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Use of Al_2O_3 layers for higher laser damage threshold at 22.5° incidence, S polarization of a 527 nm/1054 nm dichroic coating

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ABSTRACT

We have designed and reported on a dichroic beam combiner coating consisting of HfO_2/SiO_2 layer pairs to provide high transmission at 527 nm and high reflection at 1054 nm for 22.5° angle of incidence (AOI) in S polarization (Spol). The laser-induced damage threshold (LIDT) of this coating at the use AOI and polarization with nanosecond (ns) pulses at 532 nm is 7 J/cm^2, and only marginally adequate for our beam combining application. In this paper, we describe the use of a combination of Al_2O_3 and HfO_2 high index layers for the dichroic coating with the result that its LIDT at 22.5° AOI, Spol with ns pulses at 532 nm is higher, at 10 J/cm^2.

Key Words: Laser damage, dichroic optical coatings, laser beam combining coatings, coatings on large optics

1. INTRODUCTION: SANDIA'S DICHROIC COATING

In a recent report [1], we describe a dichroic coating that we designed and developed for Sandia's Z-Backlighter lasers, which produce kJ class, ns pulses of coherent light at 1054 nm and 527 nm [2]. The coating's high-index and low-index layers are HfO_2 and SiO_2, respectively, in an alternating sequence that starts at the substrate surface with a HfO_2 layer. The design requirements are for a 22.5° angle of incidence (AOI) in air with high reflection (HR) at 1054 nm in S and P polarization (Spol and Ppol) and high transmission (HT) at 527 nm in Spol. In addition, the coating needs to exhibit high laser-induced damage threshold (LIDT) to be able to withstand the high intensity Z-Backlighter laser pulses. In our dichroic coating design development, we used the OptiLayer Thin Film Software [3], exploring layers of near half-wave optical thickness in the design space for stable HT at 527 nm in an optimization process using the fewest number of layers to simultaneously maximize, for 22.5° AOI, HT at 527 nm, Spol and HR at 1054 nm, Spol and Ppol. As we reported [1], this led to a 22-layer design, which we will refer to here as Design #1, and the resulting coating afforded, at 22.5° AOI in Spol, HT of ~ 96.6 % at 527 nm and LIDT of 7 J/cm^2 at 532 nm. These results were promising, though we felt that the 7 J/cm^2 LIDT would be only marginally adequate for the 527 nm Z-Backlighter pulses. We have, in fact, deposited this Design #1 coating on a 61.5 cm diameter, 3.5 cm thick fused silica substrate in Sandia's large optics coater [4, 5], using ion-assisted e-beam evaporation of SiO_2 for the SiO_2 layers, and of Hf in a reactive process using an oxygen back pressure for the HfO_2 layers, and implemented it in the beam train. It functions well in the beam train but has suffered laser-induced damage at average fluences of ~ 2.5 J/cm^2 over the ~ 30 cm x 30 cm beam cross section. Though this is understandable, owing to the fact that the beam can exhibit hot spots in its transverse intensity distribution, it underscores the need for dichroic designs that afford higher LIDT. This paper reports on our initial efforts to develop such higher LIDT dichroic coatings.

2. MODIFYING THE DICHROIC COATING DESIGN TO ACHIEVE HIGHER LIDT

Our analysis of the E-field behavior for the Design #1 coating [1] indicated that its most vulnerable layers for laser-induced damage at 527 nm are the two outermost HfO_2 layers, because of their lower bandgap (5.1 eV) in comparison to SiO_2 (8.3 eV) and because they are the only two HfO_2 layers at which E-field intensity peaks occur. These two peaks are the ones encircled in Fig. 1, which shows the standing wave E-field intensity within the Design #1 coating for 527 nm and 22.5° AOI, Spol, as well as the sequence of HfO_2 and SiO_2 layers in terms of their locations and thicknesses. The outer two HfO_2 layers are layers 19 and 21 in the layer sequence, and we attributed the 7 J/cm^2 LIDT to their E-field intensity peaks [1]. This suggested that replacing the outer two HfO_2 layers with higher bandgap material such as Al_2O_3 (6.5 eV bandgap) might make the coating more resistant to laser damage.

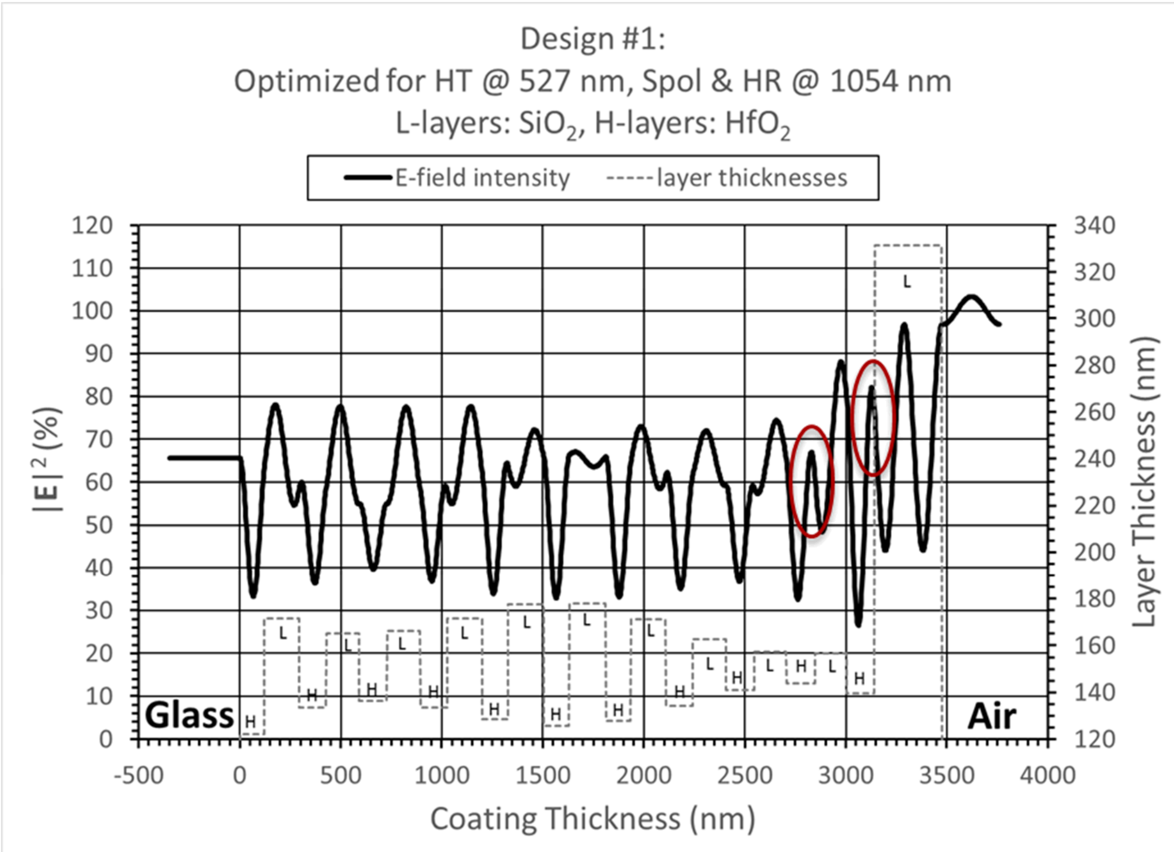

Figure 1: Layer locations and thicknesses, and E-field intensities within the layers from OptiLayer calculations, for dichroic coating Design #1. The E-field intensities are as a percent of incident intensity at 527 nm for incidence from air at 22.5° AOI, Spol. L and H label SiO_2 and HfO_2 layers, respectively, and the oblong circles highlight the E-field intensity peaks in the outer two HfO_2 layers.

We implemented this idea using Al_2O_3 layers in place of the outer two HfO_2 layers of Design #1. Since, in developing Design #1, we had optimized the layers to maximize HT for 527 nm at 22.5° AOI, Spol, and HR for 1054 nm at 22.5° AOI, Spol and Ppol, we decided we should re-optimize them to meet these same goals after modifying the design with Al_2O_3 replacing HfO_2 in layers 19 and 21. Figure 2 shows the transmission spectra at 25° AOI, Spol for Design #1, and for Design #1 modified with Al_2O_3 layers in place of the outer two HfO_2 layers and re-optimized to maximize HT for 527 nm at 22.5° AOI, Spol and HR for 1054nm at 22.5° AOI, Spol and Ppol. Re-optimization of this Al_2O_3-modified design does ensure, for 22.5° AOI, the same Spol HT of ~ 100 % at 527 nm while providing Spol HR of ~ 98.8 % at 1054 nm, as the expanded-scale insert spectra of Fig. 2 show particularly clearly.

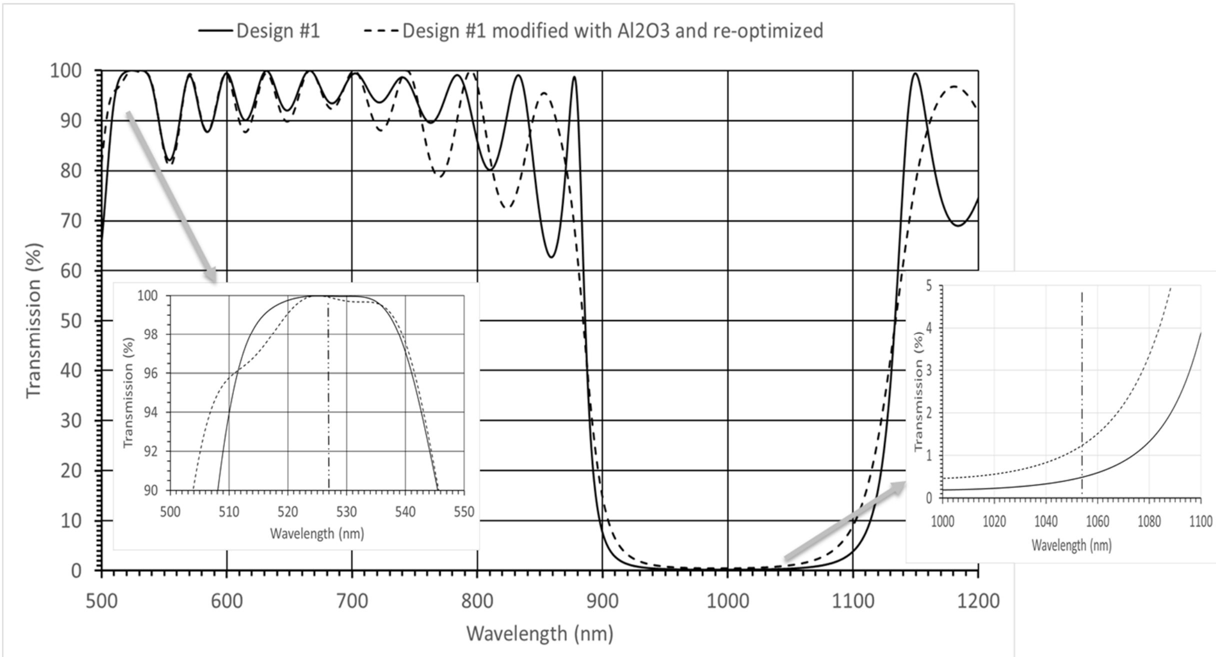

Figure 2: Transmission spectra at 22.5° AOI, Spol from OptiLayer calculations for the dichroic coatings of Design #1, and of Design #1 modified by replacement of the outer two HfO_2 layers with Al_2O_3 layers and then re-optimized to maximize HT for 527 nm at 22.5° AOI, Spol and HR for 1054 nm at 22.5° AOI, Spol and Ppol. The transmission is for the coatings alone, without taking into account Fresnel reflection losses at the uncoated side of an optic. The insets show the spectra with expanded wavelength and transmission scales near 527 nm and 1054 nm, which are marked by dash/double-dot vertical lines.

The dichroic coating that we deposited using this Al_2O_3-modified, re-optimized version of Design #1 did not prove to have a higher LIDT than that of the original Design #1 coating. This was confirmed by LIDT tests performed on both coatings by Spica Technologies, Inc. [6] using the NIF-MEL protocol [7] with 3.5 ns laser pulses of 532 nm wavelength and incidence on the coating from air at 22.5° AOI in Spol. We refer to our recent paper [1] for a detailed description of this LIDT test protocol and its raster scan procedure and delineation between non-propagating (NP) and propagating damage, and of intrinsic and extrinsic damage mechanisms. Figure 3 presents these LIDT test results in a plot of the cumulative number of NP damage sites versus the laser fluence, showing that both the Design #1 coating and its Al_2O_3-modified, re-optimized counterpart exhibit LIDTs that are not only the same, at 7 J/cm^2, but are both due to propagating damage, with little to no NP damage (no NP damage for the Design #1 coating and only 1 NP damage site evident at a fluence of 3 J/cm^2 for its Al_2O_3-modified, re-optimized counterpart). This LIDT behavior is consistent with damage mechanisms intrinsic to HfO_2.

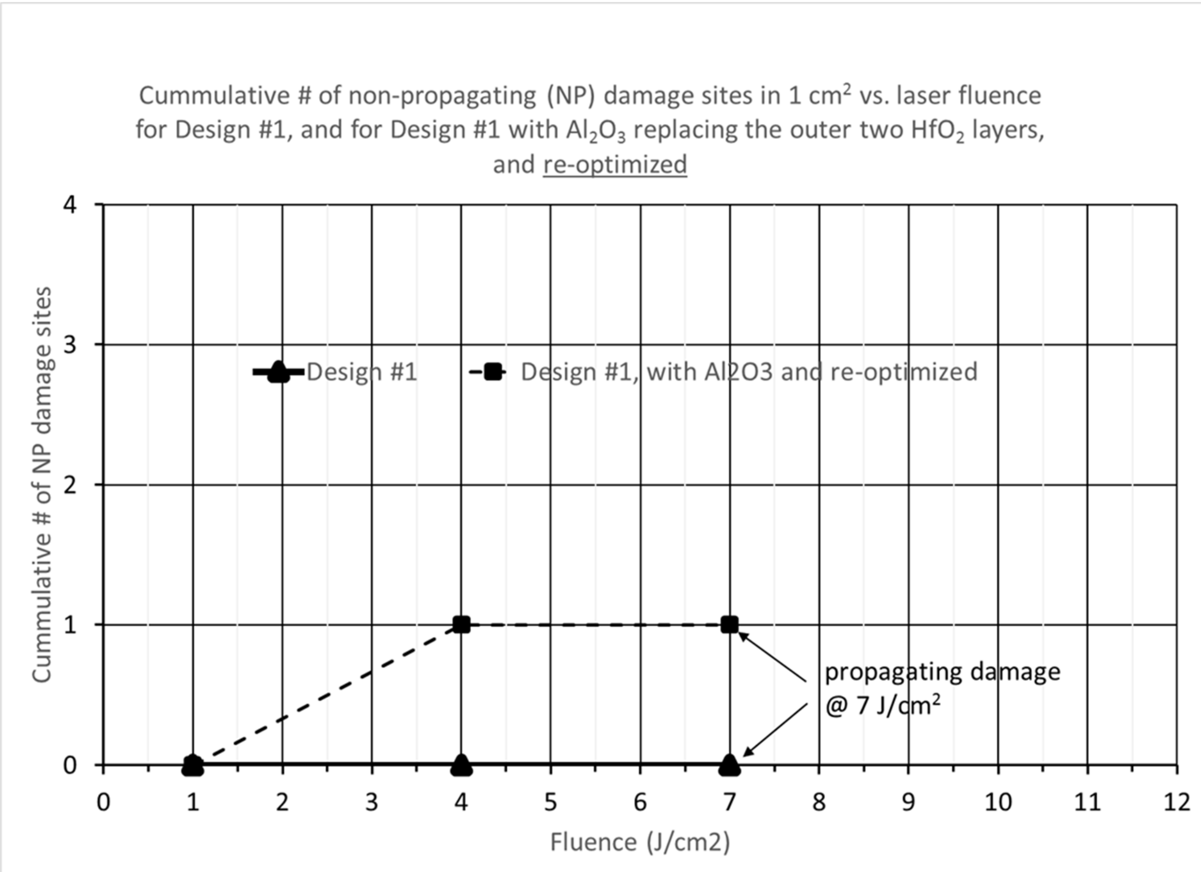

Figure 3: NIF-MEL laser damage data for 532 nm at 22.5° AOI from air, Spol, for the dichroic coatings of Design #1, and of Design #1 modified by replacement of the outer two HfO_2 layers with Al_2O_3 layers and then re-optimized to maximize HT for 527 nm at 22.5° AOI, Spol and HR for 1054 nm at 22.5° AOI, Spol and Ppol. See the text and our recent paper [1] for details of this NIF-MEL LIDT test protocol and its raster scan procedure and delineation between NP and propagating damage. Lines connecting the data points are guides for the eye. The $1/e^2$ transverse beam diameters for the tests were ~ 1 mm.

We were perplexed by this LIDT behavior until we considered the E-field intensity within the layers of the Al_2O_3-modified, re-optimized version of Design #1. This is shown by Fig. 4, which also displays the thicknesses and locations of the HfO_2, SiO_2, and Al_2O_3 layers. A comparison of Figs. 4 and 1 shows that the thicknesses of their respective layers, aside from layers 19 and 21, differ slightly from each other, which is consistent with re-optimizing after replacing the outer two HfO_2 layers with Al_2O_3. Also consistent with re-optimizing is that the two Al_2O_3 layers have optical thicknesses that are similar to but differ from those of their respective Design #1 HfO_2 counterparts. The Al_2O_3 layers are of lower index of refraction, and thus thicker than their Design #1 HfO_2 counterparts. What we find is that the E-field intensity peaks at the Al_2O_3 layers, which are encircled in Fig. 4, are, at levels of ~ 90 % and ~ 80 % of incident intensity, higher than their counterparts, at ~ 82 % and ~ 67 % levels, in the outer two HfO_2 layers of Design #1 (see Fig. 1). This means that the benefit to higher LIDT that the higher bandgap Al_2O_3 layers can have is at least partially counterbalanced by the higher E-field intensity peaks at those layers. Also, Fig. 4 shows that the other E-field intensity peaks, which are in SiO_2 layers, exceed their Design #1 counterparts (see Fig. 1) except for the outer SiO_2 layer, and the E-field intensity minima (which are mostly in HfO_2 layers) exceed their Design #1 counterparts (see Fig. 1) as well. These latter, overall higher E-field intensities further compromise achievement of higher LIDT for the Al_2O_3-modified, re-optimize version of the Design #1 coating in comparison to the Design #1 coating itself.

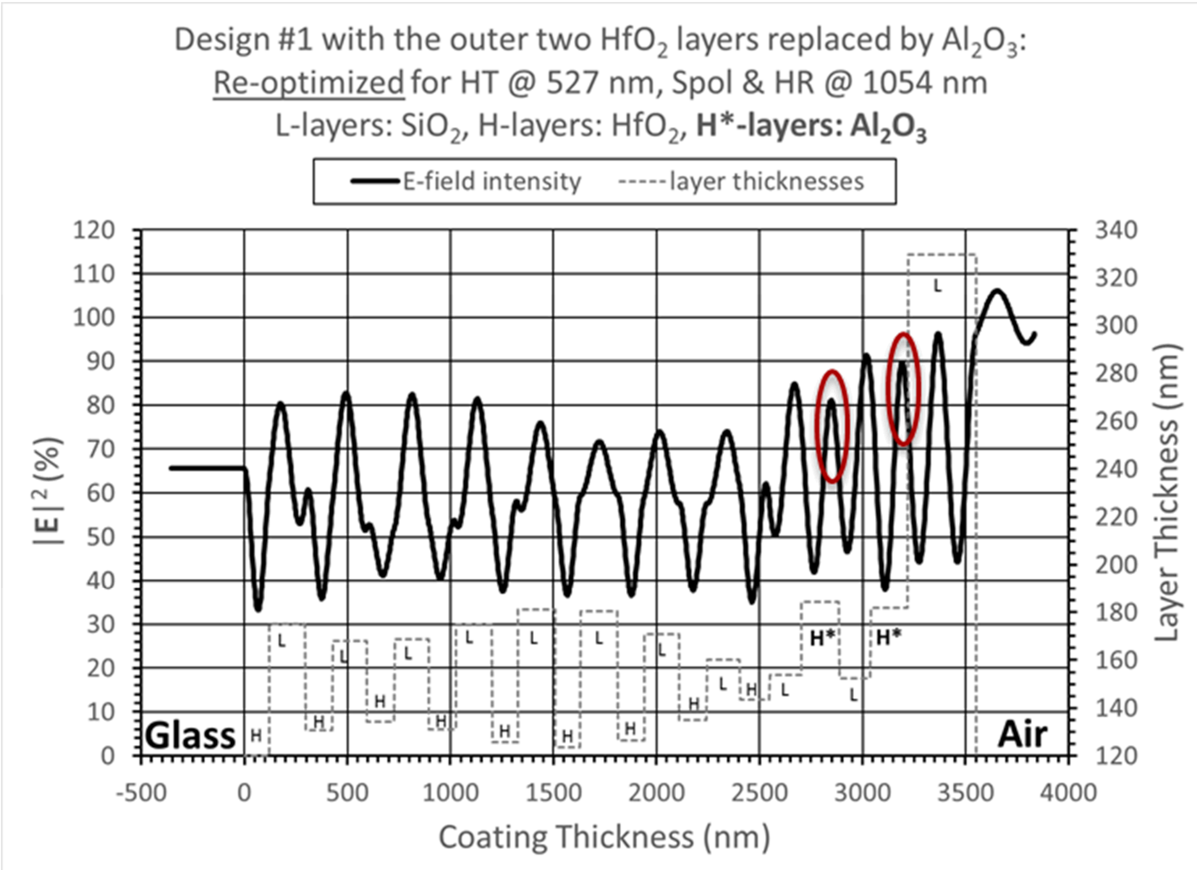

Figure 4: Layer locations and thicknesses, and E-field intensities within the layers from OptiLayer calculations, for dichroic coating Design #1 modified by replacement of the outer two HfO_2 layers with Al_2O_3 layers and then re-optimized to maximize HT for 527 nm at 22.5° AOI, Spol and HR for 1054 nm at 22.5° AOI, Spol and Ppol. The E-field intensities are as a percent of incident intensity at 527 nm for incidence from air at 22.5° AOI, Spol. L, H, and H* label SiO_2, HfO_2, and Al_2O_3 layers, respectively, and the oblong circles highlight the E-field intensity peaks in the Al_2O_3 layers.

We reasoned that, in the case of dichroic coating Design #1, the benefit of re-optimizing the Al_2O_3-modified design to maximize its HT and HR properties may be outweighed by the result that this led to higher E-field intensities in the Al_2O_3 as well as HfO_2 and SiO_2 layers, and provided no improvement in LIDT. We had also developed a second 22-layer HfO_2/SiO_2 dichroic coating design, which we will refer to here as Design #2, and chose it to test whether replacing its outer two HfO_2 layers with Al_2O_3 without re-optimizing to maximize its HT and HR properties would lead to higher LIDT while still affording acceptably good HT and HR dichroic properties. Design #2 is similar to Design #1, and they both have excellent, though slightly different, dichroic transmission properties, as Fig. 5 shows. For Design #2, the impact on 22.5° AOI, Spol HT at 527 nm and HR at 1054 nm due to not re-optimizing after substituting Al_2O_3 for HfO_2 in layers 19 and 21 is minor, with the former decreasing by ~ 1 % and the latter decreasing by ~ 0.6 %, as shown by Fig. 6. This was encouraging to us, as this dichroic performance is adequate for our dichroic beam combiner application. Even more encouraging was the LIDT performance of this Al_2O_3-modified version of the Design #2 coating without re-optimization. As Fig. 7 shows, the LIDT of this coating is 10 J/cm^2 and results from propagating damage, although with an accumulation of 14 NP damage sites at a fluence of 7 J/cm^2. These LIDT tests were also performed by Spica Technologies, Inc. [6] using the NIF-MEL protocol [7] with 3.5 ns laser pulses of 532 nm wavelength and incidence on the coating from air at 22.5° AOI in Spol.

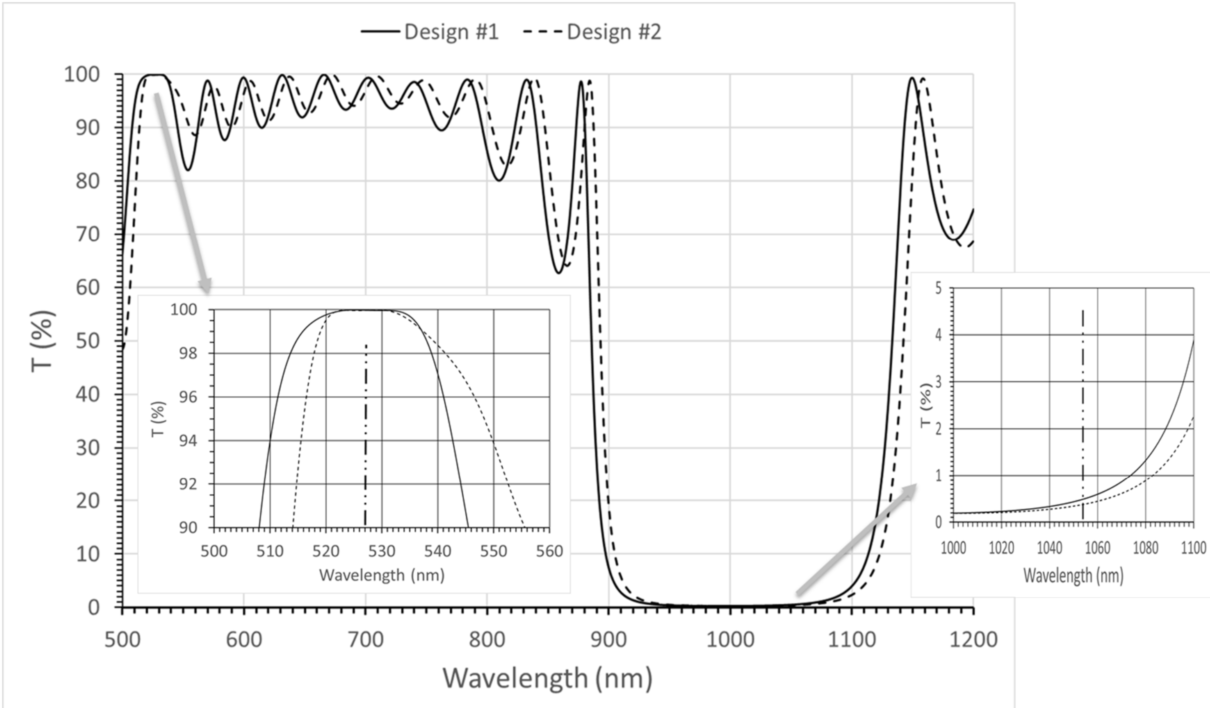

Figure 5: Transmission spectra at 22.5^o AOI, Spol from OptiLayer calculations for the dichroic coatings of Design #1 and Design #2. The transmission is for the coatings alone, without taking into account Fresnel reflection losses at the uncoated side ofan optic. The insets show the spectra with expanded wavelength and transmission scales near 527 nm and 1054 nm, which are marked by dash/double-dot vertical lines.

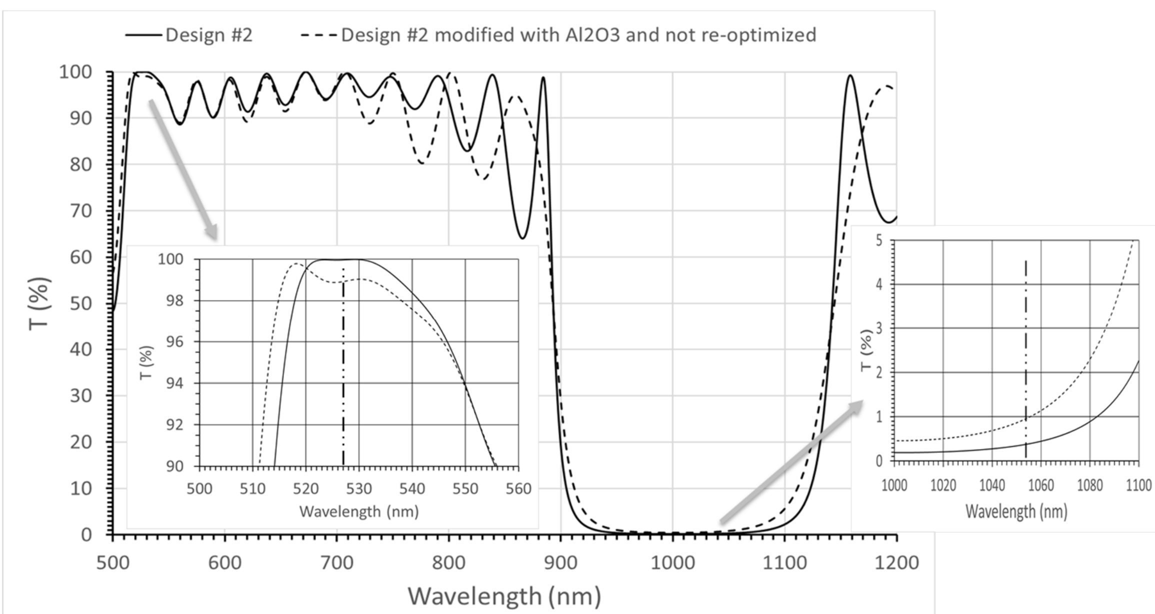

Figure 6: Transmission spectra at 22.5^o AOI, Spol from OptiLayer calculations for the dichroic coatings of Design #2, and of Design #2 modified by replacement of the outer two HfO_2 layers with Al_2O_3 layers and then not re-optimized to maximize HT for 527 nm at 22.5^o AOI, Spol and HR for 1054 nm at 22.5^o AOI, Spol and Ppol. The transmission is for the coatings alone, without taking into account Fresnel reflection losses at the uncoated side of an optic. The insets show the spectra with expanded wavelength and transmission scales near 527 nm and 1054 nm, which are marked by dash/double-dot vertical lines.

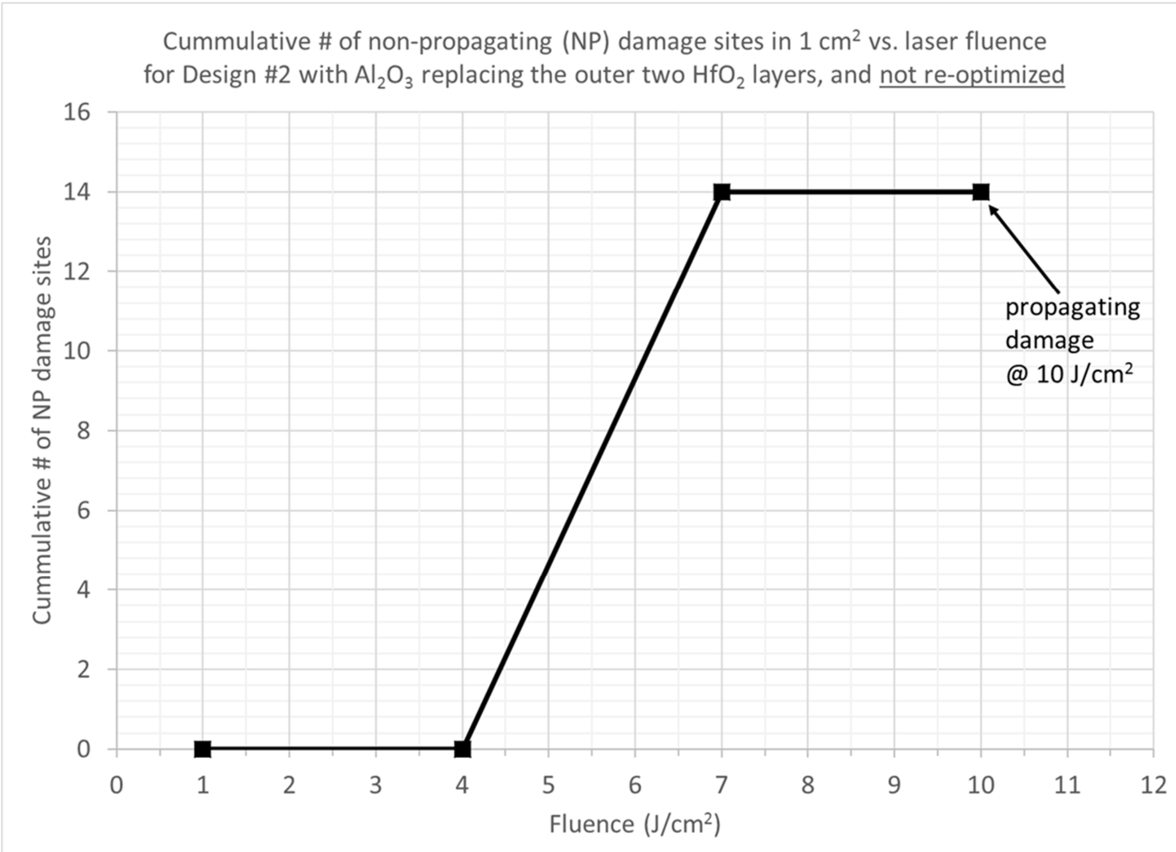

Figure 7: NIF-MEL laser damage data at 532 nm and 22.5° AOI from air, Spol, for the dichroic coating of Design #2 modified by replacement of the outer two HfO_2 layers with Al_2O_3 layers and then not re-optimized to maximize HT for 527 nm at 22.5° AOI, Spol and HR for 1054 nm at 22.5° AOI, Spol and Ppol. See the text and our recent paper [1] for details of this NIF-MEL LIDT test protocol and its raster scan procedure and delineation between NP and propagating damage. Lines connecting the data points are guides for the eye. The $1/e^2$ transverse beam diameter for the test was ~ 1 mm.

Insight into this higher, 10 J/cm^2 LIDT is provided by the E-field intensity behaviors within the coating layers for Design #2, and for its Al_2O_3-modified counterpart without re-optimization. These respective E-field intensities are shown by Figs. 8 (a) and (b), respectively. Fig. 8 also displays the thicknesses and locations of the HfO_2, SiO_2, and Al_2O_3 layers. The first 18 layers and the thicknesses of the last two SiO_2 layers in Figs. 8 (a) and (b) are identical, which is consistent with not re-optimizing after replacing Al_2O_3 for HfO_2 in layers 19 and 21. Also consistent with not re-optimizing is that the two Al_2O_3 layers are thicker, because of their lower refractive index, but have the same optical thicknesses as their respective Design #2 HfO_2 counterparts. We see that, for Design #2 with the outer two HfO_2 layers replaced by Al_2O_3 without re-optimization, all except the three outermost E-field intensity peaks are moderately low (at ~ 70 % levels; see Fig. 8 (b)) and are the same as for Design #2 (see Fig. 8 (a)). In addition, the three outermost E-field intensity peaks, at levels of ~ 78, 77 and 80 % (see Fig. 8 (b)), are much lower than their Design #2 counterparts at respective levels of ~ 88, 85 and 97 % (see Fig. 8 (a)); and the second to outermost peak is at a higher bandgap Al_2O_3 layer (see Fig. 8 (b)) rather than a lower bandgap HfO_2 layer as in Design #2 (see Fig. 8 (a)). Furthermore, the E-field intensity minima remain unchanged in the inner 9 HfO_2/SiO_2 layer pairs (compare Figs. 8 (a) and (b)) and are higher (but still moderately low, at a level of < ~ 50 %) only in the high bandgap, outer two Al_2O_3/SiO_2 layer pairs (see Fig. 8 (b)). All of these factors lead to the conclusion that, in this case, replacing the outer two HfO_2 layers by higher bandgap Al_2O_3 without re-optimization results in more moderate E-field intensities overall, and accounts for the higher LIDT of 10 J/cm^2. This is also consistent with the more prevalent NP damage (14 NP damage sites) that occurs at 7 J/cm^2 (see Fig. 7). Because of the lower E-field intensities (relative to the incident intensity) within the Al_2O_3-modified Design #2 coating without re-optimization (Fig. 8 (b)), intrinsic, propagating damage does not occur for this coating until the 10 J/cm^2 fluence, and this means that there is more opportunity for extrinsic, NP damage to occur throughout the entire coating at the lower, 7 J/cm^2 fluence.

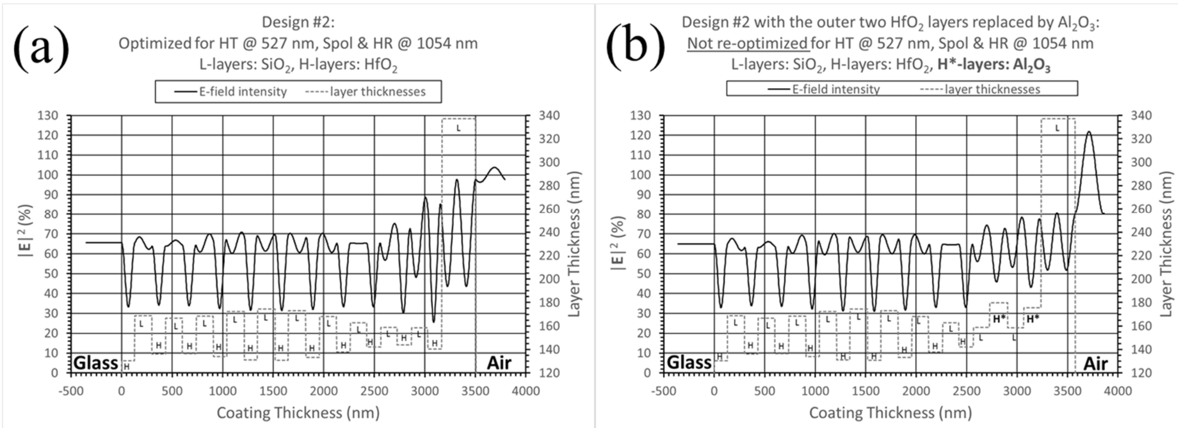

Figure 8: Layer locations and thicknesses, and E-field intensities within the layers from OptiLayer calculations, for (a) dichroic coating Design #2, and (b) dichroic coating Design #2 modified by replacement of the outer two HfO_2 layers with Al_2O_3 layers and then <u>not re-optimized</u> to maximize HT for 527 nm at 22.5° AOI, Spol and HR for 1054 nm at 22.5° AOI, Spol and Ppol. The E-field intensities are as a percent of incident intensity at 527 nm for incidence from air at 22.5° AOI, Spol. L, H, and H* label SiO_2, HfO_2, and Al_2O_3 layers, respectively.

3. CONCLUSION

We have designed and produced dichroic coatings for 22.5° AOI using HfO_2/SiO_2 layer pairs and optimized for HT at 527 nm, Spol and HR at 1054 nm, Ppol and Spol. The dichroic coating according to Design #1 functions well but suffers laser-induced damage in the Z-Backlighter beam train. We investigated achieving higher LIDT at 527 nm by replacing the outer two HfO_2 layers with higher bandgap Al_2O_3. For Design #1 with Al_2O_3 layers and <u>with</u> re-optimization to maximize HT for 527 nm at 22.5° AOI, Spol and HR for 1054 nm at 22.5° AOI, Spol and Ppol, E-field intensities in the coating were higher and the LIDT at 532 nm for 22.5° AOI, Spol remained the same as for the Design #1 coating, at 7 J/cm^2. For a second design, Design #2, with Al_2O_3 layers the outer two HfO2 layers and <u>without</u> re-optimization for optimal dichroic HT and HR properties, E-field intensities in the coating did not change except in the outer Al_2O_3/SiO_2 layer pairs where the peaks were lower, and the LIDT at 532 nm for 22.5° AOI, Spol was higher, at 10 J/cm^2. These results do not necessarily imply that re-optimizing for optimal dichroic HT and HR properties after replacement of HfO_2 layers by Al_2O_3 layers will always be unfavorable to higher LIDTs or, vice versa, that not re-optimizing will always be favorable to higher LIDTs. We are continuing to explore the use of HfO_2 and Al_2O_3 layers with SiO_2 layers in dichroic coating designs that will provide LIDTs even higher than 10 J/cm^2.

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