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## ► To cite this version:

Jérôme Neauport, Steve Hocquet, Nicolas Bonod. The role of electric field polarization of the incident laser beam in the short pulse damage mechanism of pulse compression gratings. Applied Physics Letters, 2011, 99, pp.061101. 10.1063/1.3624832 . cea-01623589

**HAL Id: cea-01623589**

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Submitted on 25 Oct 2017

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Citation: *Appl. Phys. Lett.* **99**, 061101 (2011);

View online: <https://doi.org/10.1063/1.3624832>

View Table of Contents: <http://aip.scitation.org/toc/apl/99/6>

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# The role of electric field polarization of the incident laser beam in the short pulse damage mechanism of pulse compression gratings

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(Received 24 May 2011; accepted 13 July 2011; published online 8 August 2011)

We investigate the short pulse laser induced damage initiation mechanism on multilayer dielectric pulse compression gratings. We report that damages initiate at the edge of the grating pillars opposite to the incoming wave. It demonstrates, at a nanometer scale, the role of the electric field in the damage process coupled with periodic ripple pattern developing along the polarization direction. We avoid the formation of ripples by illuminating the diffraction grating in TM polarization and measure a significantly improved laser induced damage threshold associated with a strong decrease of the electric field in the grating structure. © 2011 American Institute of Physics. [doi:10.1063/1.3624832]

The fast development of ultra high intensity large laser facilities<sup>1</sup> such as OMEGA-EP, FIREX, PETAL, HIPER, or ILE (Ref. 2) is pushing grating performances to new extent in terms of size, spectral tolerance,<sup>3,4</sup> and also in terms of laser induced damage threshold (LIDT). Typical values of 1 J/cm<sup>2</sup> to few tens of J/cm<sup>2</sup> in normal beam for picoseconds or down to a few tenths of femtoseconds, at operating incidence and wavelength (800 nm or 1053 nm), 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 multilayer dielectric (MLD) gratings consist of a multilayer dielectric mirror with a periodically engraved top layer. Hafnia (HfO<sub>2</sub>) and silica (SiO<sub>2</sub>) are generally used as high and low index materials and the grating is usually manufactured in the silica layer due to its higher LIDT (Ref. 5). MLD gratings also offer the benefit of exhibiting reflected efficiencies higher than 96% (Ref. 6) but more importantly, an enhancement of the LIDT was reported as early as 1996 (Ref. 7). However, despite some benefits obtained by optimizing the manufacturing process,<sup>8</sup> the LIDT of MLD gratings remains clearly below than that offered by silica evaporated thin films<sup>5</sup> or even bare fused silica.<sup>7</sup> Subpicosecond LIDT of dielectric materials is understood as the consequence of a multiphoton ionization occurring in this regime.<sup>5</sup> The LIDT was expected to exhibit a strong dependence on 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,<sup>8</sup> but it was numerically evidenced in 2006 that the grating profile plays a crucial role in the enhancement of the electric field. 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 2, the field intensity compared with thick pillars.<sup>9</sup> A macroscopic linear dependence of the LIDT with the electric field intensity was established on MLD gra-

tings<sup>10</sup> and the influence of the grating profile on the value of the LIDT was clearly demonstrated. This result was recently confirmed on mixed metallo-dielectric gratings<sup>11</sup> which consist 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.<sup>9,11</sup> Even if reproduced, both experiments stay macroscopic since the electric field intensity dependence is evaluated in term of LIDT, i.e., at the scale of the damage testing beam. But the location of the damage morphology inside the periodic structure has never been evidenced so far. It could be assumed that damages initiate at the maximum of the electric field enhancement, but electromagnetic simulations predict a maximum of light intensity inside the dielectric pillar, at the opposite side of the incoming wave, and we propose to address this challenging issue in this letter which will allow us to finally propose a route to improve the LIDT of compressor diffraction gratings.

MLD grating samples are manufactured by Plymouth Grating Laboratory (PGL).<sup>12</sup> They are engraved in the SiO<sub>2</sub> top layer of an HfO<sub>2</sub>/SiO<sub>2</sub> multilayer dielectric mirror with a line density of 1780 l/mm. They exhibit typical diffraction efficiencies in the 1st reflected order slightly larger than 95% at an incidence of 77.2° in TE polarization, that is, the configuration needed for PETAL vacuum compressors.<sup>13</sup> 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.<sup>9</sup> 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

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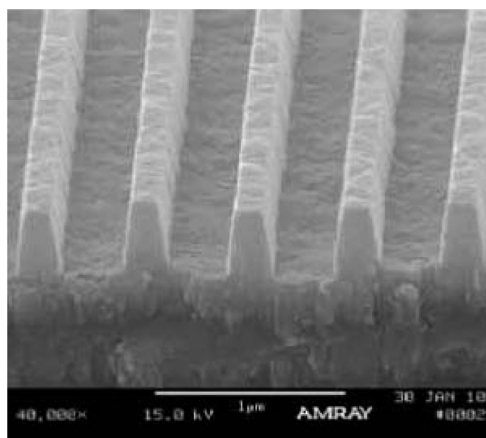


FIG. 1. SEM image of a top area of the MLD grating under study. The grating is manufactured in the silica top layer, with a trapezoidal shape. The line density is equal to 1780 l/mm.

opposite side of 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 sub-micrometer scale. To that aim, we use the DERIC damage testing facility<sup>10</sup> and we set the 10 Hz-laser at a fluence close to the LIDT of the grating (about 3 J/cm<sup>2</sup> in normal beam). Experimentally, the grating is tested at its nominal conditions, i.e., incidence angle of 77.2° and TE polarization and 1057 nm. Every damage test site is exposed to 100 laser pulses. Among the tested sites, we only consider small defects to observe damages with mainly initiation and some limited growth on the top layer. To select damage sites, observations are performed with a Nomarsky microscopy set-up associated with a scanning electron microscope (Quanta 200 from FEI company, 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 able to achieve a submicron resolution. Results are presented in Fig. 3 at three different scales. At the largest scale, ripples can be observed near the main damage site, where the fluence is close to the LIDT and also where damages initiate (see Fig. 3(a)). Fig. 3(b) shows that they are per-

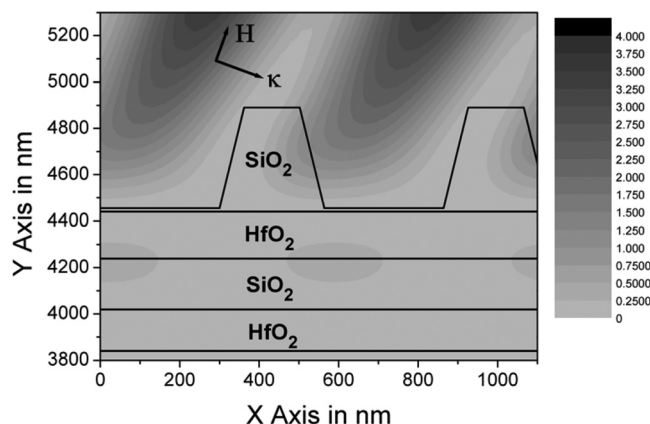


FIG. 2. Enhancement of the norm of the electric field  $|E|^2/|E_0|^2$  on the top area of the grating ( $|E_0|$  is the norm of the incoming wave electric field in vacuum). The grating is illuminated from the left side, at an angle of incidence of 77.2°, in TE polarization. The enhancement of the electric field is maximum in the grating pillars made of silica, at the opposite side of the incoming beam.

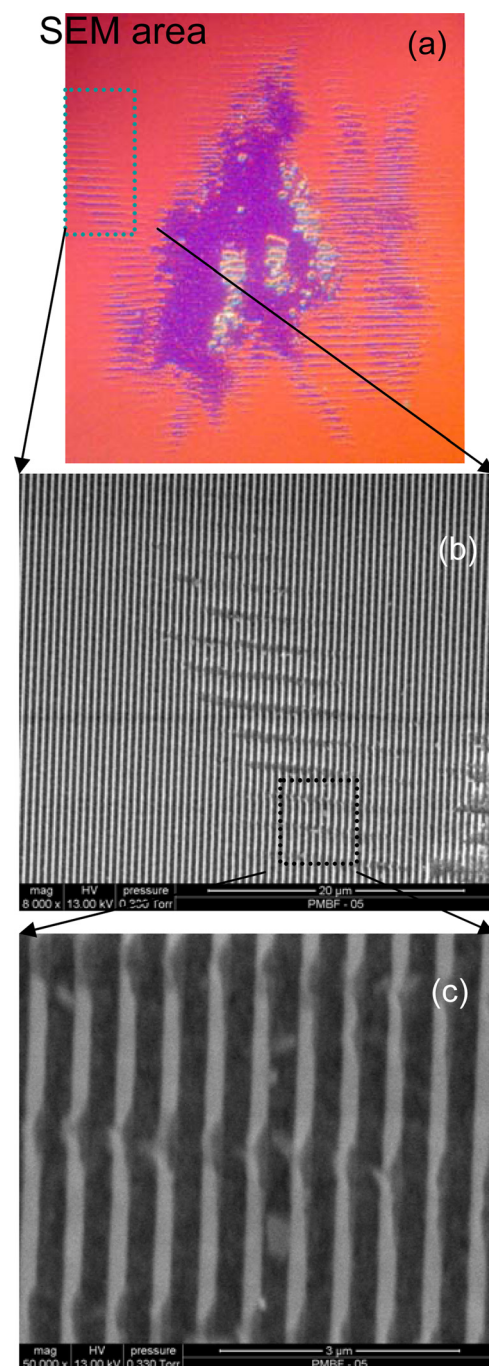


FIG. 3. (Color online) SEM images of the damage sites with increasing scales (a)-(c). (a) The ripples of period 2.5  $\mu\text{m}$  are visible near the main damage site. (b) They are perpendicular to the grating lines and (c) are responsible for the initiation damage. Incoming wave is coming from left to right.

pendicular to the grating line. More importantly, the smallest scale in Fig. 3(c) reveals that damages initiate at the ripples location, where the electric field is locally over enhanced. Fig. 3(c) also remarkably evidences that damages initiate at 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 observation proves at the nanometer scale the link between electric field enhancement and damage initiation. 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



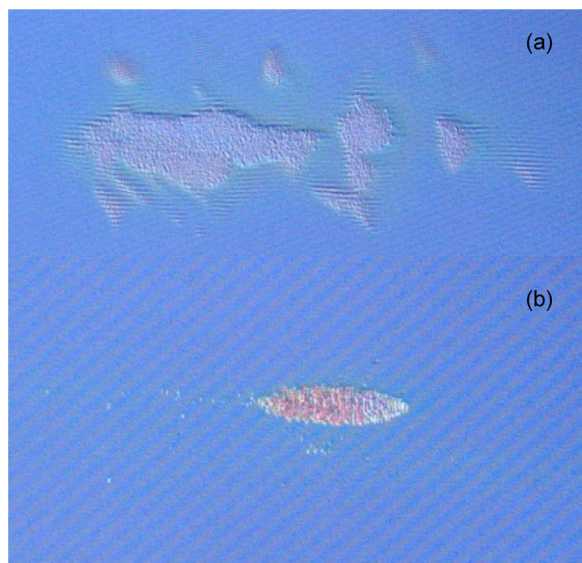


FIG. 4. (Color online) SEM images of damages in TE (top) and TM (bottom) polarization. The ripples are clearly observable in TE polarization, perpendicularly to the grating line, but they are not visible in TM polarization. The LIDT is close to  $2.9 \text{ J/cm}^2$  in normal beam in TE polarization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

of about  $2.5 \mu\text{m}$ . These modulations are called ripples and have been often observed on fs-damage testing facilities on MLD gratings from various suppliers<sup>10,14</sup> or on multilayer dielectric mirrors.<sup>15</sup> Damages initiate with the ripple structure and multiple pulse shots then induce an increase of the ripple amplitude before becoming finally a large and catastrophic damage site. Ripples are attributed to the interference of the waves scattered by the surface roughness and propagating along the direction of the incident electric field, with the illuminated beam.<sup>16</sup> The scattered waves are excited by the incident propagating beam via 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,<sup>15</sup> and invisible on superpolished fused silica substrates of very low surface roughness.<sup>7</sup> Consequently, the presence of ripples decreases the LIDT compared to that predicted by the enhancement of the electric field intensity inside the pillars.

The suppression of such ripples together with the diminution of the electric field enhancement inside the dielectric pillar would allow a significant enhancement of the LIDT. For that reason, we finally investigate the influence of the incident polarization by illuminating another grating sample (pillar height of  $540 \text{ nm}$  and duty cycle of  $0.4$ ) in both TE and TM polarizations. Fig. 4(b) shows the absence of ripples when the incident electric field lies in the plane of incidence, and the reconstruction of the electric field inside the MLD gratings predicts an enhancement of the electric field reduced to  $1.16$ . This value has to be compared with an enhancement of  $1.38$  in TE polarization. In such conditions, we measure an increase of the LIDT from  $2.9 \text{ J/cm}^2$  up to  $4.8 \text{ J/cm}^2$  in normal beam. This gain in LIDT is well beyond the electric field enhancement ratio because in TM polarization, the electric field is not over enhanced by ripples. It must be stressed that MLD gra-

tings have been designed so far in TE polarization because the number of dielectric layers needed for obtaining a quasi perfect reflection of light is much lower than in TM polarization. However, we recently demonstrated<sup>11</sup> that this problem can be avoided by the use of mixed metallo-dielectric gratings, which paves the way towards the design of high LIDT gratings optimized in TM polarization.

We first experimentally established at a nanometer scale that damages initiate at the maximum of the light intensity enhancement, at the opposite side of the incoming wave. We also showed that the LIDT of MLD gratings can be further increased by avoiding the formation of ripples at the surface of the grating and by strongly diminishing the field enhancement inside the dielectric pillars. Consequently, the surface roughness of MLD gratings together with the incident polarization is expected to play crucial roles in future developments of pulse compression diffraction gratings which still limit the power of petawatt laser facilities.

This work is supported by the Conseil Régional d'Aquitaine, the French Ministry of Research, and the European Union, and is performed under the auspices of the Institut Lasers et Plasmas (ILP). DERIC damage testing facility development was performed under the auspices of Laserlab-Europe program. We also would like to warmly thank people from PGL for grating manufacturing.

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