Deep-etched fused silica grating as a (de)multiplexer for DWDM application at the wavelength of 1.55µm

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ABSTRACT
We report on diffraction performances of deep-etched transmission gratings in fused silica at the wavelength of 1.55µm. Profile parameters of the depth and line density are optimized to achieve the first order Bragg transmitted efficiency of more than 98% theoretically under TE- or TM-polarized incident lights. Spectra performance of a 630 lines/mm grating with the depth of 3.0µm in the C+L bands is presented in which the diffraction efficiency of each spectrum can be above 90%. By holography and inductive coupled plasma (ICP) etching, we have made a fused silica grating with the period of 610 lines/mm and the depth of 0.73µm, the first order Bragg diffraction efficiency of which can reach 17% at the wavelength of 1.31 µm and 10% at 1.55 µm. Our results provide an important guideline for transmission gratings in fused silica as (de)multiplexers for dense wavelength division multiplexing (DWDM) application.

Keywords: Deep-etched fused silica grating, FSDGs, DWDM, rigorous coupled-wave analysis

1. INTRODUCTION
As the capacity of fiber communication system increases, the technique of wavelength division multiplexing (DWDM) is able to provide bandwidth in a fast, efficient, and cost-effective manner. At present, DWDM devices mainly include thin-film filters (TFFs), arrayed waveguide gratings (AWGs) as well as free-space diffraction gratings (FSDGs), etc. FSDGs are superior to others in that they can (de)multiplex optical signals in a parallel fashion dramatically increasing channel counts with low insertion loss and low polarization-dependent loss. Low Polarization Dependent Loss (LPDL) gratings can be applied for C, L or C+L bands. With the fast development of microlithography technology, it is available to fabricate the grating with high aspect ratio directly in dielectric bulk material as high-efficiency transmission gratings with subwavelength structures.

In this article, we investigate diffraction properties of deep-etched fused silica gratings at the wavelength of 1.55µm. We find by using the rigorous coupled-wave analysis (RCWA) that for a surface-relief rectangular transmission grating in fused silica, the first order Bragg transmitted diffraction efficiency reaches over 90% at the wavelength of 1.55µm on condition that the groove depth can be etched to more than 2µm and the groove density is higher than 600 lines/mm. By holographic recording and inductive coupled plasma (ICP) etching, we have fabricated a 610 lines/mm fused silica grating with the etching depth of 0.73µm. The measured diffraction efficiencies by demultiplexing two wavelengths of 1.31µm and 1.51µm are in good agreement with the theoretical results.

2. SIMULATIONS AND EXPERIMENTS
Schematic of the first order Bragg incidence is shown in Fig.1.
With the period and depth properly selected, the transmitted energy can be focused onto the 0th and the 1st orders, that is the Littrow mount at the Bragg incidence $\theta = \sin^{-1}(\lambda/2d)$, where $\lambda$ is the light wavelength in the vacuum and $d$ the grating period. We suppose that the grating vector $\mathbf{K}$ lies in the plane of incidence. For TE-polarized incident light, the electric vector field is perpendicular to the plane of incidence; for TM-polarized incident light, the magnetic vector field is perpendicular to the plane of incidence.

First, by means of the rigorous coupled-wave analysis (RCWA) technique, we analyzed the first order Bragg transmitted diffraction efficiency with the dependence of the groove density and the groove depth as shown in Figs. 2 and 3. Note that if the groove depth can be developed to from 2.8 $\mu$m to 3.1 $\mu$m with the groove density ranging from 600 lines/mm to 700 lines/mm, the efficiency can achieve more than 90% for both TE and TM polarizations, which means that low polarization-dependent losses are realized. Second, we analyze the spectra performance of the 630 lines/mm grating in the C+L bands as shown in Fig. 4. With the groove depth of 3.0 $\mu$m, the diffraction efficiency of each spectra component can achieve above 90% in both polarizations, which is very attractive to the wavelength (de)multiplexing for high efficiency.

![Fig. 2](image1.jpg)

**Fig. 2** Rigorous calculated first order Bragg transmitted diffraction efficiency of a fused silica grating as a function of the profile parameters in TE polarization at the wavelength of 1.55 $\mu$m. The peak efficiency of 98.10% occurs with the groove density of 655 lines/mm and the groove depth of 2.7 $\mu$m.

![Fig. 3](image2.jpg)

**Fig. 3** Same as Fig.2 except in TM polarization. The peak efficiency of 98.44% occurs with the groove density of 756 lines/mm and the groove depth of 4 $\mu$m.
Based on the rigorous calculations, we made one fused silica grating of 610 lines/mm by microlithography technology. At first a photoresist grating was made by holography shown in Fig. 5. One fused silica substrate is coated with Microposit S1818 photoresist at 3µm, and next placed in an interference field with the line density of 610 lines/mm formed by two beams of coherent lights from a He-Cd laser source at the wavelength of 0.441µm. The centers of the adjacent fringes are presented by $A=\lambda/2/\sin\alpha$, with $\alpha$ the half of the angles between two beams. After exposed, it is developed by Microposit developer. Then the photoresist grating is formed. The photoresist grating is etched in inductive coupled plasma (ICP) equipment with 200sccm (standard cube centimeter meter) CHF₃, 20sccm Ar, and 5sccm O₂. The etched depth is 0.73µm, and the scanning electron micrographs of the grating are shown in Fig. 5.
We measured the first order Bragg transmitted diffraction efficiencies shown in Fig.7, of the wavelengths of 1.31µm and 1.55µm diffracted by the fused silica grating in Fig.6. It is seen that the measured results are in good agreement with the theoretical ones.

3. CONCLUSIONS

In this paper, we first optimize profile parameters of the fused silica gratings by means of the rigorous coupled–wave analysis (RCWA) technique. We find that if the groove depth is etched to from 2.8µm to 3.1µm with the groove density ranging from 600lines/mm to 700lines/mm, the first order Bragg transmitted diffraction efficiency can achieve more than 90% at the wavelength of 1.55µm in both TE- and TM-polarizations. Such high efficiency can also be realized in the C+L bands, and we make an example of such a grating with the groove density of 630lines/mm and the groove depth of 3.0µm. Second, based on the theoretical calculations, we have fabricated a fused silica grating with the groove density of 610lines/mm and the groove depth of 0.73µm by microlithography technology, the measured first order Bragg transmitted diffraction efficiency of which can reach 17% at the wavelength of 1.31 µm and 10% at 1.55 µm. Note that if the surface of the grating is coated with metal of high reflectivity, such as gold or aluminum, the diffraction efficiency can be further enhanced. Such high-efficiency gratings should be highly attractive as the (de)multiplexers for DWDM application.

4. ACKNOWLEDGEMENTS

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