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Laser-induced damage properties of subwavelength antireflective grating on fused silica

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ABSTRACT

We describe the design, fabrication and performance of an optimized one-dimensional subwavelength grating for use in 1064 nm wavelength laser systems. The laser-induced damage threshold (LIDT) under the irradiation of 12 ns 1064 nm pulses on the grating was performed, and a higher LIDT was obtained compared with LIDT of traditional antireflective coatings. Laser irradiation produces some morphological modifications on grating. Light interferometric surface profiler, scanning electron microscope and atomic force microscope were used to study these modifications, and these studies indicate the significant ablation and resolidification have occurred. To understand possible damage mechanisms, the role of electric field distribution inside the grating during the laser radiation process was investigated by a three-dimensional finite difference time-domain method, and the simulation result indicates the temperature distribution resulting from the internal electric field may be the main factor behind the damage.

1. Introduction

The power output and operational lifetime of high power lasers depend critically on eliminating reflection and enhancing laser induced damage threshold (LIDT) from the surface of their numerous optical components [1]. Multilayer antireflective (AR) coating is the conventional way to reduce reflections from optical surfaces, but layer interfaces generate thermal gradients and rapid damage near coating defects that result in relatively low LIDT. Subwavelength surface-relief grating structures present an alternative way to reduce reflections [2] in the visible and infrared regions [3–9]. Due to wide band-gap materials possessing the intrinsic damage property and high resistance to laser induced breakdown, the subwavelength AR grating directly etched in bulk transparent material is expected to be applied in high-power laser systems as an advanced laser-transmitting optical element [10]. In the past few years, subwavelength grating has been well-studied and applied to the optical components in high-power laser systems for their AR properties [4,11–13] and high LIDT [14]. High-efficiency transmission grating has been produced by several groups. A grating efficiency approaching 95% for 1060 nm light [15] and a grating efficiency of 87.1% for 1550 nm [16] in fused silica have been reported. However, no one has presented the design and fabrication of the fused-silica AR grating for use in 1064 nm wavelength laser systems. In this paper we describe the design, fabrication and performance of fused-silica transmission grating that achieve more than 98% efficiency at 1064 nm wavelength. As grating is devoted to reducing the reflection in the laser system, so, it is important to investigate the laser damage characteristic of the AR grating. However, even though lots of work being done on the manufacturing of various gratings [17] and in determination of the damage threshold [18], the damage morphology and mechanism inside the periodic structure have not been investigated before, which is essential to understand the damage process.

In this paper, a one-dimensional (1D) subwavelength rectangular grating is designed by the effective medium theory (EMT) method and directly fabricated on fused silica substrate by the method of holographic laser exposure followed by an ion beam milling pattern transfer [19]. We also present results from simulating the rectangular grating with measured parameters qualitatively confirming our experimental observations. The purpose of the present work is to give insight into the effect of local electric fields (E-field) upon the laser-induced damage within the 1064 nm grating. The peak E-field amplitudes in the grating and blank substrate under the irradiation of 1064 nm pulse laser are compared using a finite-difference time-domain (FDTD) method, which is confirmed by LIDT testing. The E-field distribution and morphological modifications on grating during the laser radiation process are also discussed to reveal the possible damage mechanism.

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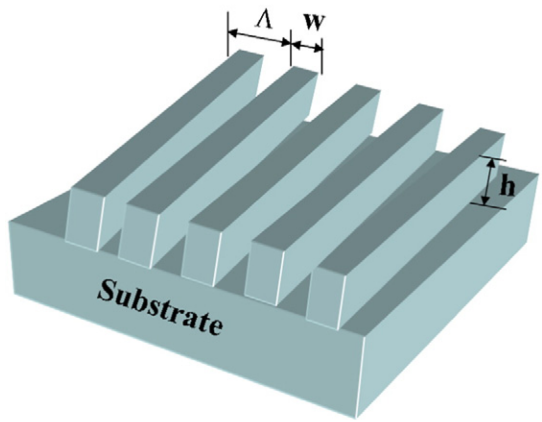

Fig. 1. Scheme of 1D grating structures.

1.1. Design

A schematic diagram of 1D rectangular surface-relief grating is shown in Fig. 1. Λ is the period of the grating, w and h are the width and the height of the grating ridge, respectively. The grating is designed by the EMT method [13].

The simple rectangular profile in fact corresponds to a single quarter-wave layer with an effective index n_{eff} depending on the fill factor f (w/Λ).

Based on the EMT method, neff can be calculated by [20]:

$$n_{eff} = \left[n_c{}^2 f + n_{air}{}^2 (1-f)\right]^{1/2} \quad (1)$$

where n_c and n_{air} are the refractive index of the fused silica ($n_c = 1.46$) and air ($n_{air} = 1$), respectively. Therefore, n_{eff} and f are calculated to be 1.208 and 0.41. To facilitate fabrication, the feature size of grating should be as large as possible, so f is chosen to be 0.5. On the other hand, the height of grating should be kept as small as possible, while the optimum height ($\lambda/4n_c = 182$ nm) at 1064 nm wavelength is a little too large to be fabricated. In order to obtain the high transmittance with smaller height of grating, we have analyzed the relationship between the transmittance (T%) and the height (h) and the period (Λ) of the grating ridge when f is 0.5, which is shown in Fig. 2. We define the transmittance (T%) as $(T_{TM} + T_{TE}) / 2$, in which T_{TM} and T_{TE} are the transmission efficiencies for TM (transverse magnetic) and TE (transverse electric) polarized light, respectively.

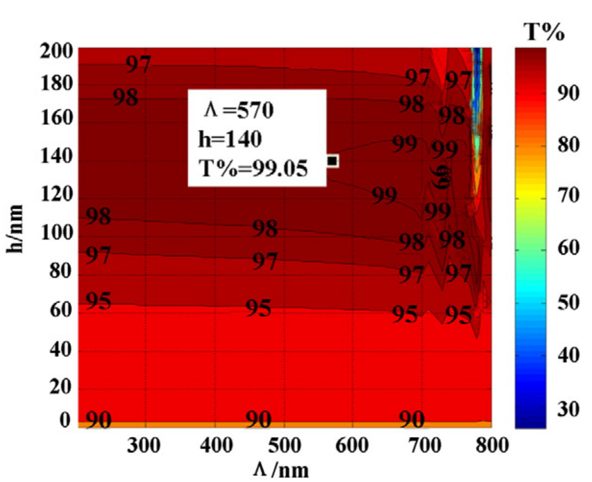

Fig. 2. The transmittance (T%) as a function of groove height (h) and period (Λ) for a rectangular profile with f of 0.5.

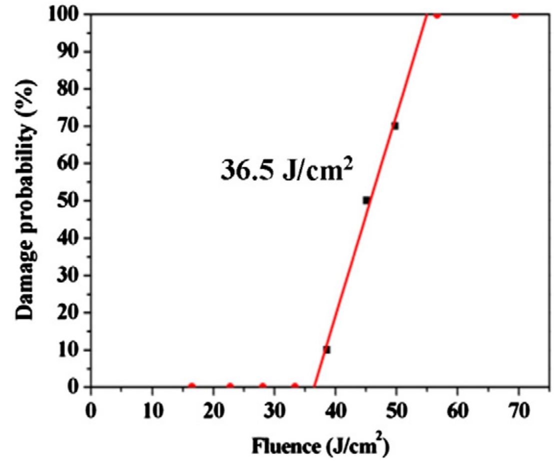

Fig. 3. A linear fit for the LIDT result.

According to Fig. 2, when the groove height is in the range between 120 nm and 150 nm, and the period is in the range between 570 nm and 750 nm, the transmittance can be close to 99.05% at 1064 nm wavelength. The smallest height and largest period of grating are limited to 120 nm and 750 nm, respectively.

1.2. Fabrication and measurement

Three bare fused silica of 3 mm-thick with a size of 30 × 30 mm^2 are cleaned prior to the grating fabrication by acetone and ethanol under sonication, which was followed by rinsing with deionized water to remove any surface contaminants. The grating is fabricated by the holographic laser exposure followed by an ion beam milling pattern transfer that involves the following steps [21]: coating the substrates with controlled thickness of photoresist (RZJ-390), formation of a grating mask by holograph interference exposure and development, transferring it into the substrate to form a permanent grating by reactive ion beam etching (RIBE). The schematic diagram of the fabricating phase mask is shown in Fig. 2 of Reference [22]. On the basis of above design, photoresist grating mask with the 650 nm period is fabricated on the fused silica substrate by conventional holographic exposure and development. The mask fill factor is 0.5 and its depth is 300 nm. Holographic lithography is employed for grating pattern generation where a Kr^+ laser emitting at 413.1 nm is used as light source. Then the photoresist is developed ~~by~~ using a standard developer (tetramethylammonium hydroxide). The photoresist mask is etched by RIBE with CHF_3 for transferring the developed pattern onto the fused silica substrate. The etching process ensures a precise etching on

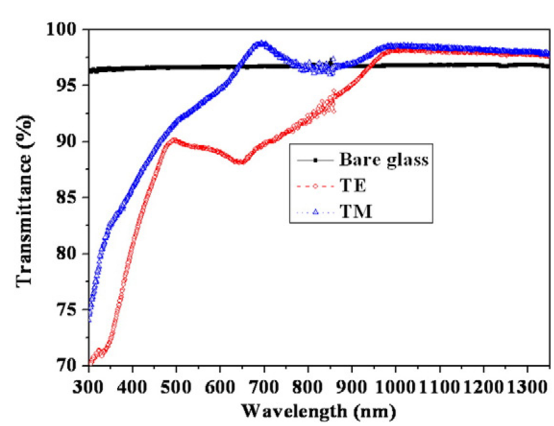

Fig. 4. Measured TE and TM polarization transmittance as a function of the wavelength.