

All the above strategies were performed at the same time in one coating, rather than tested individually in different coatings. While we prefer to address one variable at a time, in separate coatings, we conducted our experiment this way due to time constraints.

4. EXPERIMENTAL SETUP

The substrate is optically polished fused silica, 50 mm diameter by 12.7 mm thick. The substrate was cleaned using our standard cleaning process that involves manually washing with Micro 90 detergent, Baikalox alumina slurry, and deionized water [4]. Just after cleaning, the substrate was loaded into the coating chamber.

The SiO_2 layers were deposited at a rate of 7 Å/s from 1-3 mm SiO_2 granules. The HfO_2 layers were deposited from hafnium metal at 2 Å/s with O_2 backfill (0.9×10^{-4} Torr total pressure in coating chamber). The deposition temperature was 200□ C. In addition, the coating system used masking to maintain uniformity, and quartz crystal monitoring for layer thickness control [5]. As stated in the previous section, just prior to depositing the dichroic coating recipe, a 100 nm SiO_2 foundation was deposited as a strategy to improve the nucleation of the first HfO_2 layer.

Spectral transmission measurements were taken of witness samples with a spectrophotometer (Perkin-Elmer Lambda 950).

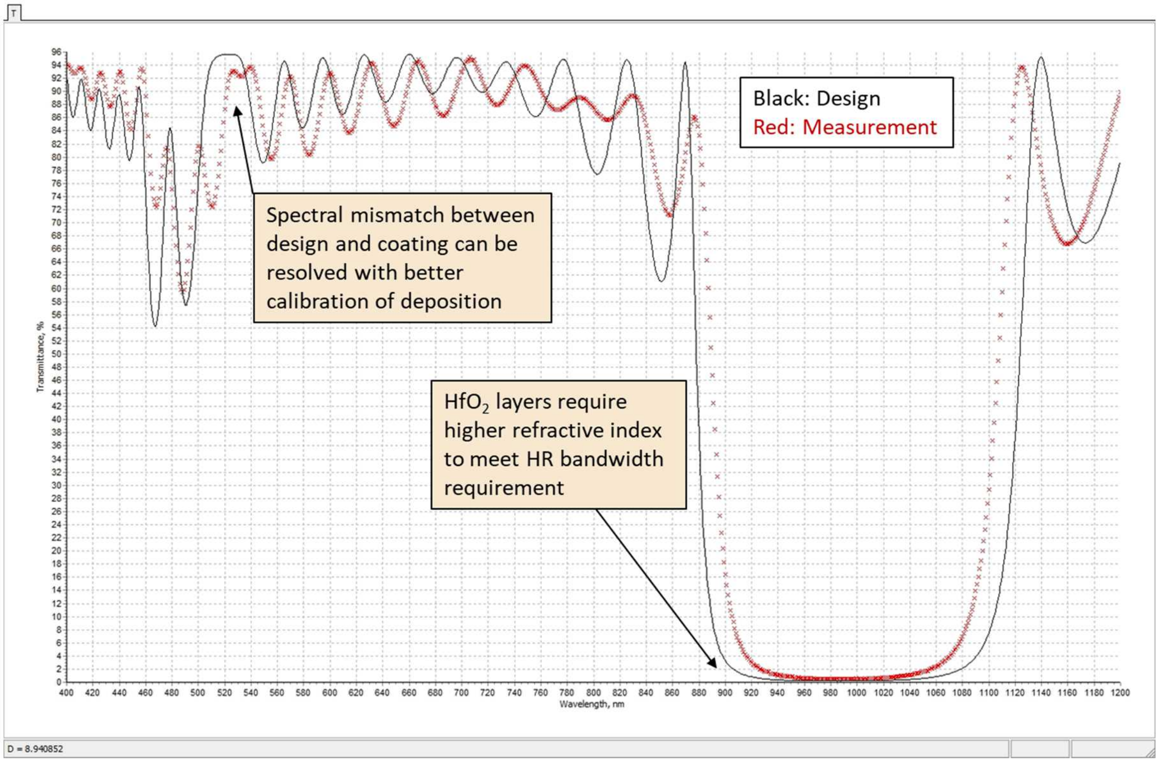
Laser damage measurements were conducted by Spica Technologies [6] at 532 nm and 1064 nm using the NIF-MEL protocol [7] at 3.5 ns, 22.5□ AOI, S-pol, and 0% humidity environment. In this protocol, the coated surface of the test optic first undergoes an alcohol drag-wipe cleaning step. Then, single transverse mode (Gaussian), multi-longitudinal 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 cm^2 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 starts at 1 J/cm^2 in the cross section of the laser beam. After testing the 2500 sites at 1 J/cm^2, the fluence is increased in a 1 J/cm^2 increment and the 2500 sites are tested again. This progression repeats until the damage threshold fluence is reached. The accuracy is +/- 3%.

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 – that is, grow in size – as the laser fluence increases. These non-propagating (NP) damage sites tend to be caused by the interaction of the laser field with nano-defects (pits, nodules, or contamination) in the coating. In other cases, the damage does propagate. Propagating damage tends to be intrinsic, governed by how the laser field interacts directly with the coating molecules.

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 NP damage sites accumulates to at least 25, whichever fluence is 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 cm^2 coating area tested. Our reason for choosing an LIDT test with these damage criteria 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; and 25 or more NP damage sites per cm^2, while they are benign because they may not grow, are flaws in the coating that scatter about 1% of the laser light out of the beam, and that level of loss of laser intensity is unacceptable for us.

5. RESULTS

The spectral transmission of the dichroic coating, as compared to the design, is shown in Fig. 1 below. Two observations can be made. One, the high reflection bandwidth of the coating is narrower than the design. This is because the index of refraction of the HfO_2 layers is too low, which means the O_2 backfill pressure during deposition was too high and requires adjustment. The second observation is that the high transmission portion of the coating at 527 nm is shifted to longer wavelength. Proper centering of the high transmission band can be achieved through better calibration of the layer thicknesses during deposition.



Spectral mismatch between design and coating can be resolved with better calibration of deposition

HfO_2 layers require higher refractive index to meet HR bandwidth requirement

Figure 1: Spectral transmission of the dichroic coating (red) as compared to the coating design developed in Optilayer (black). Adjustments to the hafnia index of refraction and layer thickness calibration will lead to a better match between the actual coating and the design.

The laser damage performance at 532 nm is shown in Fig. 2. The LIDT is 12.5 J/cm^2, which is higher than any LIDT we have seen in our previous dichroic coatings, even those containing alumina layers. While this is reassuring, the LIDT was established by the presence of 25 non-propagating defects, which means that defects dominate the LIDT. At this point, it is unknown whether these defects originate in the coating and/or on the substrate. Therefore, further investigation is required to determine the source of the defects and inform strategies to mitigate them. Ultimately, mitigation of the defects should lead to even higher LIDTs than 12.5 J/cm^2.

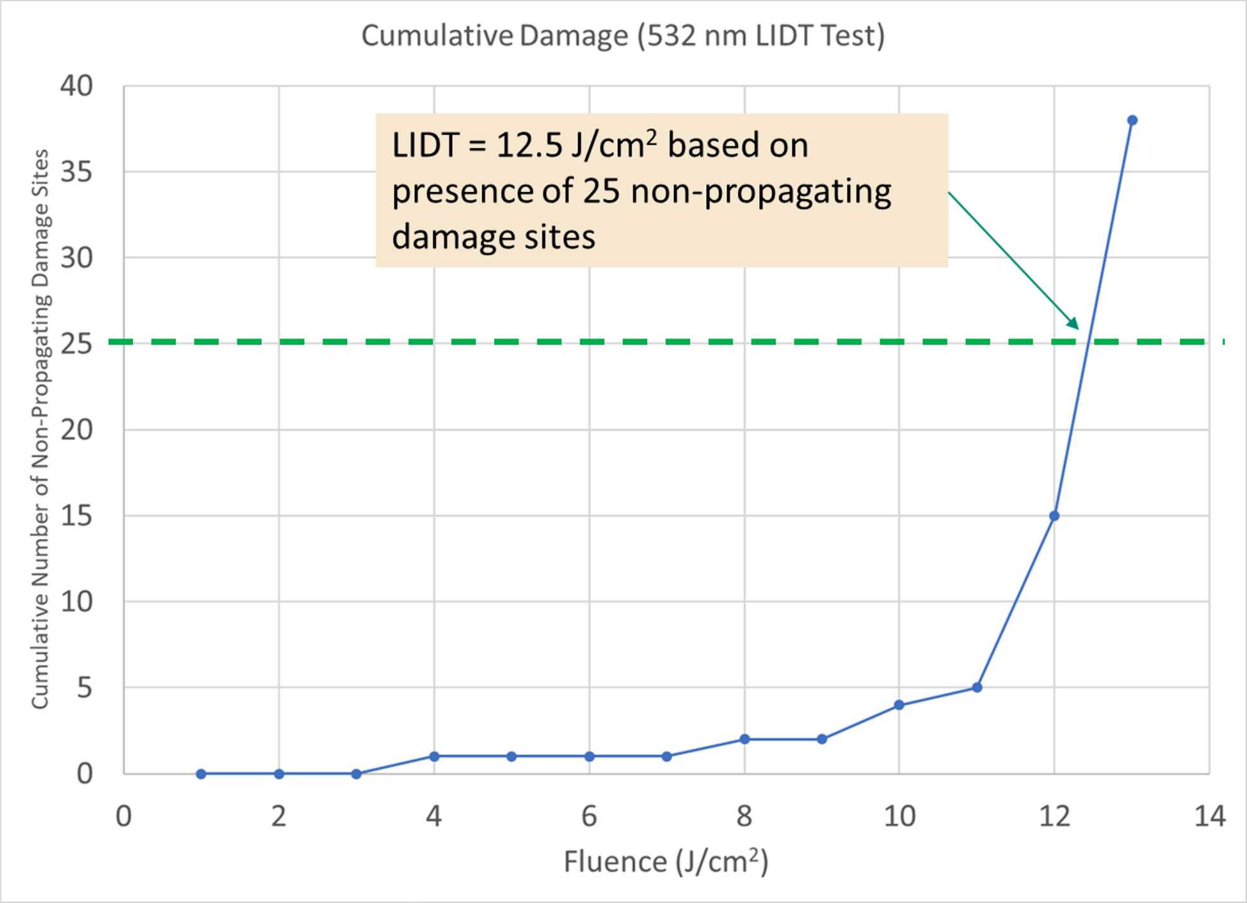


Figure 2: LIDT of 12.5 J/cm^2 at 532 nm was established by the presence of 25 non-propagating sites.

The laser damage performance at 1064 nm is shown in Fig. 3. The LIDT is 32 J/cm^2 based on propagating damage. At the fluence of 32 J/cm^2, there were also 10 non-propagating damage sites. However, the lower number of non-propagating sites at 1064 nm compared to 532 nm suggests that these defects are less absorbing at higher wavelengths (lower photon energy), and therefore play a lesser role in the damage susceptibility of the coating at 1064 nm. Also, the LIDTs of our high reflection coatings are generally twice as high as 32 J/cm^2 [8,9]. However, the electric field behavior in the dichroic coating was not optimized at 1064 nm as a compromise, in order to enable better laser damage resistance at 532 nm.

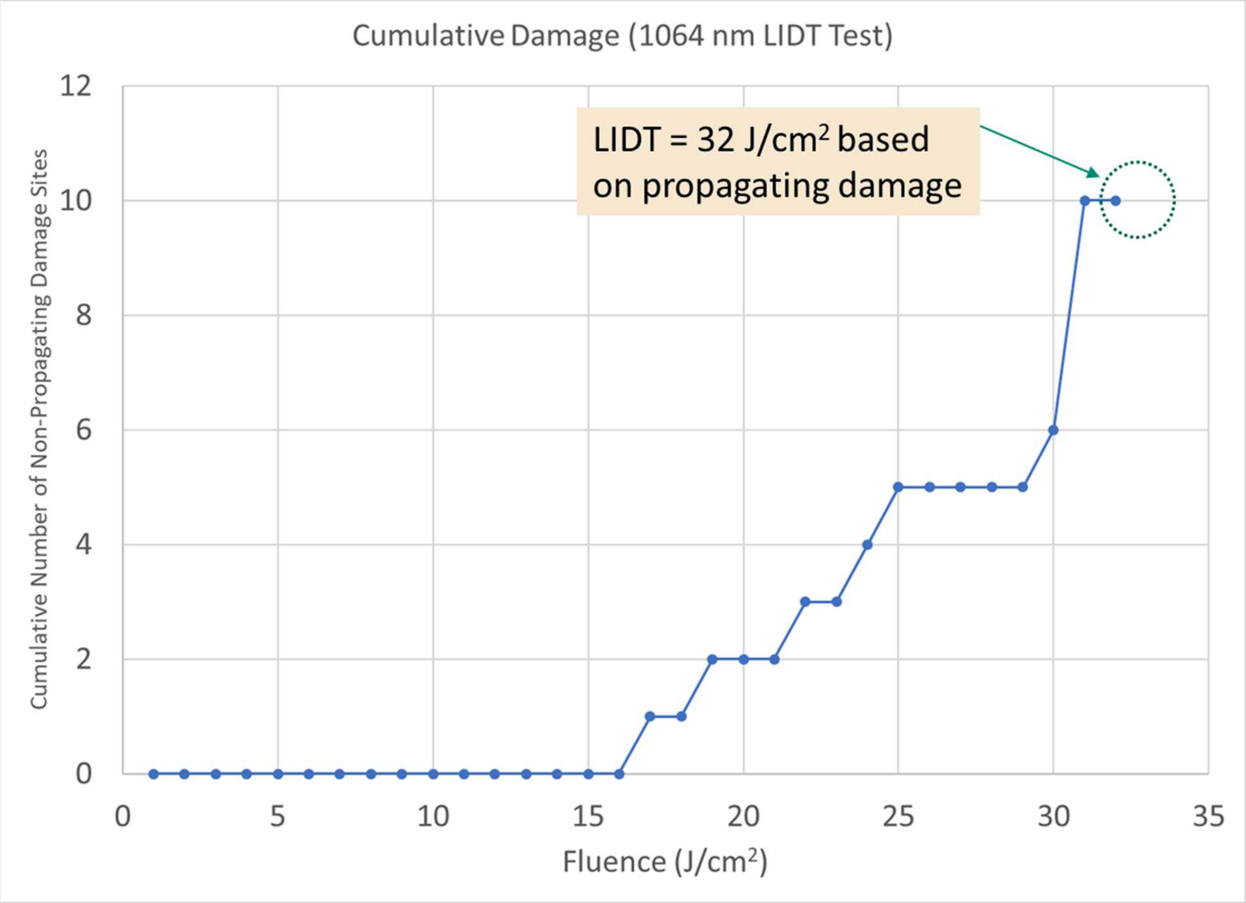


Figure 3: LIDT of 32 J/cm^2 at 1064 nm was established by propagating damage.

6. CONCLUSIONS

The HfO_2/SiO_2 dichroic coating presented in this study has achieved a higher LIDT at 532 nm compared to our previous coatings, even those that contained alumina layers. However, the LIDT was based on the accumulation of defects rather than the intrinsic damage limit of the materials. Therefore, we expect that an even higher LIDT approaching the intrinsic limit can be achieved if the sources of the defects are found and mitigated in future work.

The higher LIDT achieved in this study is a result of several adjustments to the coating process (100 nm SiO_2 foundation layer, slower HfO_2 deposition rate, and no ion-assisted deposition). More investigation is required to determine how each adjustment to the deposition process contributed to the improved LIDT results. Also, the refractive index of the HfO_2 layers must be increased to meet the high reflection bandwidth requirement. However, the lower refractive index of HfO_2 in the current dichroic coating may also be responsible for the improved laser damage performance seen in this study.

ACKNOWLEDGEMENT

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