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Laser-induced damage of multilayer dielectric gratings with picosecond laser pulses under vacuum and air

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ABSTRACT

In this study, laser damage tests of multilayer dielectric gratings (MDGs) are performed in vacuum (5×10^{-4} Pa) and in air at a wavelength of 1053 nm with pulse widths of 0.56 ps ~9.7 ps. The laser-induced damage threshold (LIDT) of MDGs in vacuum/air ranges from 2.1/2.2 J/cm^2 to 4.4/4.8 J/cm^2 for laser beams of normal incidence. The LIDT of MDGs follows a $\tau^{0.26}$ scaling in the pulse width regime considered. The typical damage morphologies in the two environments caused by the near threshold pulse were observed using a scanning electron microscope (SEM); the results indicate that the damage features of MDGs in vacuum are the same as those in air. The testing results reveal that a clean vacuum environment neither changes the laser damage mechanism nor lowers the LIDT of MDGs.

1. Introduction

Chirped-pulse amplification (CPA) is a popular technique for developing Petawatt-class laser systems throughout the world [1]. A Petawatt-class laser system has a pulse energy that is greater than 1 kJ and a pulse duration in the 1–10 picosecond time regime [2]. The diffraction gratings, as the critical elements in the compressors of a CPA system, must meet the requirements of high diffraction efficiency and high LIDT. With the development of pulse compression gratings, gold-coated gratings have been gradually replaced by MDGs because of the problem of the inherent absorption loss of metals [3,4]. The so-called MDG is composed of a multilayer dielectric mirror and a grating structure. Generally, the -1st order diffraction efficiency of a MDG can exceed 96% [3]. The typical LIDT of a MDG is in the range of 1 J/cm^2 for a beam at normal incidence for pulse durations in the range of picoseconds down to a few tenths of femtoseconds at many laser wavelengths [5,6].

In CPA systems, the pulse compression gratings, as with other optics, must be used in a vacuum environment to avoid laser breakdown in air. Numerous research studies on laser-induced damage of high-reflection mirrors in a vacuum environment have concluded that the contamination in vacuum is easily attracted to the optical surfaces because of the low pressure; such contamination becomes the source of laser-induced damage of these mirrors [7–9]. Therefore, the vacuum environment will reduce the laser damage resistance of the optics. However, a comparative study on the laser-induced damage of a MDG in vacuum and in air is lacking.

In this study, the LIDT of a MDG in vacuum or air is measured for a laser at a wavelength of 1053 nm and with a pulse width in the range of 0.56 ps ~9.7 ps. Next, the damage morphologies of the damaged sites (near threshold) in the two environments are observed in detail using SEM. Finally, in combination with the near electric-field distribution (NEFI), the measured results are discussed.

2. Sample preparation

The MDG used for 1053-nm picosecond pulse compression was designed to have a line density of 1740 lines/mm on a dielectric

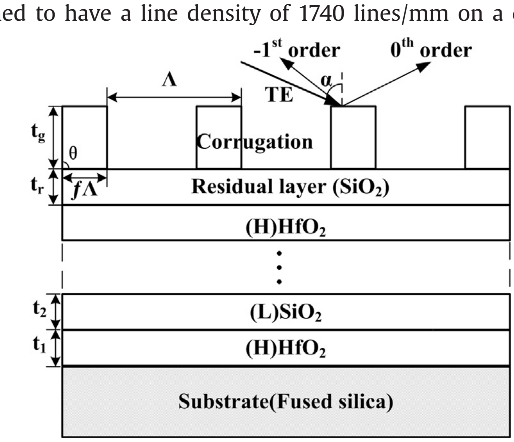

Fig. 1. Schematic diagram of the MDG.

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high-reflectivity (HR) mirror. The HR mirror is composed of alternating SiO_2/HfO_2 layers. A schematic diagram of the MDG is shown in Fig. 1, where {t_1, t_2, t_r, t_g, f, Λ, and θ} represent {H layer thickness, L layer thickness, residual layer thickness, groove depth, fill factor, period, and base angle of a grating pillar}, respectively. The alternating HfO_2 and SiO_2 layers are deposited onto a fused silica substrate (50 mm × 50 mm) via electron beam evaporation. The grating structures are fabricated by ion-beam etching of the top layer (SiO_2 layer) of a HR mirror. The cross-sectional profile of the MDG was observed using a SEM (model:Carl Zeiss Auriga), as shown in Fig. 2. The structure of each grating pillar is trapezoidal in shape, and no visible etching residue is attached to the pillar and the groove bottom. The -1st order diffraction efficiency of well-cleaned samples is greater than 96% at an incident angle of 70 degrees for laser light at a wavelength of 1053 nm with TE polarization [10]. The parameters of the grating structure combined with the film thickness are measured for accurate inversion calculation of the -1st order diffraction efficiency, bandwidth and NEFI of the MDG using our software developed in the framework of the Fourier mode method [11]. The calculated -1st order diffraction efficiency spectrum of the MDG at the Littrow angle is consistent with the measured result, as shown in Fig. 3.

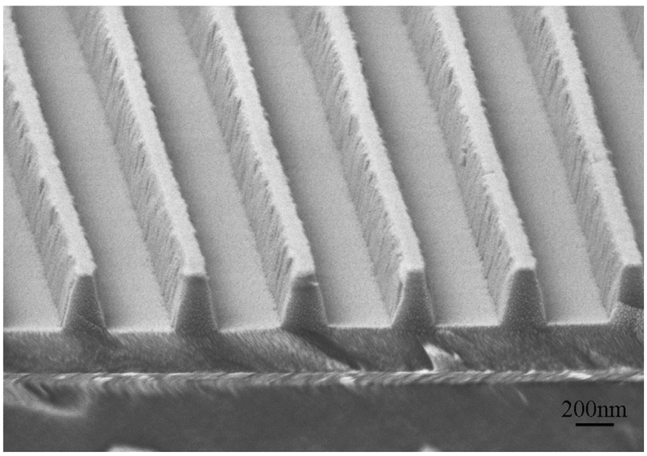

Fig. 2. SEM image of the cross-sectional profile of the MDG under observation. The grating is etched into the SiO_2 top layer with a trapezoidal shape. The line density is equal to 1740 l/mm.

3. Damage test

3.1. Test setup

A schematic of the laser damage test setup is shown in Fig. 4, including the optical system and the vacuum system. Fig. 4a shows a 1053-nm CPA Ti:sapphire laser system that produces a near-Gaussian spatial profile compressed P-polarized pulse with up to 50 mJ of energy. The pulse duration of the laser system can be continuously varied in the range of 0.5 ps to 60 ps. The repetition frequency of the system is 1 Hz. The first half-wave plate (λ/2) combined with a polarizer (P) is used to adjust the incident laser energy, and the second half-wave plate (λ/2) is used to vary the pulse polarization

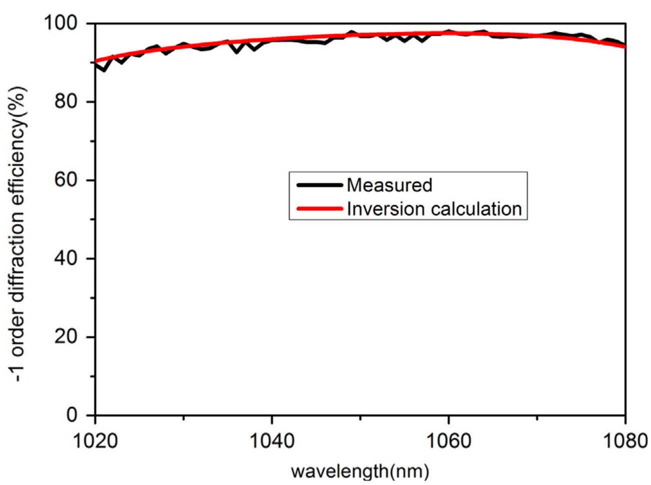

Fig. 3. The measured and calculated -1st order diffraction efficiency spectra of the MDG at the Littrow angle.

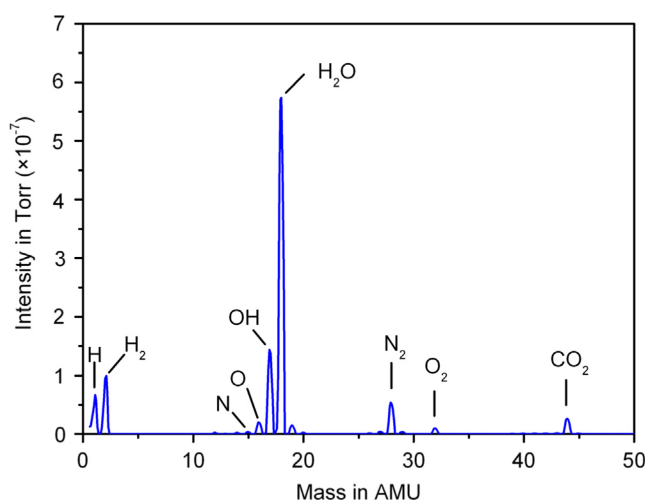

Fig. 5. The residual gas composition in the vacuum chamber (5 × 10^{-4} Pa).

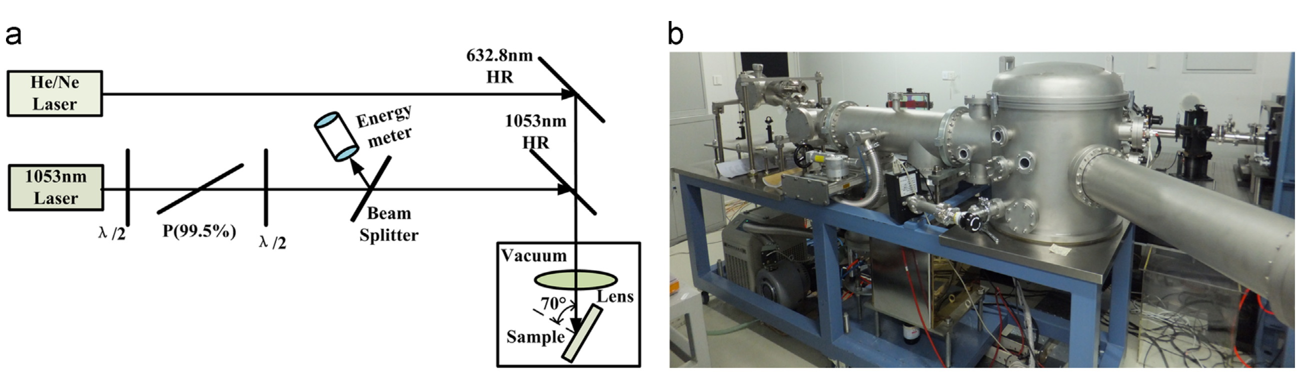

Fig. 4. Schematic of the laser damage test setup