UCRL-JC-123585
PREPRINT

CONF-960493--7

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S. Falabella, R. D. Boyd, and M. D. Perry

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MAY 17 1996
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This paper was prepared for submittal to the
1996 Diffractive Optics and Micro Optics Topical Meeting
Boston, MA
April 29-May 2, 1996

March 1, 1996

Lawrence Livermore National Laboratory

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Lawrence Livermore National Laboratory, P.O. Box 808, L-493, Livermore, CA 94550
Tel. (510) 423-2111, FAX (510) 422-9294

ABSTRACT

We present the design and performance of high-efficiency transmission gratings fabricated in bulk fused silica for use in ultraviolet high-power laser systems. The gratings exhibit a diffraction efficiency exceeding 95% in the $m = -1$ order and damage threshold greater than 13 J/cm^2 for 1 nsec pulses at 351 nm. Model calculations and experimental measurements are in good agreement. We describe the design and fabrication of these gratings based on the transfer ion etching of photoresist patterns produced by interference lithography.

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.

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I. Introduction

High power ultraviolet lasers are now widely used in the semiconductor industry and inertial confinement fusion research, and are finding increased application in medical therapy. Whether based on excimers or frequency converted solid-state, high power ultraviolet lasers continue to be plagued by issues of optical damage and a limited choice of optical components for beam manipulation. In particular, system performance is often limited by the damage threshold of cavity and transport mirrors. Beam transport and steering based on refractive optics are limited not by surface damage as is the case with reflective systems but instead by bulk damage induced by two photon absorption, color center formation and self-focusing. These limitations can, in principle, be overcome in many applications by the use of transmission gratings fabricated in high damage threshold, transparent materials.

We present the design and performance of high-efficiency transmission gratings fabricated in bulk fused silica for use in ultraviolet high-power laser systems. By controlling the shape, depth, and duty cycle of the grooves we have achieved a diffraction efficiency exceeding 95% in the $m = -1$ order. By directly etching the grating profile in bulk fused silica we have achieved damage threshold greater than 13 J/cm^2 for 1 nsec pulses at 351 nm.

II. Theory

The efficiency of a grating depends, for given wavelength λ, polarization and angle of incidence α, on groove period d, groove depth h, and the shape of the grating profile. For suitable choice of these parameters the transmission efficiency can approach 100%. The most efficient gratings are obtained when only two orders can propagate, namely the zero order (specular reflection) and the -1 order, and when the incident radiation impinges close to the Littrow angle, arcsin($\lambda/2d$) (autocollimation). By suitably choosing the groove spacing d for given wavelength λ we can exclude all other orders. This possibility follows from the basic grating equation relating angle of incidence α to angle of diffraction β_m for order m,

$$\sin \beta_m = \sin \alpha + (m\lambda / d). \tag{1}$$

Our goal for permitting only two orders can be assured by fixing the grating period to be smaller than the wavelength. For light of wavelength 351 nm this implies a groove period of 351 nm or less.

The geometry of diffraction is entirely set by the grating equation, and is independent of groove depth or profile. With period = 350 nm the Littrow angle, at which reflective diffraction into order -1 coincides with incident radiation, is 30°. With this incident angle the transmitted light into order -1 emerges into air at an angle of 30°. Thus there will be a 60° angle between the two transmitted orders as they emerge into air.

Taking the groove spacing to be 350 nm, we found that there was a range of parameters at which the efficiency was 97% or better. Our target design is for a period of 350 nm, a depth of around 600 nm, and with duty cycle of 0.5 (i.e. the grooves have width 175 nm) to be used with TE polarized light. Figure 1 illustrates the profile and efficiency for this design. This design has a theoretical efficiency of 98% into $m =$ -1 order.

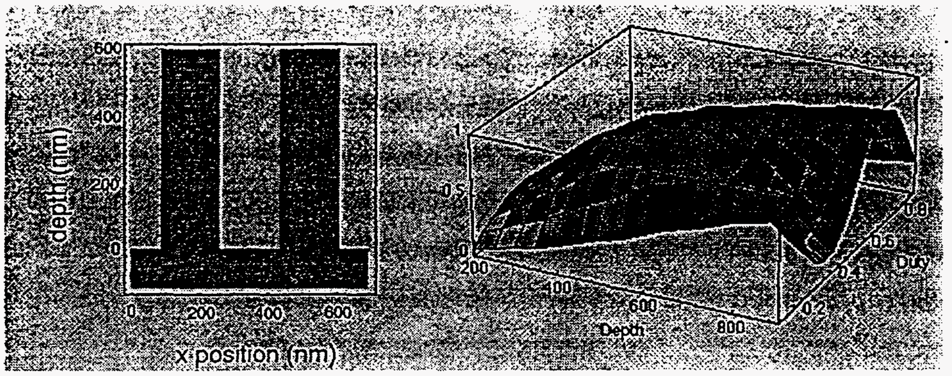

Figure 1. Right: Theoretical transmission efficiency, $\lambda = 351$ nm, order -1 and TE polarization, as a function of groove depth (nm) and duty cycle for a rectangular-profile grating etched into silica (left frame). Incident angle is Littrow angle, groove spacing is d = 350 nm. The peak efficiency (97.6%) occurs for depth of 600 nm and duty cycle 0.5.

III. GRATING FABRICATION

Our fabrication of gratings proceeds through several steps. We first prepare, on suitably flat and polished substrates, carefully controlled thickness of photoresist. We next use laser interference lithography to pattern the photoresist with the desired profiles. We develop the resultant latent image to form a corrugated photoresist grating, which we transfer etch into the substrate. A typical photoresist grating and a grating etched into bulk fused silica is shown in Figure 2.

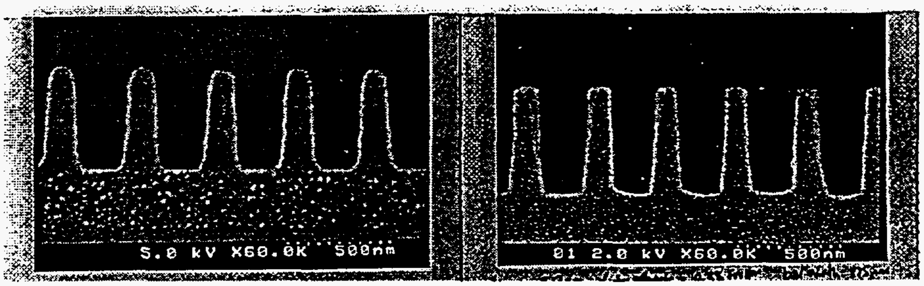

Figure 2A. Grating profile patterned in photoresist, 2B) Grating profile etched into bulk fused silica.

IV. EXPERIMENTAL RESULTS

We have fabricated a grating that exhibits a diffraction efficiency in excess of 95% in the $m = -1$ order and 2% in the transmitted 0 order at the Littrow angle of the grating. The light that is not present in these two orders appears to be diffusely scattered. This can be seen from the hazy appearance of the sample. We attribute this to the defects in the bulk fused silica substrate that was used. This can be corrected by using super polished fused silica substrates (fused silica substrates that have been etched/polished to minimize substrate polishing damage). It is expected that with these substrates a diffraction efficiency of greater than 97% can be obtained. Experimental results are in good agreement with our theoretical computations.

In addition, we have conducted damage test of these transmission grating using a 3 ns pulse from a frequency-tripled Q-switched Nd:YAG laser. The grating was situated to the TE-polarized laser beam at the use angle of 30°. Both front and back surfaces had a damage threshold of 13.2 J/cm^2. These values are typical for standard bulk fused silica.