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Phase masks fabricated by interferometric lithography for working in 248 nm wavelength

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Abstract

We demonstrate that phase masks can be generated by using interferometric lithography along with the Taguchi method as an optimization tool for processing phase masks. The optimized fabrication process, allows phase masks of sub-micron period, centimeter long, with the zero-order intensity suppressed down to 8%. For the demonstration of its practicality, one optimized phase mask with 1.08 μm period and 5% zero-order diffraction efficiency is shown capable of fabricating fiber Bragg gratings with 7 dB transmission loss at 1.563 μm wavelength. Furthermore, another 0.44 μm period phase mask is used to produce a photoresist pattern with halved period.

Keywords: Phase masks; Interferometric lithography; Taguchi method

1. Introduction

A phase mask is a diffractive optical element which, when properly designed, can diffract a normally incident beam into $+1$ and -1 diffraction orders with equal intensity while the zero-order intensity is suppressed. It can be then easily proved that the period of the interference pattern produced by these ± 1 order beams is exactly half of the period of the original phase mask. Since the interference pattern is generated by either contact printing or proximity printing, the stringent spatial coherence requirement on a light source is much relaxed, which is especially helpful when the source has an intrinsically short coherent length, e.g., an excimer laser is used. Such phase masks may find applications in many fields, for example, the grating formations for distribution feedback (DFB) lasers and fiber gratings, which are very important active and passive components for optical fiber communication. Additionally they can even be served as test bed for characterizing the printing capability of the photoresists being under development.

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Traditionally, the phase masks are made by employing electron beam writing which offers the unique advantage of very high resolution. However, the above mentioned applications may require large area phase masks, for example, phase masks more than a few inches long and wide in some cases. The e-beam writing then becomes very time consuming, if not impossible. Therefore, we propose to use interferometric lithography (IL) instead of e-beam writing and demonstrate that the phase masks thus fabricated can work for a KrF excimer laser in 248 nm wavelength. As for the optimization of the process parameters, the Taguchi method is applied for time saving.

With the optimized conditions, phase masks of 0.44 μm and 1.08 μm periods with suppressed zero-order efficiencies of 8 and 5%, respectively, are obtained. Their potential usefulness are also demonstrated in two applications.

2. Modeling and experiments

2.1. Modeling of phase masks

Assume a phase mask has the profile of an array of rectangular shapes where the height of each rectangle (or tooth) is d. The relative phase delay caused by the optical path difference as light passes through a phase mask can be expressed as:

$$\phi_d = \frac{2\pi}{\lambda} \cdot d\left(\sqrt{(n^2 - \sin^2 \theta_i)} - \cos \theta_i\right) \tag{1}$$

where n is the refractive index of phase mask material; λ is the wavelength of light; θ_i is the incident angle of light; d is the tooth height.

The simple scalar diffraction theory is used to determine the dependence of diffraction efficiencies of mth order on grating parameters such as duty cycle, tooth height, etc. [1,2]. A commercial software G-solver based on the rigorous coupled-wave theory [3] is used to simulate the effects of proximity printing, etched profiles, wavelength dependence, etc.

2.2. Fabrication of phase masks

A schematic diagram of phase mask fabrication is shown in Fig. 1. We use a chromium layer as "hard mask" for a fused silica substrate. The layer had a thickness of ~30 nm deposited on the substrate by thermal evaporation. The deposition rate shall be as slow as possible (0.01~0.05 nm/s) to have the best effect. The resist used was an I line positive photoresist (EPG510) spun with a thickness of 100 nm, and was then baked at 90 °C for 60 s. The resist had an excellent etching selectivity against the chromium layer. IL was employed for grating pattern generation where an Ar^+ laser working in 351 nm was used as light source. The period of grating pattern Λ can be expressed as:

$$\Lambda = \frac{\lambda}{2\sin\theta} \tag{2}$$

where θ is the incident angle of each beam as for symmetric two-beam interference configuration. The incident angle could be easily varied to have grating patterns of different periods. And the area

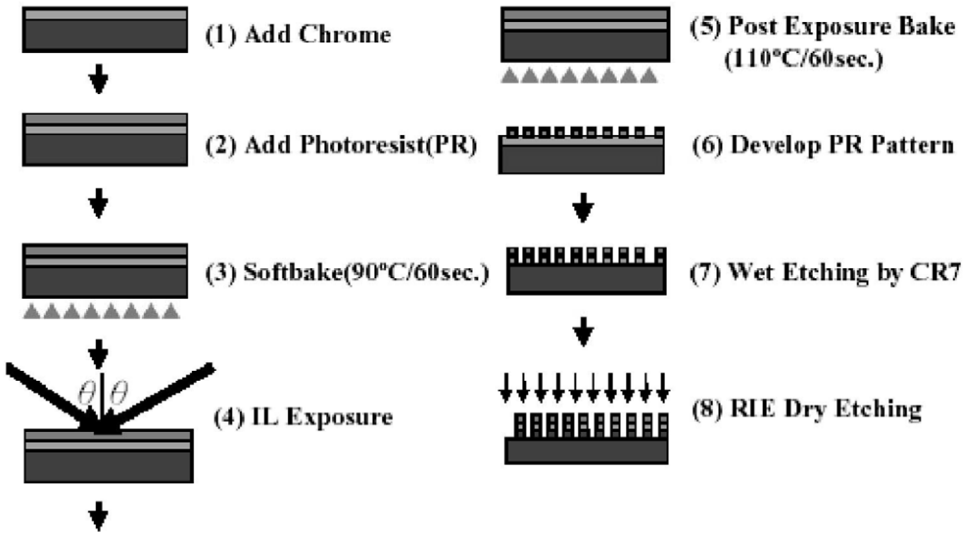


Fig. 1. Schematic diagram showing steps for making a phase mask.

containing such fine periods could be very large basically determined by the exposing beam size and beam's uniformity.

After exposure the sample was then treated with post-exposure-bake (PEB) at 110 °C for 60 s to harden and increase the adhesion of the photoresist, and to reduce the line-edge roughness. The photoresist was developed by using standard developer (tetramethylammonium hydroxide, TMAH, 2.38%) with appropriate development time. After development the chromium layer is selectively removed in the resist open region by using a commercial wet etching solution CR7.

The final pattern on the fused silica was obtained by electron cyclotron resonance (ECR) reactive ion etching (RIE) [4,5] according to the following conditions: 18 sccm of CHF_3, 2.5 sccm of O_2. Under such conditions an etching rate of 72.9 nm/min has been achieved. The process enables a precise etching on the silica with a nearly vertical profiles and controlled etching depth the entire exposure area. A portion of the phase mask is shown in Fig. 2. Phase masks fabrication are completed by the removal of Cr in a CR7 solution. Finally, we used KOH as a rinse agent to flatten the valley's roughness.

3. Results and discussion

3.1. Simulated intensity distribution

Since the duty cycle and the etched depth of a phase mask affect the amount of power diffracted into the first orders, a useful figure of merit is defined as $\eta = P_1/P_0$, where P_1 is the power diffracted into the first order and P_0 is the one into the zero-th order. Based on the tools described previously, the simulated three-dimensional (3D) plot of η versus duty cycle and etched depth is shown as Fig. 3 for wavelength of 248 nm. The results show that to have a large η we must have a duty cycle close to 0.5. There are two peaks, corresponding to two depths. The larger depth belongs to the phase

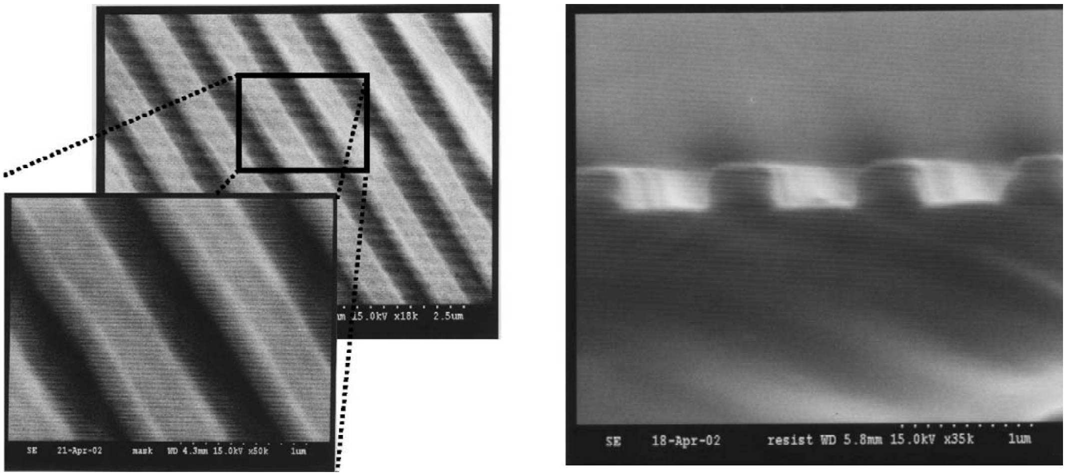


Fig. 2. A phase mask of 1080 nm period made from fused silica.

retardation $\phi_d = 3\pi/2$. For the duty cycle 0.5 and a refractive index 1.509, from Eq. (1), the etched depth shall be close to 243.8 nm to have an infinite η, i.e., no power in zero-order intensity.

3.2. Optimization by Taguchi method

The fabrication of phase masks involves many process parameters, and optimization among the parameters is desirable for time saving; therefore, the Taguchi method was employed. Form the past

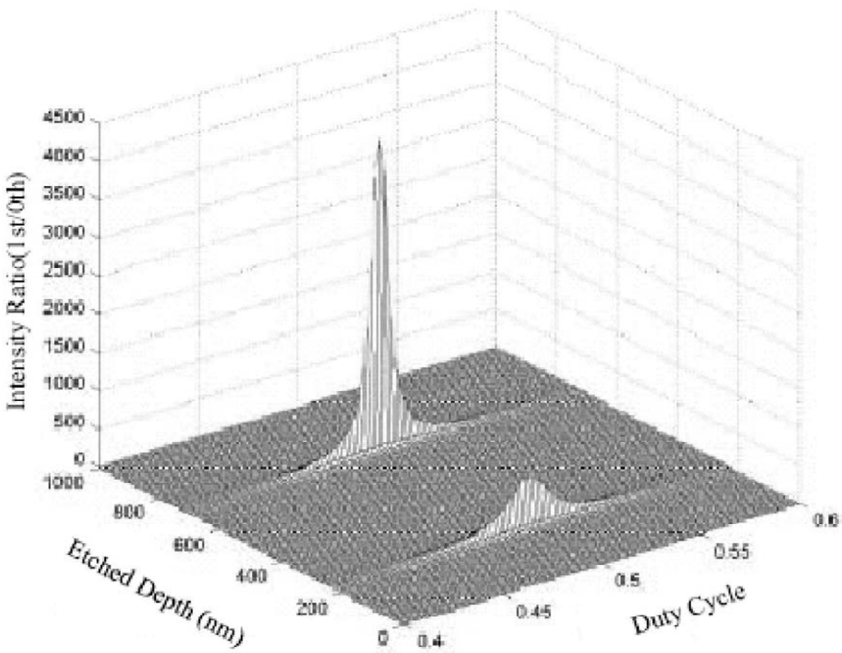


Fig. 3. Calculated diffracted intensity ratio for various duty cycles and etched depths.

Table 1
Optimized conditions for fabrication process

Exposure dose	25 mJ
Photoresist development time	3 s
Chrome wet etching time	35 s
RIE dry etching time	3 min 20 s

experiment experiences, we have learned the most important elements are the following four: exposure doses in IL, development time of photoresist, chrome wet etching time by CR7, and RIE dry etching time. We utilized the Taguchi method [6] to expedite and resolved the mentioned four parameters. The optimized process conditions are listed in Table 1.

Fig. 4 shows the transmission spectra of zero-order beam for both measurement and simulation. As for the measurement, the mask was made with parameters optimized by the Taguchi method as mentioned above. The mask had a period of about 440 nm. A Hitachi spectrometer was used for transmission measurement. Note the minimum transmittance (~8%) is around 250 nm wavelength, consistent with the calculated one.

3.3. Applications

Application of utilizing phase mask to sub-micron photoresist grating and fiber grating fabrication are also demonstrated. A phase mask of 440 nm period was used to make a photoresist pattern. Fig. 5a shows a scanning electron microscopy (SEM) picture of resist pattern, indicating the period of resist pattern is halved. The technique is useful for making gratings in III–IV materials required by DFB and distributed Bragg reflector lasers. A phase mask with 1080 nm period was used to imprint a fiber grating in a germanium-doped fiber [7]. Fig. 5b shows the resultant transmission spectrum of the fiber grating where the Bragg wavelength is 1563 nm, consistent with the calculated value given the refractive index of fiber core is 1.445. The transmission loss was higher than 7 dB and the bandwidth was ~0.3 nm.

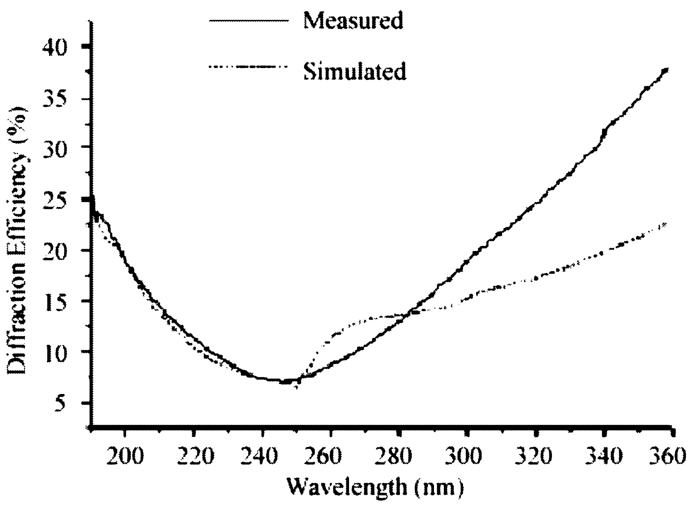
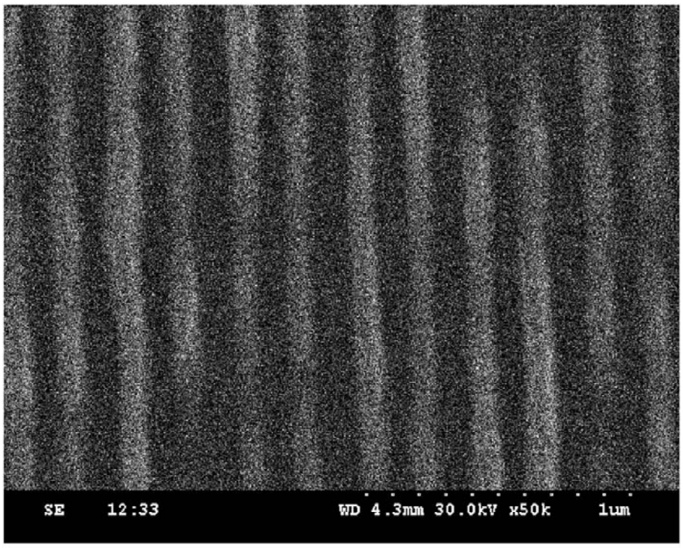
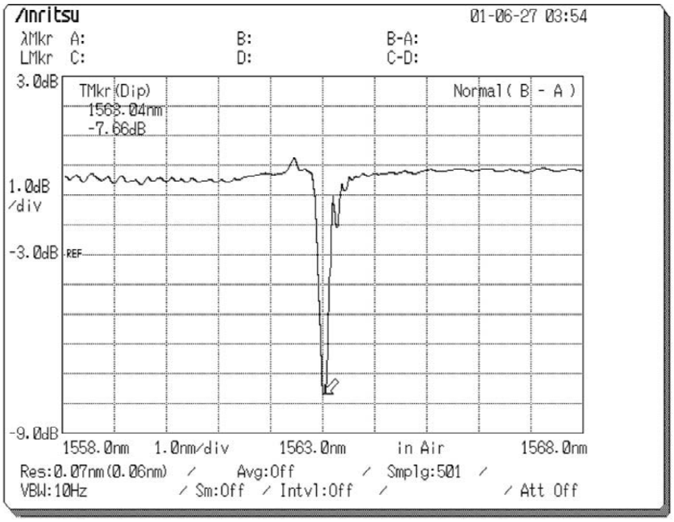


Fig. 4. Calculated and measured transmission spectra for the mask with 440 nm period.



(a)



(b)

Fig. 5. (a) A photoresist pattern of 220 nm period made by using the phase mask, (b) transmission spectrum of an FBG of period ~540 nm imprinted by using the phase mask.

4. Conclusions

Phase masks have been fabricated by utilizing interferometric lithography instead of traditional e-beam lithography. The photoresist pattern is first formed by applying interferometric lithography, and then transferred to a fused silica substrate using electron cyclotron resonance reactive ion etching.

The Taguchi method is employed to optimize processing parameters. The phase masks thus made have been successfully applied to the generation a photoresist pattern with halved period as compared to the original mask's period, and to the formation of a fiber Bragg grating.

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