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COST-EFFECTIVE FABRICATION OF A PHASE MASK BY DIRECT ETCHING OF THE LASER-INTERFERENCE GRATING ON FUSED SILICA SUBSTRATE

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ABSTRACT: *A simple and cost-effective method to manufacture a phase mask with high diffraction efficiency for deep UV application is proposed. The deep rectangular grating fabricated by using laser interference is etched directly into a fused silica substrate, instead of the dielectric coating on a substrate (done in a previous method). Using the metal layer on a dielectric layer for masking in the deep, dry etching process is also unnecessary in our technique. A fabricated rectangular grating with high diffraction efficiency is presented in this paper. We also demonstrate the fabrication processes and show the optimum parameters for our proposed technology.* © 2003 Wiley Periodicals, Inc. Microwave Opt Technol Lett 38: 362–365, 2003; Published online in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/mop.11061

Key words: *phase mask; laser-interference grating; fiber grating*

1. INTRODUCTION

Recently, utilization of a phase mask for a deep ultraviolet (DUV) wavelength regime has become important, especially in the manufacturing of active and passive devices for optical communication [1, 2]. The phase mask is widely used to fabricate the periodic structure in laser chips for spectral control, in either distributed-feedback or distributed-Bragg-reflector types for optimum bandwidth [3]. Another important application is to fabricate the fiber Bragg grating as an optical filter and as a sensor for sensing the variation of temperature or strain [4–9]. In recent years, a great deal of research has been devoted to either the theoretical analysis of diffraction efficiency [10, 11] or the phase-mask fabrication technologies [12–16]. Commercialized phase masks for the applications mentioned above have also been available. However, the phase mask for DUV application is expensive and always becomes damaged due to intensive UV exposure.

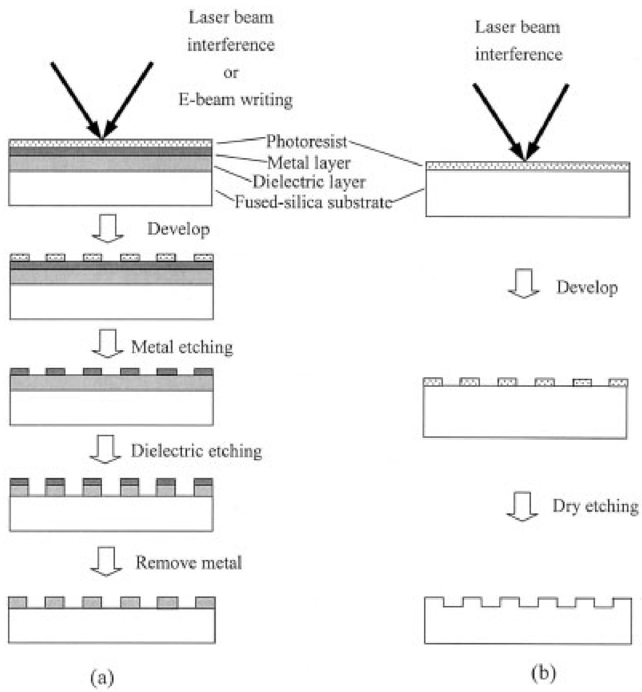

Figure 1 (a) Fabrication process of a phase mask with dielectric and metal coating. (b) Fabrication process of the proposed method

After reviewing previous technologies, we found the methods reported for the fabrication of phase mask with high diffraction efficiency to be complicated. In order to improve diffraction efficiency, it is necessary to coat a dielectric layer on the fused-silica substrate to enhance the etching depth of the grating, or coat the dielectric as the etching stop layer, following the laser beam interference or E-beam inscribing. Moreover, as shown in Figure 1(a), a metal layer such as chrome needs to be deposited on the dielectric layer for masking in the dry etching process. Based on the increasingly low-cost requirements for fabricating the devices in the applications of laser and optical communication, an inexpensive method to manufacture phase masks with high-diffraction-efficiency is required. In this paper, we demonstrate the fabrication of a laser-interference phase mask by etching the grating directly on fused silica substrate without prior dielectric and metal coating. Our method simplifies the process and results in lower costs for the fabrication of phase masks.

2. DESIGN PRINCIPLE OF A GRATING WITH HIGH DIFFRACTION EFFICIENCY

In order to pursue a phase mask with optimized efficiency of ± 1 diffraction order, the scalar or vector diffraction theory can be used to design the grating with a suitable aspect ratio. The aspect ratio is defined by d/Λ, where d is the grating depth and Λ is the grating period, as shown in Figure 2. For the applications in the UV wavelength regime that closes to the period of grating, the rigorous coupled wave theory provides more accurate analysis [17–18]. For a non-absorption grating (Fig. 2), the variation of permittivity for a rectangular corrugation in Fourier series along the x direction is [19]:

$$\varepsilon(x) = \sum_{l=-\infty}^{+\infty} \varepsilon_l \exp\left(i \frac{2\pi l}{\Lambda} x\right), \tag{1}$$

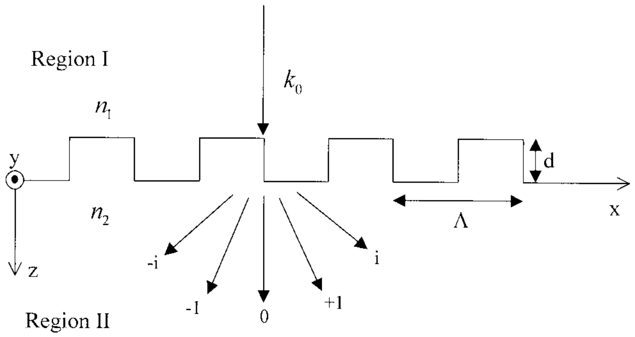

Figure 2 Schematic diagram of a rectangular grating with an incident TE wave

where ε_l is the l^{th} Fourier component and Λ is the grating period. For a rectangular grating with fill factor of 1/2, we have

$$\varepsilon_0(x) = (1/2)(n_I^2 + n_{II}^2),$$

$$\varepsilon_{l\neq 0}(x) = \frac{1}{\pi l}\,(n_I^2 - n_{II}^2)\cdot\left(\sin\left(\frac{\pi l}{2}\right)\right). \tag{2}$$

In up-to-date technology for the fabrication of a Bragg grating, the double-frequencied argon-ion laser is used as the light source associated with a phase mask rather than the excimer laser, because the former provides a well-polarized beam for the application. For a normal incident TE wave upon a grating, the electric field is expressed as

$$E_{inc,y} = \exp(-jk_I z), \tag{3}$$

where $k_I = k_0 n_I = 2n_I\pi/\lambda_0$, with the incident wavelength in free space. Therefore, the normalized total electric fields in region I ($z < 0$), and region II ($z > d$) are given by

$$E_I = E_{inc,y} + \sum_i R_i \exp\{-j[k_{xi}x - k_{I,zi}z]\}, \tag{4}$$

$$E_{II} = \sum_i T_i \exp\{-j[k_{xi}x - k_{II,zi}(z-d)]\}, \tag{5}$$

where R_i and T_i are the normalized electric-field amplitudes of the i^{th} backward and forward diffracted wave in regions I and II, respectively. In Eqs. (4) and (5), k_I and k_{II} are the wave vectors of the fields in regions I and II. The parameter k_{xi} is determined from the Floquet condition [20] and is given by

$$k_{xi} = -i(\lambda_0/\Lambda), \tag{6}$$

and

$$k_{L,zi} = \begin{cases} +k_0[n_L^2 - (k_{xi}/k_0)^2]^{1/2} & k_0 n_L > k_{xi} \\ -jk_0[(k_{xi}/k_0) - n_L^2]^{1/2} & k_0 n_L < k_{xi} \end{cases}, \tag{7}$$

where $L = \text{I, II}$. The magnetic fields in regions I and II are then obtained from Maxwell's equations, given by

$$H = \left(\frac{j}{\omega\mu}\right)\nabla \times E, \tag{8}$$

where μ is the permeability of the region and ω is the angular frequency. In the grating region ($0 < z < d$), the electric (y-component) and magnetic (x-component) fields can be expressed as

$$E_{gr,y} = \sum_i S_{yi}(z)\exp(-jk_{xi}x), \tag{9}$$

$$H_{gr,x} = -j\left(\frac{\varepsilon_0}{\mu_0}\right)^{1/2} \sum_i U_{xi}(z)\exp(-jk_{xi}x), \tag{10}$$

where ε_0 is the permittivity of free space, and $U_{xi}(z)$ and $S_{yi}(z)$ are the normalized amplitudes of the i^{th} space-harmonic fields. In the grating region, the electric and magnetic fields also satisfy Maxwell's equations, leading to

$$\frac{\partial E_{gr,y}}{\partial z} = j\omega\mu_0 H_{gr,x}, \tag{11}$$

$$\frac{\partial H_{gr,x}}{\partial z} = j\omega\varepsilon_0\varepsilon(x)\,E_{gr,y} + \frac{\partial H_{gr,z}}{\partial x}. \tag{12}$$

Consequently, substituting both (9) and (10) into (11) and (12) yields the following coupled-wave equations:

$$\frac{\partial S_{yi}}{\partial z} = k_0 U_{xi}, \tag{13}$$

$$\frac{\partial U_{xi}}{\partial z} = \left(\frac{k_{xi}^2}{k_0}\right)S_{yi} - k_0 \sum_{p\neq i} \varepsilon_{(i-p)} S_{yp}. \tag{14}$$

By calculating the coupled-wave equations based on the matrix algorithm [18], the diffraction efficiency of the $\pm i^{\text{th}}$ order is expressed as

$$\eta_i = T_i T_i^* \operatorname{Re}\left(\frac{k_{II,zi}}{k_0 n_I}\right). \tag{15}$$

Therefore, for an incident TE wave @ 244 nm, the simulated diffraction efficiency of a ± 1-order beam from a rectangular fused-silica (index = 1.5085) grating based on the coupled-wave

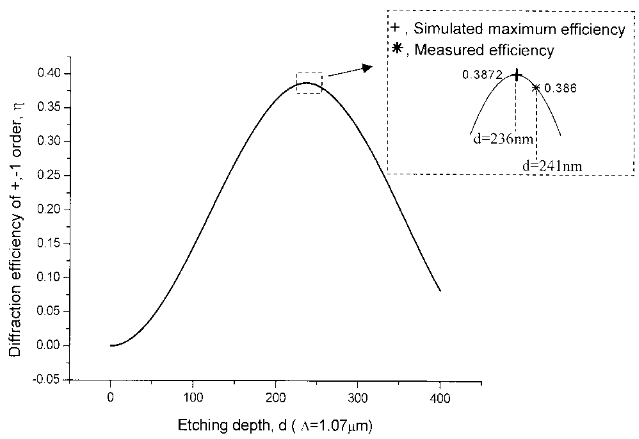

Figure 3 Simulated diffraction efficiency of ± 1 order vs. the etching depths of a rectangular grating. The asterisk and the plus sign represent the measured and the simulated maximum values, respectively

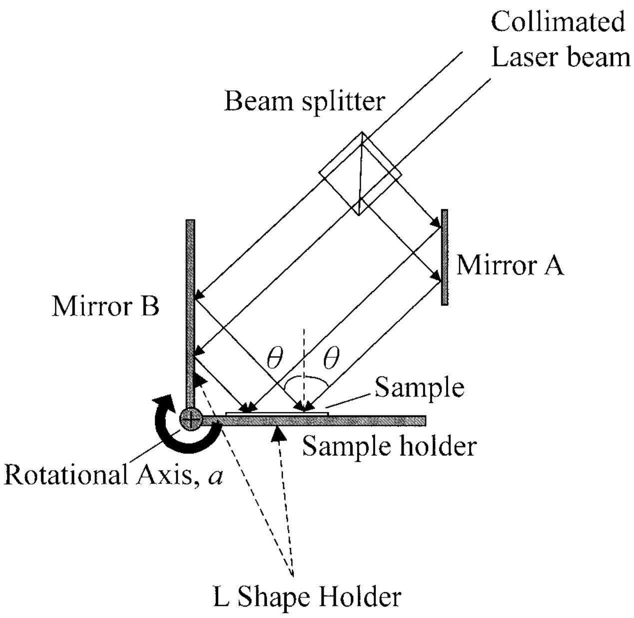

Figure 4 Tunable laser-beam-interference setup for fabricating the interference grating

calculation are shown as Figure 3. To obtain the maximum efficiency of ±1 diffraction order to fabricate the Bragg reflector for selecting wavelength at 1550 nm, the optimized depth of a rectangular fused-silica grating is 236 nm while the grating period is 1.07 μm.

3. EXPERIMENT

The setup for the fabrication of the phase mask directly on the surface of fused-silica substrate is shown in Figure 4. The period of the grating fabricated can be adjusted flexibly with a resolution of about 1 nm by turning the L-shaped holder around the axis a. The grating period is determined by

$$\Lambda = \frac{\lambda}{2 \sin \theta}, \qquad (16)$$

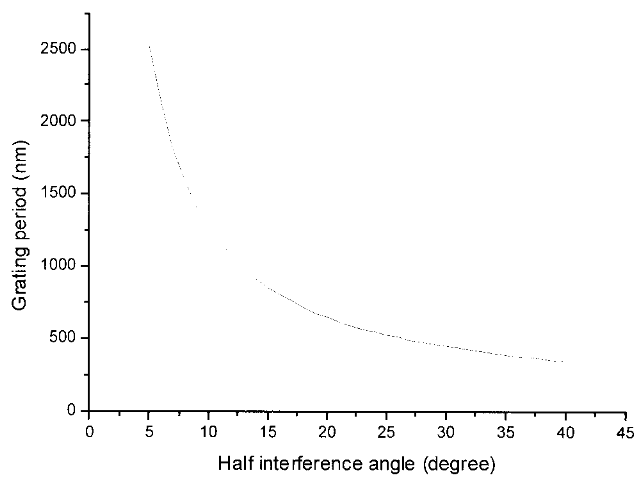

Figure 5 Simulation of the grating period Λ vs. the half interference angle θ according to the optical setup shown in Fig. 4

TABLE 1 Process Parameters for the Fabrication of the Proposed Phase Mask

Items	Parameters
Photoresist layer	0.4-μm thick Shipley S1805 Spin-coated with 4000 rpm for 25 sec
Coating condition	3500 rpm for 25 sec
Soft bake	90°C for 90 sec
Laser	He-Cd @ 442 nm from Kimmon Co.
Laser power on photoresist	228 mJ/cm^2
Development	Shipley MF-319 for 10 sec
Hard bake	100°C for 90 sec
Dry etching	Etcher: ICP RIE
	Process power
	RF power: 75 Watt
	BIOS: 50 Watt
	DC power: 200 V
	Process recipes:
	Ar^{+3}: 20 sccm
	CHF_3: 20 sccm
	Etching time: 30 min

where λ is the wavelength of the laser beam and θ is the half interference angle. Figure 5 shows the grating period versus the half interference angle at $\lambda = 442$ nm. By adopting the positive sign of the differential of Eq. (16), the grating period is changed with the following resolution:

$$\Delta\Lambda = \frac{1}{2} \lambda \frac{\cos \theta}{\sin^2\theta} \Delta\theta, \qquad (17)$$

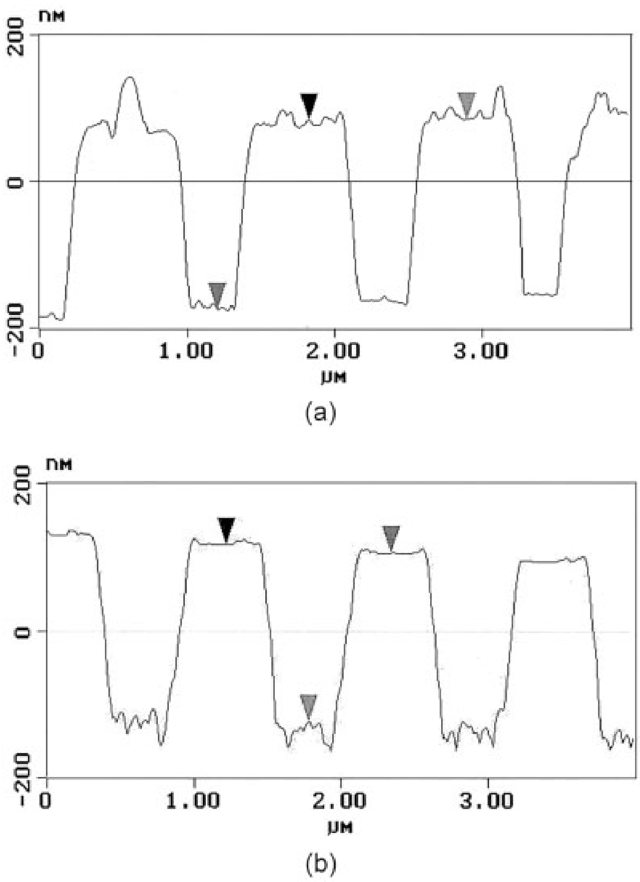

Figure 6 Surface profile of the grating (a) on the MgF_2 layer of a commercial phase mask; (b) fabricated directly on fused-silica substrate

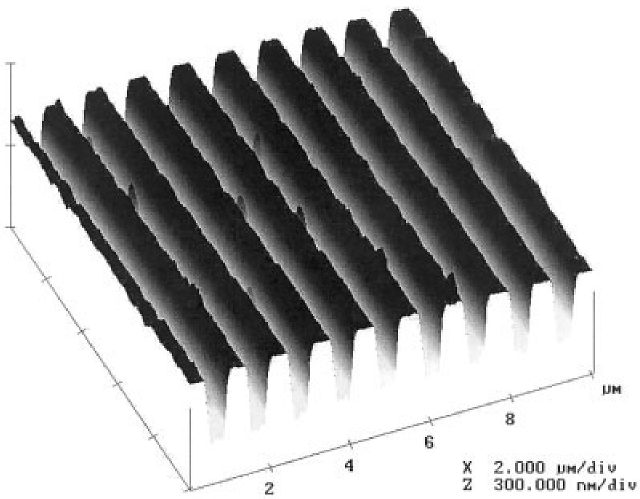

Figure 7 AFM picture of the rectangular grating directly fabricated on fused-silica substrate with a depth of 241 nm

where $\Delta\theta$ is the rotational resolution of rotation stage. According to Eq. (17), various grating periods can be obtained at a resolution better than 1 nm by using a common stage rotated with a resolution of 0.001 radian.

The process of fabricating the grating on a common fused-silica substrate is shown in Figure 1(b). A photoresist model S1805 from the Shipley Company was used to record the interference grating of the He-Cd laser beams. After development, an inductive-coupled plasma (ICP) RIE was used to dry etch the recorded interference grating into the fused silica. By omitting the dielectric and metal layer, or other additional procedures, the rectangle-shaped grating with a high-aspect ratio was obtained by using the process parameters listed in Table 1. Figure 6(a) shows that the profile of the grating fabricated directly on the fused silica is almost the same as that of the commercialized one fabricated on the dielectric (MgF_2 or CaF_2) layer, shown in Figure 6(b). The depth of grating was smaller than that of commercialized one because the index of the fused silica was larger than that of dielectric layer. The AFM graph of the grating is shown in Figure 7. The measured $\pm$1-order diffraction efficiency of 38.6% for our phase mask is shown as the asterisk in the inset of Figure 3. It is close to the maximum value of simulation, and is larger than that (less than 38%) of the commercialized one.

4. CONCLUSION

A simple and successful method for the fabrication of a phase mask with high diffraction efficiency was demonstrated. The parameters for deep etching were optimized in our experiment. The cost of fabrication can be substantially reduced because the coating processes of the dielectric and metal layers are unnecessary. A rectangular grating with sufficient efficiency of $\pm$1 order is suitable to fabricate the DBR laser or fiber Bragg grating with low zero-order noise. Moreover, by using our proposed laser interference setup, the grating with various periods can be fabricated more flexibly and precisely than that made by using E-beam writing.

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