Fabrication of large mosaic gratings by locking the exposure fringes to the latent gratings

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Large-size diffraction gratings are key components for pulse compression in chirped-pulse-amplified high-power laser systems. We present a method to make optical mosaic grating in a multilayer dielectric (MLD) stack. Based on the use of the latent gratings, we combine exposure, phase locking, and adjustment of substrate into one exposure system, making it compact and the drift error decreased. To get high diffraction efficiency, the grating in a resist layer is then transferred into the top layer of the MLD stack by ion-beam etching. The peak-valley (PV) and root-mean-square (RMS) values of a mosaic grating with a size of (40+40)×70 mm^2 are 0.101 λ and 0.019 λ, respectively. The diffraction efficiency of the mosaic grating is 95.4% with a nonuniformity of 0.6%.

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1. Introduction

Large-aperture diffraction gratings are key optical components in contemporary chirped-pulse-amplified (CPA) high-power laser system. To make large gratings, extremely high quality laser beams with very large apertures are needed, which becomes a bottleneck problem. To solve this problem, two kinds of methods are developed. One is the scanning beam interference lithography (SBIL) technique developed at MIT[1], which is very complex incorporating many high accuracy control techniques. The other is the optical mosaic technique. Turukhano et al. reported the relative technique in 1996[2]. They called it as phase synthesis technique and used it to make grating scales. Three years ago, our group developed an optical mosaic method based on the latent grating[3] rather than the reference grating as in [2]. (Holographic exposure of a photoresist film creates a weak volume grating whose diffraction efficiency is very weak, typically of the order of 10^{-5}, hence the term latent grating). Subsequently, the technique is improved to make the system more stable and with higher success rate. Here we present the procedure of making mosaic gratings, including exposure and ion-beam etching. The experimental results are given in the following sections.

2. Exposure system and ion-beam etching

The optical mosaic means that after one area of substrate is exposed, another area is moved into the beams for next exposure. The key technique is to adjust the attitude and position of the substrate precisely between consecutive exposures, and to lock them during each exposure. The aim is to ensure between different areas, the grating groove parallel, the grating periods same, and the gap equal to an integer multiple of the grating period.

Making a mosaic resist grating includes following steps: 1) exposing one area of substrate to generate a latent grating with extremely low diffraction efficiency of ~10^{-5}; 2) recording the attitude and position of substrate by using the interference fringes generated from the latent grating; 3) moving the substrate to another area for next exposure, and adjusting the attitude and position of substrate relative to the exposure fringe pattern (interference fringes of the exposure beams) before next exposure; 4) locking the phase and tilt angle of the exposure beams, and then expose next area of the substrate. For these procedures, the exposure system needs three functions: exposure, phase locking, and adjusting the attitude and position of the substrate relative to the exposure beams. The two latter functions are performed by using the latent gratings.

Figure 1 shows the exposure system. The light source is a vertically (parallel to the y axis) polarized 413.1 nm Kr^+ ion laser. Passing spatial filters SF_1 and SF_2, and apertures D_1 and D_2, the laser beams I_1 and I_2 are collimated by lenses L_1 and L_2. Then the exposure fringe pattern from I_1 and I_2 symmetrically is projected onto the substrate G that is mounted on a translation stage to perform the exposure function. After an exposure, the latent grating is formed in photoresist. Next, the specially designed wedged attenuators A_1 and A_2 with transmittivities of ~10^{-2} and 10^{-6} are inserted into I_1 and I_2, respectively. The interference fringes are formed by the −1st- and 0th-order diffractions of the attenuated and tilted exposure beams from the latent grating, and named as the latent interference fringes, which are used to describe the position and attitude of the substrate. The latent interference fringes are taken by a high-sensitivity Electron-Multiplying CCD (EMCCD). The edges B_{A1}, B_{D1}, B_{A2}, and B_{D2} are used to block the stray light to entrance EMCCD and unwanted exposure. Then, the substrate is moved to another position for next exposure. Before next exposure, the position and attitude of substrate relative to the exposure fringes should be adjusted. The variations in attitude and position of substrate result in the varying in width and phase of the latent interference fringes, respectively. By comparing the real-time latent interference fringes with that recorded in previous step, we can adjust either the attitude and position of substrate or the tilt angle and phase of exposure beams to make the real-time top and bottom latent interference fringes aligned with the recorded ones, respectively (Fig. 1). Because the substrate is too heavy, we adjust the tilt angle of one exposure beam by driving the spatial filter SF_2 vertically via piezoelectric transducer PZT_a and the phase of another exposure beam by driving the reflector M along its normal via PZT_p. After adjustment the substrate is exposed, meanwhile, the tilt angle and phase of exposure beams are locked using the latent grating during the exposure.

The resist mosaic grating is made on the MLD stack coated by a chromium layer on top to avoid the stray light from the rear surface of the substrate to affect the detection of the latent interference fringes. The resist grating should be transferred into the dielectric top layer by ion-beam etching. Firstly, we use the resist grating as mask to etch the chromium layer by Ar^+ ion-beam etching; next, use the chromium grating as mask to etch SiO_2 of the top layer of the MLD stack by CHF_3 reactive ion-beam etching. The in situ endpoint judgment is used during this process.

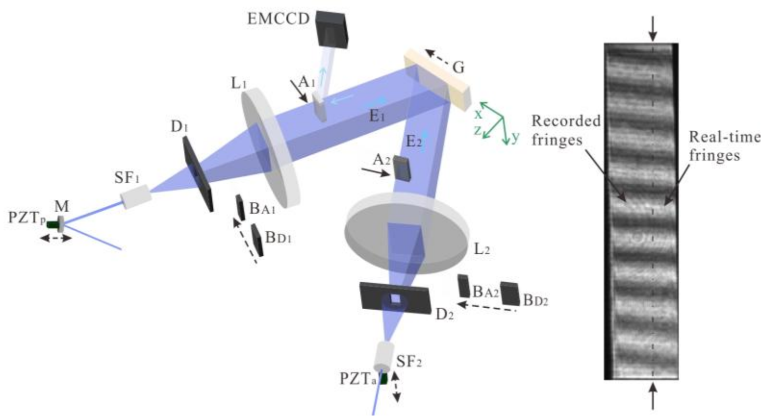

Fig. 1 Exposure system

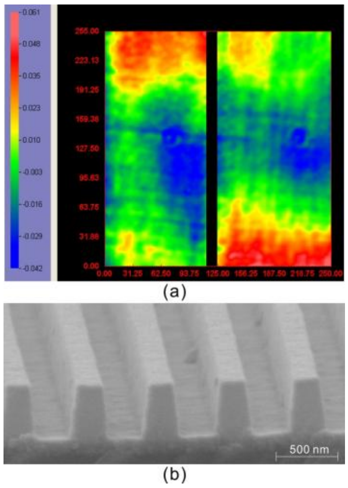

Fig. 2 Etching results. (a) wavefront from a mosaic MLD grating, (b) SEM image of a sample MLD grating.

3. Results

Using the procedure introduced above, we made an optical mosaic MLD grating with a size of (40+40)$\times$70 mm^2 on the fused silica substrate with a size of 110$\times$80$\times$17 mm^3. In exposure process, the MLD stack was coated by a chromium layer with the thickness of 80 nm, and then the mosaic resist grating with a height of ~300 nm and a period of 0.57 μm was made on it. The single exposure time is 220 seconds with the exposure intensity of ~24 lx. The electron-multiplying mode of the EMCCD with a max gain of 1000 is even disabled due to the enough diffraction intensity, allowing us to extend this technique to large-aperture exposures with weaker exposure intensity. Figure 2(a) shows the wavefront of the mosaic MLD grating. The PV and RMS errors of the −1st-order diffraction wavefront are 0.101 λ and 0.019 λ, respectively. The main errors come from the nonuniformity in resist coating, and the mosaic errors are hardly perceived. Figure 2(b) shows the groove shape of a sample MLD grating etched by the same process. The duty cycle and the etching depth are 0.42 and 426 nm, respectively. The mean diffraction efficiency of the mosaic grating is 95.4%, and the nonuniformity is 0.6%, verifying that the variation in grating grooves caused by the employment of latent grating can be neglected.

4. Conclusions

We propose and demonstrate a technique to make mosaic gratings on MLD stack. The key point is locking the exposure fringes to the latent grating, reducing the drift errors. Meanwhile, the protection of the latent grating is done well by employing two attenuators and EMCCD. It is possible to extend this technique to fabricate large-aperture gratings.

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