Microscopic evidence of the role of the near field enhancement in the short pulse damage mechanism of diffraction gratings

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We investigate the short pulse laser induced damage initiation mechanism on multilayer dielectric (MLD) pulse compression gratings. We report by means of scanning electron microscopy that damages initiate on the edge of the grating pillars opposite to the incoming wave. It demonstrates, at the scale of a grating line, the role of the electric field in the damage process but we also that grating pillars damage is also spatially modulated in the form of a periodic ripple pattern developing along the polarization direction.

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The fast development of Ultra High Intensity (UHI) large laser facilities [1] such as OMEGA-EP, FIREX, PETAL, HIPER or ILE [2] is pushing grating performances to new extent in term of spectral tolerance [3], [4] but also in terms of laser induced damage threshold (LIDT). Typical values of 1 J/cm^2 to some J/cm^2 in beam normal for picoseconds or down to a few tenths of femtoseconds, at operating incidence and wavelength (800nm or 1053nm) are requested depending on the laser facility. For this reason, gold coated gratings that were widely used in compressors have been gradually replaced by all dielectric gratings. These so called MLD gratings consist in a multilayer dielectric mirror where the top layer is periodically engraved. Hafnia (HfO_2) and silica (SiO_2) are generally used as high and low index materials respectively due to their high LIDT. The grating is usually manufactured in the silica layer due to its higher LIDT [5]. MLD gratings also offer the benefit of exhibiting reflected efficiencies higher than 96% [6] but more importantly, an enhancement of the LIDT was reported as early as 1996 [7]. However, despite some benefits obtained by optimizing the manufacturing process [8], the threshold of MLD grating remains clearly beyond than that offered by silica evaporated thin films [5] or even bare fused silica [7]. Subpicosecond LIDT of dielectric materials is understood as the consequence of the multiphoton ionization occurring in this regime [5]. LIDT was expected to exhibit a strong dependence to the near electric field intensity in the periodic structure of the MLD grating. The electric field intensity can be minimized by increasing the angle of incidence [8], but it was numerically evidenced in 2006 that the grating profile plays a crucial role in the enhancement of the electric field [9]. In particular, it was shown that at a given period, the thickness of the pillars strongly impacts the field enhancement, and that thin pillars permit to decrease by 3 the field intensity compared with thick pillars. A macroscopic linear dependence of LIDT with the electric field intensity was first established by our group on MLD grating [10] and the influence of the grating profile on the value of the LIDT was clearly demonstrated. This result was recently confirmed on mixed metal dielectric gratings [11] which consists in a mirror made of a gold reflective layer below a very limited number of pairs of low and high refractive index dielectric layers and a grating engraved in its top low index layer [9], [11]. Even if reproduced, both experiments stay macroscopic since electric field intensity dependence is evaluated in term of LIDT, i.e. at the scale of the damage testing beam. Such an effect should also be observable in terms of damage morphology at the scale of a grating line, and we propose to address this challenging issue in this letter.

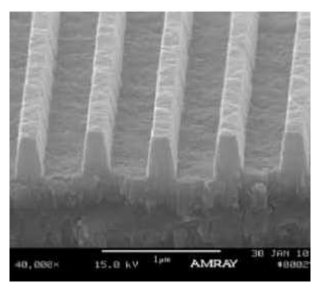

Fig. 1. MEB image of a the top area of the MLD grating under study. The grating is manufactured in the silica top layer, with a trapezoidal shape. The line density is equal to 1780 l/mm.

MLD grating samples were manufactured by Plymouth Grating Laboratory (PGL) [12]. They are engraved in the SiO_2 top layer of an HfO_2/SiO_2 multilayer dielectric mirror with a line density of 1780 l/mm. They exhibit typical diffraction efficiency in the -1st reflected order slightly larger than 95% at an incidence of 77.2 deg for TE polarization. This grating configuration is the one needed for PETAL vacuum compressor [13]. The grating profile is measured by Scanning Electron Microscopy (SEM) (Fig.1). The measure of the angle of slope, pillar height and duty cycle permits the accurate calculation of the near electric field intensity in the periodic structure with our software developed in the framework of the differential method [9]. Let us remark that the reflected efficiency calculated with the measured profile is concordant with the measured efficiency. The method allows the reconstruction of the electric field intensity distribution in the grating. The distribution displayed in Fig.2 shows that the electric field is maximum on the top area of the grating, more precisely in the pillars of the grating made of silica. Let us remind that the electric field is calculated with a laser coming from the left, which means that the electric field is maximum at the opposite side from the incoming wave. In order to demonstrate that this local enhancement of the near electric field is responsible of the LIDT, we have to carry out damages on a facility able to probe initiation of defects at a submicrometer scale.

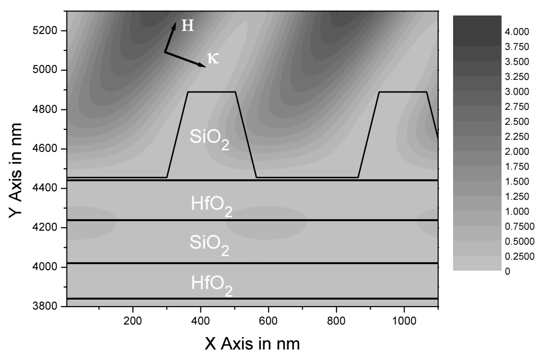

Fig. 2. Reconstruction of the enhancement of the field intensity on the top area of the grating. The grating is illuminated from the left side, at an angle of incidence of 77.2 deg, in TE polarization. Light intensity is maximum in the grating pillars made of silica, at the opposite side from the incoming beam.

To that aim, we used the DERIC damage testing facility [10] and we set the 10Hz-laser at a fluence close to the LIDT of the grating (about 3J/cm^2 in normal beam). Experimentally, the grating was tested at its nominal conditions, i.e. incidence angle of 77.2 deg and TE polarization. Every damage test site was exposed to 100 laser pulses. Among the tested sites, we only consider small defects to observe damage with mainly initiation and some limited growth on the top layer. To select damage sites, observations must achieve a submicron resolution and they are performed with the a Nomarsky microscopy set-up associated with a scanning electron microscope (Quanta 200 from FEI, with an optimal resolution of 3 nm at 30 Kv. Images of Fig.3 are obtained at 13 Kv with low vacuum of 0,33 Torr). Results are presented in Fig. 3 at three different scales. Ripples can be observed near the main damage site, where the fluence is close to LIDT and damage initiates (Fig.3a), and they are perpendicular to the grating line (Fig.3b). Fig.3c unveils the important result that damage initiates at the ripples location, where the electric field is locally over enhanced. Fig.3c also remarkably reveals that damage initiates on the edge of the pillar grating, at the opposite side of the illuminating beam, where the enhancement of the electric field is maximum (see Fig. 2). This microscopic observation definitely proves the link between electric field enhancement and damage initiation.

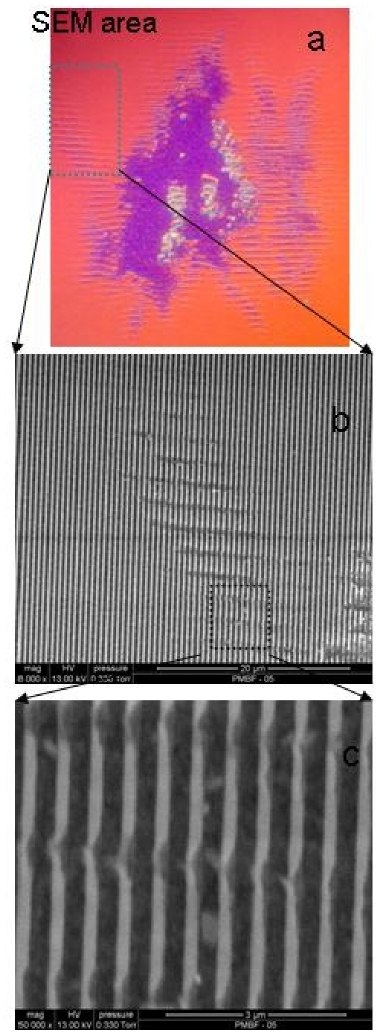

Fig. 3. Scanning Electrons micrography images of the damage sites with increasing scales (a-c). (a) The ripples of period 2.5 μm are visible near the main damage site. (b) They are perpendicular to the grating lines and (c) are responsible for the initiation damage. Incoming wave is coming from left to right.

However, it is clearly visible in Fig. 3 that during the initiation, the damage structure is spatially modulated perpendicularly to the grating lines with a period of about 2.5 μm. These modulations are called ripples and have been oftenly observed on fs-damaged facility on MLD gratings from various suppliers [10], [14] or on multilayer dielectric mirrors [15]. Noteworthy, Fig.3c clearly shows that the damage initiates with the ripple structure. Multiple pulse shots then make ripples grow and be more visible to become finally a large and catastrophic damage site. Ripples are attributed to the interference of surface waves propagating along the direction of the incident electric field and the illuminated beam [16]. The coupling of this surface wave to the incident propagating beam is allowed by the presence of roughness at the surface of the grating (see Fig.1) . This role of roughness is also emphasized by the fact that ripples are clearly visible on MLD gratings (high roughness surfaces), less visible on MLD coatings [15] and invisible on superpolished fused silica substrates [7]. Consequently, the presence of ripples decreases the LIDT compared to that predicted by the enhancement of the electric field intensity inside the pillars, and it can be expected that the lifting of roughness would significantly increase the LIDT of MLD gratings. Lastly, we investigated the influence of the incident polarization by illuminating the grating in TM polarization. LIDT is in this case increased up to 4.8 J/cm^2 in normal beam and Fig.4b shows the absence of ripples.

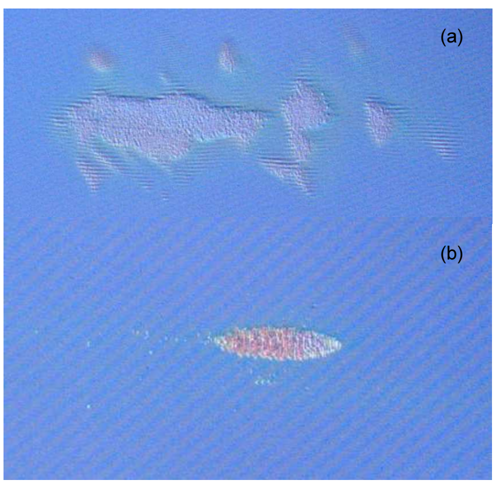

Fig. 4. SEM images of damages in TE (top) and TM (bottom) polarization. The ripples are clearly observable in TE polarization, perpendicularly to the grating line, but they are not visible in TM polarization. The LIDT is close to 2.9 J/cm^2 in normal beam in TE polarization and 4.8 J/cm^2 in normal beam in TM polarization.

We experimentally demonstrated that the local enhancement of the electric field intensity in dielectric grating pillars is responsible of the LIDT. We also emphasized the crucial role of ripples in the initiation of the damage. This result shows that the LIDT of MLD gratings could be further increased by avoiding the formation of ripples at the surface of the grating. Consequently, the surface rugosity of MLD gratings is expected to play a crucial role in future developments of pulse compression diffraction gratings which still limit the power of petawatt laser facilities.

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