Damage Mechanisms in Multilayer Dielectric Gratings at Different Pulse Durations

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Multilayer dielectric (MLD) diffraction gratings typically consist of an etched layer of SiO_2 that resides on top of a multilayer dielectric high-reflector stack composed of alternating layers of SiO_2 and HfO_2 to form a periodic structure of lines and trenches with a predetermined line density and line width. This design allows for higher laser-induced–damage thresholds (LIDT's) compared to their metal grating predecessors.[1,2] The LIDT of optical components incorporated in high-power, short-pulse laser systems is of critical importance since it affects the maximum laser output and/or the operational cost. The current generation of MLD gratings has a LIDT that is limited by defects embedded in the coating, which can be separated into two general categories. The first category is atomic defects and nanoscale defect structures introduced during coating that cause localized absorption. The second category is the defects introduced during the photolithographic and etching stages of grating manufacturing.[3,4] Determining the laser-damage–initiation mechanisms in MLD gratings has been elusive mainly because it is associated with the removal of grating pillars, thereby erasing any characteristic signatures. To study the laser-damage signatures, we created 5-mm grating-like structures that simulate the magnitude of the electric-field–intensity (EFI) enhancement observed in MLD gratings. The macroscopic lateral scale of the pillars in the structure allow for spatially targeted damage testing, while the inherent mechanical stability of the structure enables the preservation of damage signatures for postmortem study. The results from the grating-like structures can subsequently elucidate the damage morphology and associated laser-damage mechanisms in actual MLD gratings.

The grating-like structures were etched into a SiO_2 coating using processes similar to those used for MLD gratings. The grating-like structures are 700 nm in height, which is of the order of the MLD grating pillar height [see Fig. 1(a)]. The pillar height of the grating-like structures results in a 3× internal EFI enhancement factor, which is similar to that observed near the

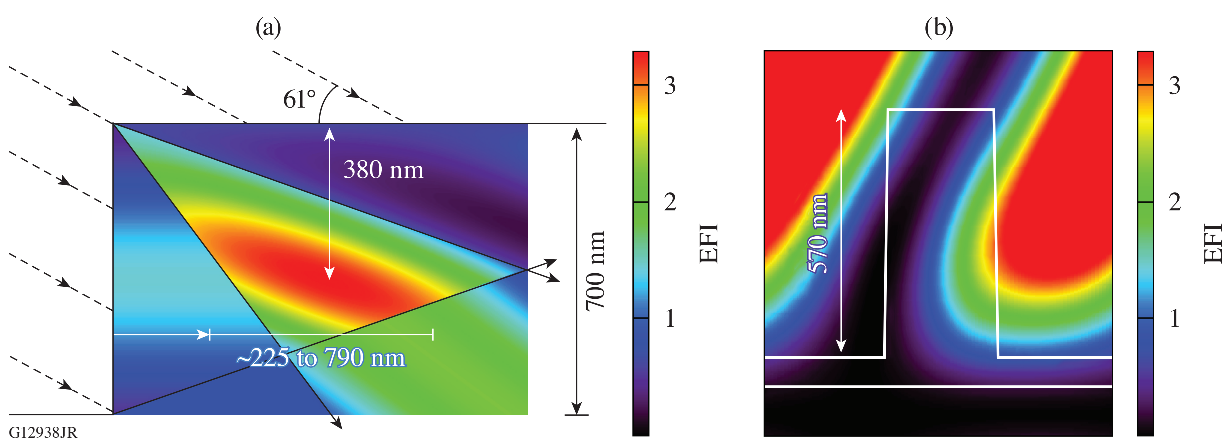

Figure 1
The EFI enhancement (a) near the millimeter-pitch pillar wall region and (b) for the MLD grating design used in this work. The laser excitation is incident on the samples at a 61° angle from the left side.

right side of the MLD grating pillars [see Fig. 1(b)]. The grating-like structure and the MLD grating samples were damage tested in vacuum at 0.6 ps and 10 ps.

Previous work by Kozlov *et al.*[5] demonstrated that there are three types of laser-induced–damage mechanisms in multilayer dielectric coatings. Type-I damage is driven by the EFI enhancements within the most vulnerable material layer and involves removal of the overlying material over the area of peak laser intensity. Type-I damage occurs with pulse widths shorter than 2.5 ps. The damage mechanisms of the pillar wall of the grating-like structure for 0.6-ps laser pulses showed distinct signatures of the type-I damage mechanisms, such as a removal of coating sections within the area of the peak laser-beam intensity [see Fig. 2(a)] and a damage crater depth similar to the depth of the EFI enhancement [see Fig. 2(b)]. The morphology of the crater involves melted nanoscale projections from the explosive boiling process and the sharp crater edges, which are reminiscent of type-I craters observed with MLD high-reflector coatings [see Fig. 2(a), right inset image].

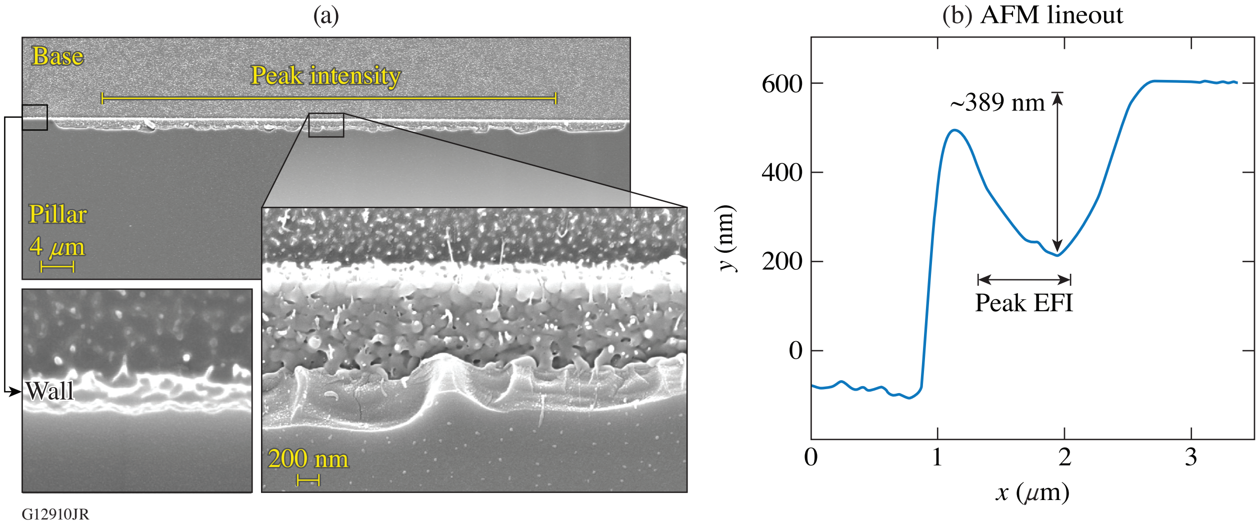

Figure 2
(a) Scanning electron microscope (SEM) images of the wall region in millimeter-pitch grating-like structures containing a damage site generated with a 0.6-ps pulse. The left inset shows in higher magnification the undamaged part of the wall region, and the right inset shows a section of the damage region. The laser beam impinges from the top at 61°. (b) A cross-sectional lineout of the damage region obtained with atomic force microscopy imaging reveals the depth and exact position of the damage site.

The type-II and type-III damage initiation processes in MLD coatings occur with laser pulses longer than 2.5 ps and are defect driven, resulting in the formation of micrometer-size craters. It was previously discussed that the temperature and pressure relaxation pathways following plasma formation at the defect location govern the morphology of the type-II damage.[5] The damage mechanisms observed on the grating-like pillar wall irradiated by 10-ps laser pulses (see characteristic examples in Fig. 3) are consistent with defect-driven damage near the EFI maximum enhancement, which is analogous to the type-II damage observed with MLD coatings.

Although damage in MLD gratings includes pillar removal, thereby concealing the primary signatures of the damage mechanisms, the use of grating-like structures helped us to recognize fingerprint signatures on which to draw correlations. MLD grating damage sites generated with 0.6-ps pulses exhibit modification on the pillar wall, primarily on the right side where the EFI enhancement is known to be maximum [see Figs. 1(b) and 4] along with melted nanoparticles between damage pillars [see Fig. 4(b)]. These observations are consistent with the mechanisms and signatures observed with the grating-like structures seen in Fig. 2. Specifically, damage causes removal of sections of the pillar at the locations of maximum EFI while melted nanoparticles are observed between the pillars, which correspond to the nanoscale projections observed at the bottom of the type-I crater for the grating-like structures (separation of nanodroplets from the superheated material).

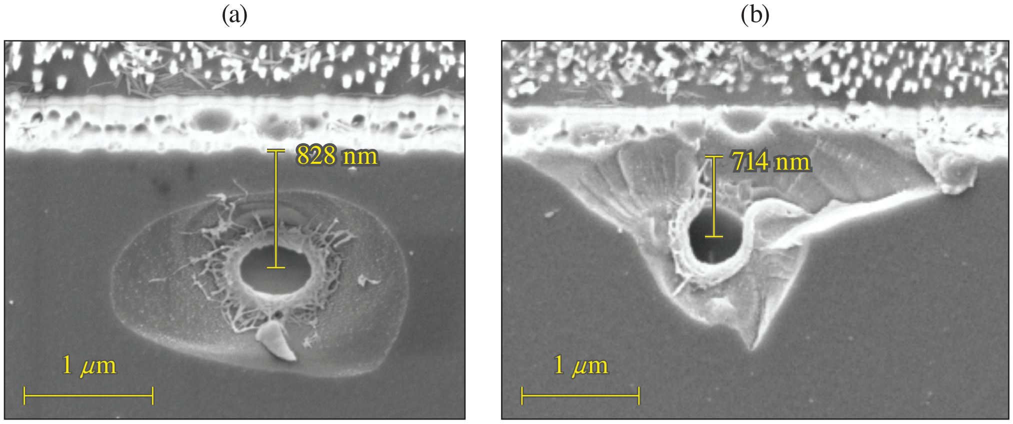

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Figure 3
SEM images of damage sites generated under 10-ps pulses in the wall region in a millimeter-pitch grating.

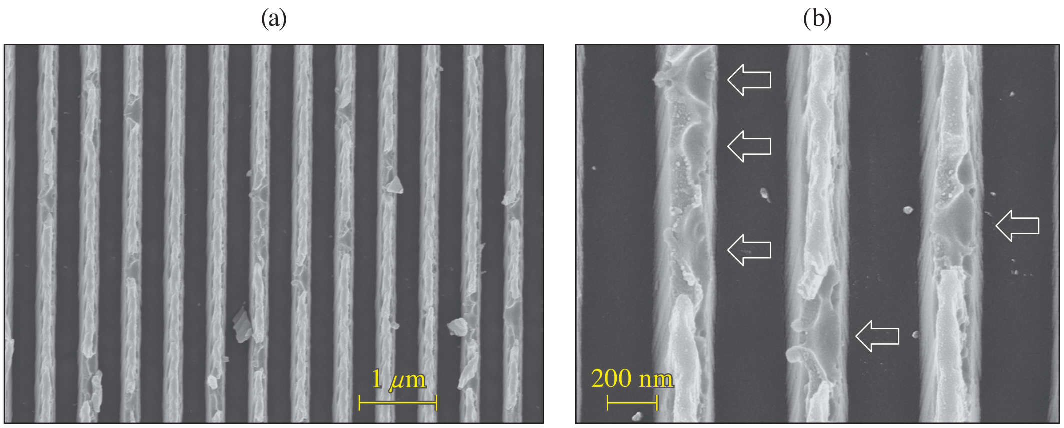

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Figure 4
SEM images of areas of an MLD grating where (a) laser-induced damage was initiated under a single 0.6-ps laser pulse and (b) the image of the central region at a higher magnification shows nanoparticle distribution. The laser excitation impinges on the samples at a 61° angle of incidence from the left side.

The primary morphology of laser damage in MLD gratings under 10-ps irradiation also involves removal of pillars, but there are characteristic differences from the pillar damage observed with 0.6-ps pulses. First, pillar removal often involves the entire pillar, not just the side. Second, the 10-ps damage consists of isolated sites that often span multiple pillars [see Fig. 5(a)]. Lastly, a larger number of melted nanoparticles [see Fig. 5(b)] as well as fragments [see Fig. 5(a)] are present within or near damage sites. This type of damage is suggestive of the type-II damage as also observed with the grating-like structures. However, the boundary conditions due to the small size of the grating pillars must be considered. Specifically, since the depth of the damage-initiating defect can vary, damage can initiate at different locations within the pillars. This gives rise to a variability on the damage morphology, including the height of the removed sections of the pillars as well as the number of pillars involved for each individual damage site. However, the distribution of generated nanoparticles within the trenches provides a fingerprint of the exact locations of the pillar involving the explosive boiling (damage).

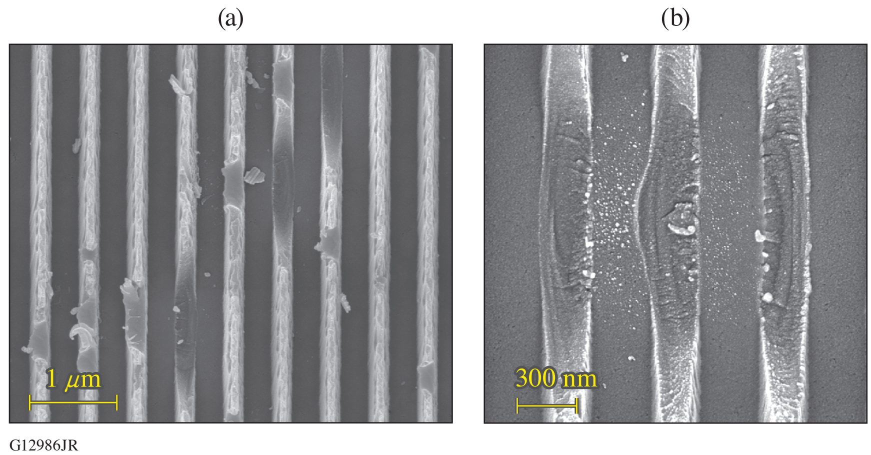

Figure 5
SEM images of areas of an MLD grating where (a) laser-induced damage was initiated under a single 0.6-ps laser pulse and (b) the image of the central region at a higher magnification shows nanoparticle distribution. The laser irradiation impinges on the samples at a 61° angle of incidence from the left side.

In summary, by studying the damage mechanisms and signatures of grating-like structures, we were able to better understand the damage mechanisms for MLD gratings. This information will help advance our ability to design and fabricate the next-generation gratings that will exhibit a significantly higher damage threshold.

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