Long-Term Monitoring of the Damage Performance of Multilayer Dielectric Grating Samples Residing Inside the Compressor Chamber of the OMEGA EP Laser

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The laser-induced–damage threshold (LIDT) of the final transport optics is a critical factor limiting the output energy in ultrahigh-power lasers (e.g., OMEGA EP) based on chirped-pulse amplification. The multilayer dielectric (MLD) gratings in such laser systems are expensive, hard to manufacture/replace, and highly susceptible to laser-induced damage.[1] Two pulse compressors on OMEGA EP are stacked vertically in a single grating compression chamber (GCC) having internal dimensions of 4.57 m × 4.57 m × 21.34 m (15 ft × 15 ft × 70 ft) and operating under nominal vacuum of 2×10^{-6} Torr. The GCC is populated with over 100 optomechanical structures, control devices, and optical components and vented for quarterly maintenance. Although all materials and manufacturing processes used in the OMEGA EP vacuum systems are subject to approval through a qualification process,[2] it is necessary to monitor in-vacuum LIDT for optical components residing inside the GCC to ensure the failure-free and cost-effective operation of the laser. Since the OMEGA EP Laser System is designed to operate in a wide range of pulse durations (from about 500 fs up to 100 ps), the recent discovery that more than one type of defect species can initiate damage in regimes[3] of different pulse lengths has made the continuous evaluation of the LIDT more complex than originally anticipated.

A special protocol for a long-term damage testing campaign was established on OMEGA EP from the beginning of GCC population to monitor the damage performance of representative optics under exposure to the vacuum chamber environment. A set of small-size optics samples was selected and placed inside the GCC during normal operation, and routinely tested for damage on every quarterly GCC vent using the in-house short-pulse damage testing system. The samples were positioned near the most-critical optical elements and in areas undergoing the most intense maintenance activities. Over the last ten years, the long-term campaign was divided into three smaller campaigns.

The Round I Campaign (2007–2010) started using a set of development MLD gratings. Damage testing at a 600-fs pulse length showed no changes in the damage performance. The damage testing results at a 10-ps pulse length showed no significant change for 15 of the grating samples used during the GCC population period. A decline was observed, however, for three gratings. Due to the extensive damage testing schedule, only one grating sample remained under monitoring for the remainder of the Round I Campaign. This grating showed a 30% decline in the 10-ps damage testing results after three years of vacuum exposure inside the GCC.

The Round II Campaign (2010–2016) utilized three production witness grating samples (denoted as II-1, II-2, and II-3) and involved damage testing at a 10-ps pulse length in vacuum. The damage testing results for this round are summarized in Fig. 1(a). Variations in the LIDT values, observed over this six-year test period, may be separated into two regimes: (1) during the first three years where changes were small and (2) during the following three years where a considerable decline was observed. These results must be evaluated, taking into account that the system was in full operational mode during the period of the most LIDT decline. Overall, the 1-on-1 and N-on-1 thresholds dropped by ~40% concurrently. In addition, the online grating inspection system[4] on OMEGA EP detected damage onset during operation at a 100-ps pulse length at a fluence level significantly below the initial damage threshold measured using the production witness grating samples. Near the end of Round II testing, the LIDT's of all grating samples at 100 ps were similar to those at a 10-ps pulse length.

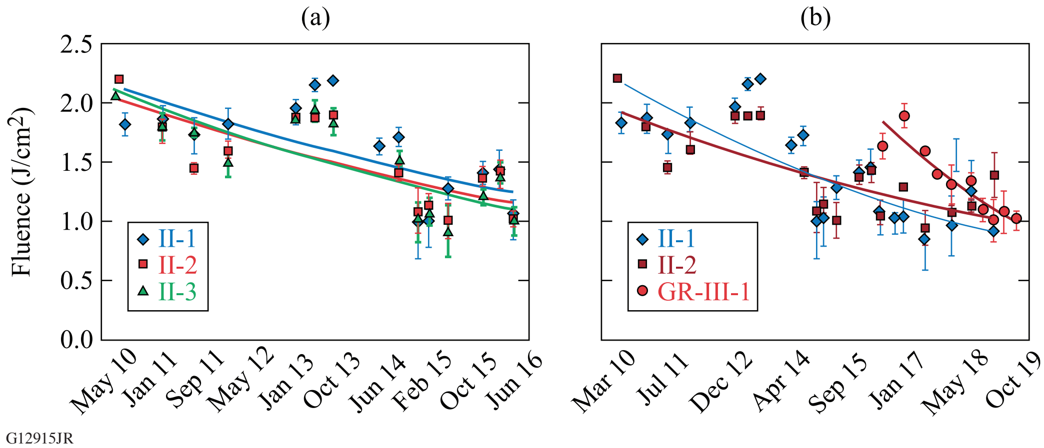

Figure 1
(a) The Round II and (b) Round III, N-on-1 damage testing results.

The Round III Campaign (2016–2019) encompassed an expanded protocol to monitor damage testing at a 100-ps pulse length. A "fresh" grating sample (GR-III-1) and the representative grating high-reflector (GHR) coating (HR-III-1) were included in the experiment to study potential differences in the vacuum performance between the MLD gratings and regular coatings. The representative grating high reflector is identical to the regular grating MLD coating with the exception of the top silica layer, which has a reduced thickness (609 nm to 440 nm) and no etched grating structure. To separate the vacuum effects from the aging-related changes in the optics performance, the fresh grating and coating samples had an equivalent twin (GR-III-2 and HR-III-2, respectively) that was stored in air throughout the campaign. Furthermore, one sample (II-3) from the Round II Campaign was removed from the study and stored in air.

Figure 1(b) summarizes the 10-ps-pulse-length damage testing results obtained during the Round III campaign combined (to enable direct comparison) with the data from Round II. Both 1-on-1 and N-on-1 damage thresholds for the fresh grating sample GR-III-1 were reduced by 40% over three years. This decline is exactly the same as the reduction of the damage threshold experienced by the gratings II-1 and II-2 during Round II, but it occurred twice as fast. The 10-ps damage thresholds for these two remaining Round II grating samples continued to decline during Round III with the 1-on-1 and N-on-1 LIDT reduced by 20% and 10%, respectively. However, the damage thresholds for the Round II gratings II-1 and II-2 showed no further measurable decline at the 100-ps pulse length.

Damage testing results at a 100-ps pulse length of Round III, GCC-stored fresh grating GR-III-1 are presented in Fig. 2, combined for comparison with the 10-ps data for the same sample. The damage testing results at a 100-ps pulse length for the fresh grating GR-III-1 declined significantly faster in comparison with the 10-ps data. Specifically, the 100-ps 1-on-1 and N-on-1 damage thresholds dropped by ~50% and ~70%, respectively. As a result, the damage threshold at 10 ps and 100 ps converged. On the other hand, no convergence between 10-ps and 100-ps damage thresholds was observed for grating GR-III-2, which was stored in air.

The GHR coating sample HR-III-1, stored inside the GCC, showed no change in damage thresholds at 10 ps, but the damage behavior changed significantly at a 100-ps pulse length. The 1-on-1 damage threshold at 100 ps dropped by ~50% after three years in vacuum, while the N-on-1 remained unchanged.

The overall percentage decline in the damage thresholds in all, GCC and in-air stored, samples (Fig. 3) depicts a clear difference in the vacuum damage performance between the MLD gratings and GHR coatings. The damage thresholds of the MLD's grating were reduced in vacuum by up to 70%, depending on the pulse length. For the GHR coatings, only the 1-on-1 damage threshold at a 100-ps pulse length was affected by the environment inside the GCC. Both grating and GHR-coating samples revealed no change in the damage performance after three years of aging in ambient air.

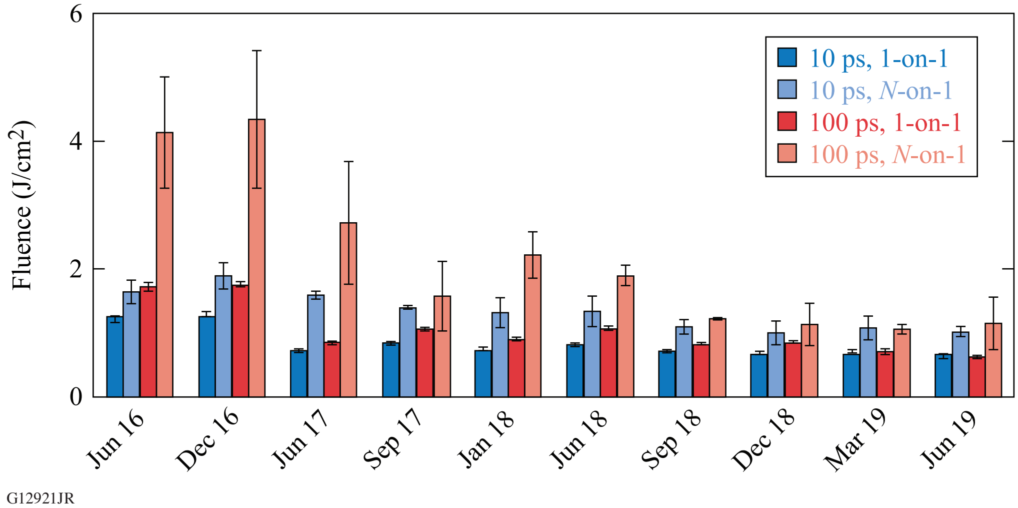

Figure 2
Round III, "fresh" grating GR-III-1: The 10-ps and 100-ps damage thresholds converged under vacuum exposure inside the GCC.

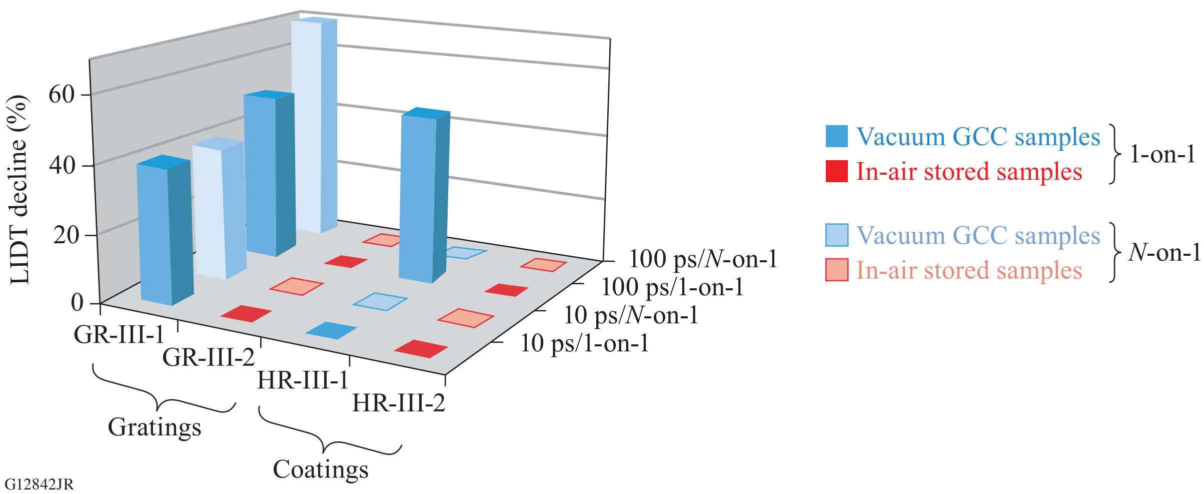

Figure 3
The evolution of the damage performance of the MLD-grating and GHR-coating samples during Round III.

Surface plasma cleaning was used on grating sample II-3 to target potential organic volatile contaminants, presumably accumulated on the grating surface under vacuum inside the GCC.[5] The results indicated that the air–plasma cleaning method did not improve the damage performance of the grating. This suggests that the degradation of the grating damage performance under vacuum conditions inside the GCC is not related to volatile organic contamination.

Particles that attach to the surface of optics (contaminants) can be precursors for damage initiation on these optics at significantly lower fluences than the corresponding pristine optical elements. Offline studies have shown that particles on the surface can significantly lower the damage thresholds.[6] It is currently unclear, however, what types of particles may be present inside the GCC and if they correlate with the reduced damage performance of the compression gratings discussed in this work. In an effort to perform a preliminary analysis of the contamination load inside the OMEGA EP GCC, particles were collected from seven locations near optical elements during the December 2019 vent period. The initial analysis was focused on determining the particle composition and was limited to the larger particles (>50 μm diameter). Particles were found at every collection location with the most frequently observed type being metallic particles and fibers, for the subset of particles that were chemically characterized. Several different metal particles were identified, including aluminum, stainless steel, silver, and copper. Plastic (PVC) particles were also found near the compressor grating and the lower compressor deformable mirror. Glass particles were less commonly observed.

Differences in damage degradation behavior between the MLD grating and corresponding GHR coating may arise from the different damage initiation mechanisms. As reported in Ref. 3, the damage of HfO_2/SiO_2–based HR's by laser pulses longer than 10 ps is defect-driven Type II or Type III, originating at depths around 600 nm and >100 nm, respectively. Conversely, damage initiation in gratings with picosecond pulses originates in the pillars (the location of peak electric-field intensity enhancement) and is associated with defect-induced localized absorption.[7] Therefore, damage in the MLD grating and the GHR coating occurs at different locations. The damage-initiation mechanisms described above apply for the case of the "pristine" optic (grating or GHR coating). Assuming there is contamination involved, the problem becomes more complex and would require additional studies to resolve. However, the existing results may help obtain insight into the possible processes.

Recent work that considered the interaction of model contamination particles (metal, plastic, and glass) located on the surface on an MLD mirror with pulses at 0.6 and 10 ps revealed that the threshold for metal particle ejection and secondary contamination (via nanodroplets) is largely dependent on only the fluence.[6] These processes take place at fluences below the particle-induced LIDT of the mirror. If we further consider that damage is initiated by the generated (secondary contamination) nanoparticles, due to their small size, heat diffusion would be limited and damage would be only a function of total fluence. This would explain the convergence of the 100-ps 1-on-1 LIDT toward the 10-ps 1-on-1 LIDT (as depicted in Fig. 2). Regarding the behavior of the grating samples, the introduction of metal contamination particles would alter the localized electric-field distribution near the pillars creating "hot" spots with higher electric-field intensity. This in turn would facilitate a reduction of the LIDT. Additional work would be required to validate the above hypothetical.

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