Laser induced damage of multi-layer dielectric used in pulse compressor gratings

Weijin Kong (孔伟金)[1,2], Yuanan Zhao (赵元安)[1], Tao Wang (王 涛)[1],
Jianda Shao (邵建达)[1], and Zhengxiu Fan (范正修)[1]

[1]*Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Shanghai 201800*
[2]*Graduate School of the Chinese Academy of Sciences, Beijing 100864*

Received October 12, 2004

Laser induced damage threshold (LIDT) of multi-layer dielectric used in pulse compressor gratings (PCG) was investigated. The sample was prepared by e-beam evaporation (EBE). LIDT was detected following ISO standard 11254-1.2. It was found that LIDTs of normal and 51.2° incidence (transverse electric (TE) mode) were 14.14 and 9.31 J/cm^2, respectively. A Nomarski microscope was employed to map the damage morphology, and it was found that the damage behavior was pit-concave-plat structure for normal incidence, while it was pit structure for 51.2° incidence with TE mode. The electric field distribution was calculated to illuminate the difference of LIDT between the two incident cases.

OCIS codes: 140.3330, 310.6860, 230.1950.

As research in the fields of laser technology advances, ultrashort pulse, high-intensity lasers offer an effective means for the study of light-material interaction and of inertial confinement fusion (ICF). Contemporary high-power pulsed lasers based on chirped pulse amplification (CPA) technology employ the reflective diffraction gratings[1−3] to compress and stretch laser pulse. The reflection gratings are required to have diffraction efficiency nearly as 100% and a damage threshold as high as possible. Multi-layer dielectric gratings (MDG) have been more and more used in CPA system because of its higher diffraction efficiencies and higher damage threshold, which are compared with metallic gratings[4−6]. The properties of pulse compressor gratings (PCGs) depend greatly on the characteristic of multi-layer dielectric stack. Most important of all, it is necessary to prepare multi-layer dielectric with high laser induced damage threshold (LIDT) firstly in order to get high LIDT of PCG. Many authors have investigated laser damage threshold of PCG[7,8], but few literatures have been focused on laser induced damage threshold of multi-layer dielectric used in pulse compression gratings. In this paper, special attention was paid to study the mechanics of laser induced damage on the multi-layer dielectric.

The spectrum of multi-layer dielectric used in PCG should satisfy two requirements based on the basic design of PCG. Firstly, high reflectivity at 1053 nm and 51.2° incidence for transverse electric (TE) mode. Secondly, high transmittance at 413.1 nm and 17.8° incidence with TE mode.

Multi-layer dielectric stack was deposited by e-beam evaporation (EBE) and its structure was G|H3L (H2L)ˆ9H0.5L2.03H|A, where H denoted high index material HfO$_2$ with one quarter wavelength optical thickness (QWOT), and L denoted low index material SiO$_2$ with one QWOT[9,10], G denoted BK7 substrate, and A denoted the incident medium (air). Deposition parameter is listed in Table 1.

The comparison of theory and experimental transmittance spectra is given in Fig. 1, which is tested by Lamb900 spectrophotometer. It can be seen that not only the experimental curve is in good agreement with the theory design, but also they satisfy well with the design goal at 1053 and 413.1 nm.

LIDT of the samples was tested in the “1-on-1” regime according to ISO 11254-1.2[11,12]. Nd:YAG laser system was operated at the TEM$_{00}$ mode and the pulse width was 12 ns. Laser beam was focused on the target plane normally with 1-mm diameter spot (1/e^2) by a non-spherical lens of 250-mm focal length. An attenuator comprised of a half wavelength plate and a polarizer was used to adjust the laser energy. Ten sites of the sample were exposed at the same fluence and the fraction of sites which were damaged was recorded, this procedure was repeated for other fluence until the range of fluence was sufficiently broad to include points of zero damage probability and points of 100% damage probability to develop a plot of damage probability versus fluence. Nomarski microscope of 100× magnification was used to decide whether the radiation sites were damaged or not.

In order to investigate the mechanism of laser-induced damage, two laser-induced experiments were designed in this paper. One was for the laser normal incidence onto the sample; the other was for 51.2° with TE polarization.

LIDTs of the samples for normal incidence and 51.2° with TE mode were summarized in Fig. 2. As can be seen from the figure, LIDT is much higher when laser is normal incident than that when the laser is incident at 51.2° with TE mode. Same experiment was repeated and got the same result.

Table 1. The Parameters of Deposition

Base Vacuum (Pa)	Temperature (°C)	Baking (h)	Gas	O$_2$ Pressure (Pa)	HfO$_2$ (mA)	SiO$_2$ (mA)
2.6×10^{-3}	300	3	O$_2$	8×10^{-3}	110	50

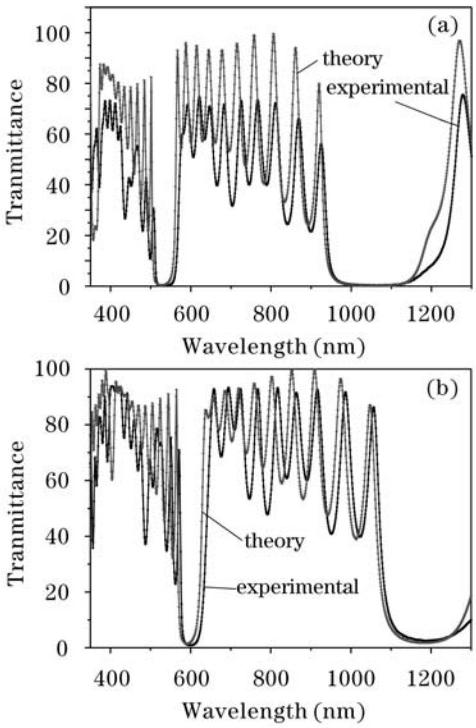

Fig. 1. The optical characteristics of H3L (H2L)ˆ9H0.5L 2.03H. (a) For 1053 nm at Littrow angle (51.2°) with TE mode; (b) for 413.1 nm with 17.8° and TE mode.

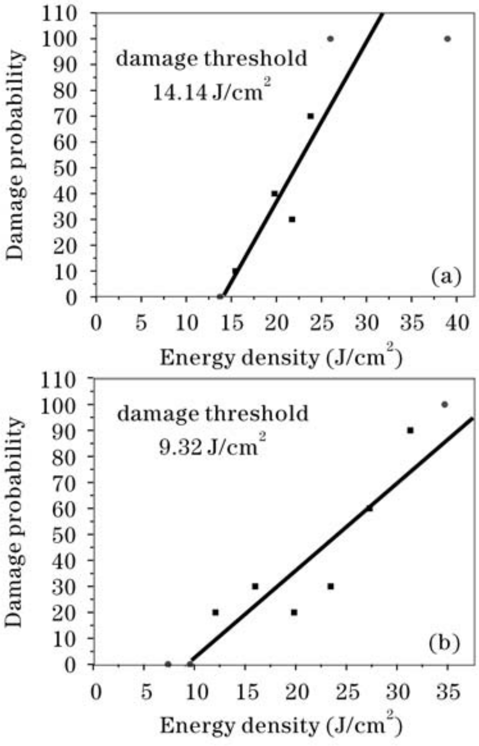

Fig. 2. Laser induced damage probability fitting. (a) For normal incident; (b) for 51.2° incident with TE mode.

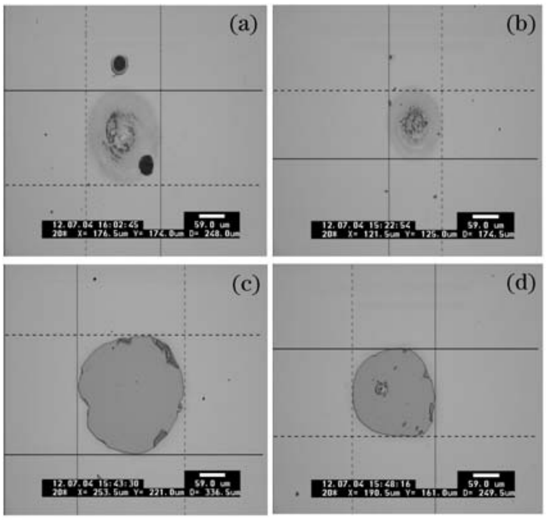

Fig. 3. Damage morphologies of the samples. (a) and (b) are of the normal incident case; while (c) and (d) for 51.2° with TE mode.

The typical damage morphologies were shown in Fig. 3. Here (a) and (b) were taken when laser is normal incident, while (c) and (d) were taken when laser is incident with 51.2° and TE mode. The incident energy densities corresponding to the damage morphologies from (a) to (d) are 21.5, 16.8, 17.5, and 12.5 J/cm^2.

From damage morphologies, one can conclude that damage behavior was defect-initiated for both samples. When in normal incident condition, the damage morphology is plat-bottom-pit with an inclusion in it, and there is plasma scalds around an inclusion. The damage is caused mainly by multiphoton ionization, Joule heating and collisional (avalanche) ionization. While for 51.2° with TE mode, the damage morphology is much more plat than the normal one and the damage is fusing structure. Joule heating and boiling are the main reason for damage.

Electric field distribution is important to analyze the laser damage mechanism. When the maximal electric field is located at the interface of multi-layer stack and air, it is easy to cause heat at the interface and come into being the laser damage. While the maximal electric field is situated far away from the multi-layer, it contributes to high laser damage threshold. Electric field distribution is given in Fig. 4. Figure 4(a) is for the stack H3L (H2L)ˆ9H0.5L2.03H when laser normal incident at 1064 nm, while Fig. 4(b) is for 1064 nm wavelength at the Littrow angle (51.2°) with TE mode.

As shown in Fig. 4(a), the maximal electric field distribution is far away from the interface of multi-layer and air when laser is normal incident the system. While in Fig. 4(b), the maximal electric field is situated at the interface of multi-layer and air when laser is incident at the Littrow angle (51.2°) with TE mode. Furthermore, maximal electric field is also situated at the interface of high and low refractive index material. The main reason that causes the difference of LIDT between normal and 51.2° incidences with TE mode lies in the different electric distribution at the interface of air and multi-layer stack. The other reason lies in defect, nodule and void that caused by detailed processing parameter.

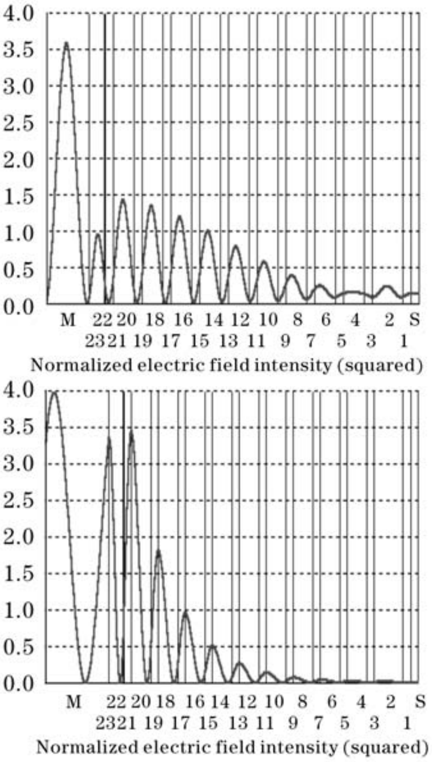

Fig. 4. Electric field distribution when laser is normal incident and 51.2° with TE mode at 1064 nm.

In conclusion, the properties of multi-layer, especially the laser induced damage threshold, determine the character of pulse compressor gratings. LIDT has been investigated on the multi-layer stack used in PCG, which is prepared by e-beam evaporation. LIDT of normal incidence and 51.2° incidence with TE mode are 14.14 and 9.31 J/cm^2, respectively. From damage morphologies, it can be seen that the former is pit-concave-plat structure, while the latter is plat structure. Electric field distribution leads to the difference in the two cases.

This work was supported by the National Natural Science Foundation of China (No. 10376040) and the National "863" Project of China (No. 863-804). The authors thank Professor Ruiying Fan for the suggestion of designing the multi-layer stack. The fruitful discussion with Professor Lifeng Li was appreciated. W. Kong's e-mail address is kwjsd@163.com.

References

1. C. D. Li, Z. Q. Zhang, and Z. Z. Xu, Acta Opt. Sin. (in Chinese) **16,** 1077 (1996).
2. J. J. Yang, Y. L. Sun, S. C. Ruan, S. C. Wang, S. Feng, and X. Hou, Acta Opt. Sin. (in Chinese) **18,** 457 (1998).
3. C. P. Hauri, P. Squire, G. Arisholm, J. Biegert, and U. Keller, Opt. Lett. **29,** 1369 (2004).
4. M. D. Perry, R. D. Boyd, J. A. Britten, D. Decker, and B. W. Shore, Opt. Lett. **20,** 940 (1995).
5. L. Li and J. Hirsh, Opt. Lett. **20,** 1349 (1995).
6. J. A. Britten, M. D. Perry, B. W. Shore, R. D. Boyd, G. E. Loomis, and R. Chow, Proc. SPIE **2714,** 511 (1996).
7. B. W. Shore, M. D. Perry, J. A. Britten, R. D. Boyd, M. D. Feit, H. T. Nguyen, R. Chow, G. E. Loomis, and L. Li, J. Opt. Soc. Am. A **14,** 1124 (1997).
8. K. Hehl, J. Bischoff, U. Mohaupt, M. Palme, B. Schnabel, L. Wente, R. Bödefeld, W. Theobald, E. Welsch, R. Sanerbrey, and H. Heyer, Appl. Opt. **38,** 6257 (1999).
9. J. D. T. Kruschwitz and W. T. Pawlewicz, Appl. Opt. **36,** 2157 (1997).
10. J. M. Yuan, Z. S. Tang, H. J. Qi, J. D. Shao, and Z. X. Fan, Acta Opt. Sin. **23,** 984 (2003).
11. ISO 11254-2: Lasers and Laser-Related Equipment — Determination of Laser-Induced Damage Threshold of Optical Surfaces — Part 1: s-on-1 Test (1995).
12. "Laser-induced damage threshold and certification procedure for optical materials" (NASA Reference Publication 1395, Langley Research Center · Hampton, Virginia, 1997).