High-efficiency diffraction gratings in fused silica at the wavelength of 632.8 nm

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We describe high-efficiency diffraction gratings fabricated in fused silica at the wavelength of 632.8 nm by rigorous coupled-wave analysis (RCWA). High-density holographic gratings, if the groove density falls within the range of 1575–1630 lines/mm and the groove depth within the range of 1.1–1.3 μm, can realize high diffraction efficiencies at the wavelength of 632.8 nm, e.g., the first Bragg diffraction efficiency can theoretically achieve more than 93% both in TE- and TM-polarized incidences, which greatly reduces the polarization-dependent losses. Note that with different groove profiles further optimized, the maximum efficiency of more than 99.69% can be achieved for TM-polarized incidence, or 97.81% for TE-polarized incidence.

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High-density diffraction gratings have found extensively wide use in many applications such as quantum electronics, integrated optics, spectroscopy, etc.. High-efficiency diffraction gratings have traditionally comprised metallic reflection gratings, which can achieve diffraction efficiencies of more than 90% by high reflectivity of the metal[1]. However, the absorption loss of the metal or the metal-coated surfaces limits the maximum attainable diffraction efficiency to 75%–95%, and the absorbed power turns into heat with an inherently low damage threshold. It is preferable to use gratings that consist completely of dielectric optical materials, for dielectric materials absorb heat so little that they provide a threshold for optical damage significantly above that of metals. L. Li *et al.* reported one dielectric reflection grating, which is formed by a highly reflecting (HR) dielectric stack below a surface-relief grating, can achieve nearly 100% diffraction efficiency for TE-polarized light in the 1st Littrow mount[2]. With the fast developments of microlithography technology[3−5], it is available to fabricate the grating with high aspect ratio directly in dielectric bulk material for high-efficiency transmission gratings. Nguyen *et al.* have designed and fabricated a fused silica grating with a period of 0.35 μm and a depth of 0.58 μm whose 1st Bragg efficiency was measured as high as 93.7% for TE-incidence and 86% for TM-incidence at the wavelength of 0.351 μm[6]. Clausnitzer *et al.* have reported a fused silica grating with a period of 0.8 μm and a depth of 1 μm whose 1st Bragg efficiency was measured 95% for TE-incidence at the wavelength of 1.06 μm[7] Yokomori reported diffraction characteristics of the photoresist gratings at the wavelength of 632.8 nm[8]. Note that the task of optimizing the grating structure is very important for improving the diffraction efficiency, followed by the feasibility of the grating fabrication technology in fused silica with higher aspect ratios.

In this paper, we describe the diffraction properties of the surface-relief rectangular holographic gratings in fused silica at the wavelength of 632.8 nm, by means of the rigorous coupled-wave analysis (RCWA) technique[9]. Profile parameters such as the depth and period are optimized so that the 1st Bragg peak diffraction efficiency can theoretically achieve more than 97% in TE and TM polarizations. By micro-lithography technology for fabrication our work should be highly interesting for the laser application near the wavelength of 632.8 nm such as anti-reflectors.

Figure 1 shows the geometry of a dielectric surface-relief grating. A linearly polarized electromagnetic wave of λ (in the vacuum) is obliquely incident at the grating at an arbitrary angle of incidence θ. We suppose that the grating vector K lies in the plane of incidence. In TE-polarization, the electric vector field is perpendicular to the plane of incidence; in TM-polarization, the magnetic vector field is perpendicular to the plane of incidence. The region 1 and region 3 are homogeneous with different refractive indices n_1 and n_2. The grating region is region 2, and it has a periodic structure with alternate refractive indices n_1 and n_2. In this paper, $n_2 = 1.46$, $n_1 = 1$. Λ denotes the period of the grating, and d denotes the depth of the grating region ($0 < z < d$), and f denotes the duty cycle or the aspect ratio, which is the ratio of the ridge width to the grating period Λ and is assumed to be 0.5 in this paper.

With the period and depth properly selected, the transmitted energy can be focused onto the $0th$ and the $1st$ orders, which is the first-order Bragg incidence $\theta_{\text{Bragg}} = \sin^{-1}(\lambda/2/\Lambda)$ at the 1st Littrow mount. First we have analyzed by the rigorous coupled-wave analysis (RCWA) technique[9] the first-order Bragg transmitted efficiencies of the rectangular-groove fused silica gratings as a function of groove depth (0−4 μm) and line density (0−3000 lines/mm) at the wavelength of 632.8 nm for both TE- and TM-polarization incidences shown in Figs. 2 and 3. For TE polarization, the peak efficiency of 97.81% occurs with the line density of 1580 lines/mm and the depth of 1.1 μm; for TM polarization, the peak efficiency of 99.69% occurs with the line density of 2430 lines/mm and the depth

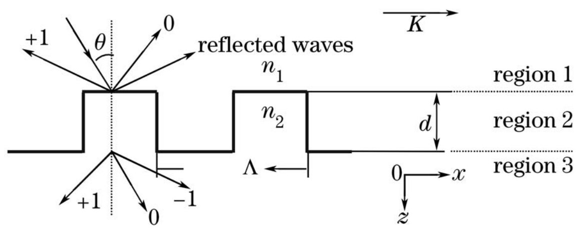

Fig. 1. Schematic of a dielectric rectangular grating.

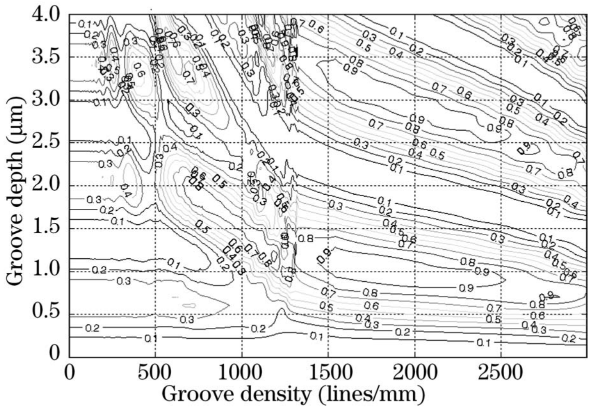

Fig. 2. Rigorous calculated 1st Bragg transmitted diffraction efficiency of a holographic grating in fused silica as a function of the profile parameters in TE polarization at the wavelength of 632.8 nm.

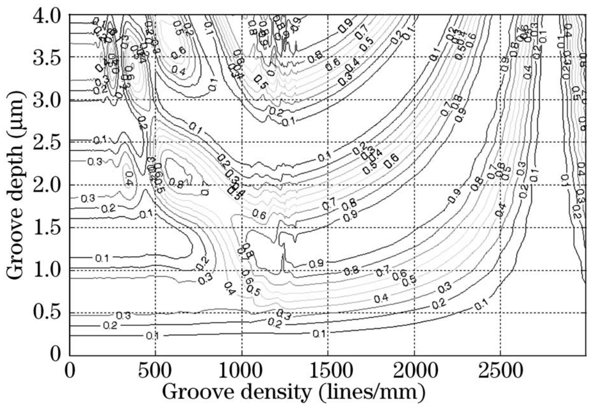

Fig. 3. Same as Fig. 2 except in TM polarization.

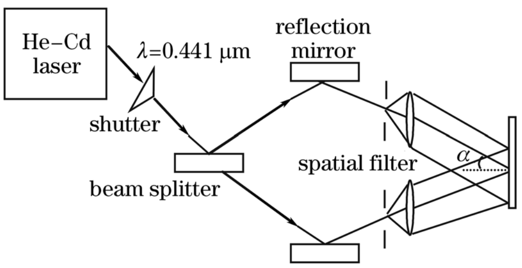

Fig. 4. Experimental setup for recording the photoresist gratings.

of 3.2 μm. Note that if the gratings can be etched to 1.1–1.3 μm with the line density within the range of 1575–1630 lines/mm, the calculated efficiency of most of the gratings can achieve more than 85% for both polarizations, which means that polarization-dependent losses are very low. For instance, the first-order Bragg transmitted efficiency can be more than 93% for both polarizations if the fused silica grating can be etched to 1.2 μm with the line density of 1575 lines/mm.

Figure 4 shows the optical setup for holographic exposure. Filtered by the pin-holes and collimated by two lenses, two plane waves interfere with each other to produce the interference pattern. The centers of the adjacent fringes are presented by $\Lambda = \lambda/2/\sin\alpha$, with α the half of the angles between two beams. In our experiment, a He-Cd laser with the wavelength of 0.441 μm is used as the exposure source. Due to the duality of the photoresist, the profile of the photoresist grating approaches in rectangular form instead of the cosine one. When the angle α is 20.3°, the corresponding groove density of the holographic grating is 1575 lines/mm.

In this paper, we optimize the profile parameters of the holographic gratings in fused silica by means of the RCWA technique. We find that if the groove depth is etched from 1.1 to 1.3 μm with the groove density ranging from 1575 to 1630 lines/mm, the 1st Bragg transmitted diffraction efficiency can achieve more than 85% at the wavelength of 632.8 nm in both TE- and TM- polarizations, especially the efficiency can be more than 93% if the fused silica grating can be etched to 1.2 μm with the line density of 1575 lines/mm. Such high-efficiency fused silica grating should be highly attractive for laser applications such as common He-Ne laser.

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