LA-UR-85-1208

CONF-8410186--4

RECEIVED BY OSTI MAY 06 1985

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TITLE: Picosecond-Pulse Damage Studies of Diffraction Gratings

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LA-UR--85-1208

DE85 010785

SUBMITTED TO: Proceedings of Sixteenth Annual Symposium on Optical Materials
for High Power Lasers

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Picosecond-Pulse Damage Studies of Diffraction Gratings

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Diffraction gratings are frequently used in dye-laser cavities as wavelength-tuning elements. These gratings often limit the maximum laser output energy because of their low damage thresholds. We have measured the damage characteristics of both ruled and holographically produced gratings, under a variety of conditions. Using the single-shot-per-site mode, the samples were irradiated by 30-ps, 1.064- μm pulses having a spot size of 0.5-mm radius.

It was found that holographic gratings have damage thresholds from 1.5 to 5.0 times higher than similar ruled gratings. Thresholds for S-polarized light (E parallel to grooves) were higher by factors of 1.5 to 6. For the same type grating, gold coatings yielded higher thresholds than aluminum, although this is wavelength dependent. For holographic gratings, replicas have slightly higher thresholds than masters. Dependence upon groove spacing was weak.

Data are presented to show a variety of comparisons between different types of gratings, including two different manufacturers and usage at higher orders of incidence.

Key words: laser-induced damage; holographic gratings; ruled gratings; picosecond pulses; 1064 nm; polarization effect; metallic overcoat.

1. Introduction

Diffraction gratings are frequently used in laser systems, e.g., dye-laser cavities, as wavelength-tuning elements. These gratings usually have the lowest damage threshold of any component in the system and thus determine or limit the maximum energy output available from the laser. It is therefore important to understand the damage characteristics of gratings and how they can be improved.

Damage-threshold characteristics have been measured for both conventionally ruled (replica) gratings and for the newer holographically produced gratings. A comparison between aluminum and gold as the surface coating has been made, and the effect of the number of lines per millimeter on the damage threshold has been determined. Grating damage thresholds were measured for both S- and P-polarizations. The effect of using ruled gratings in higher orders was investigated. Comparisons were made between master and replica holographic gratings and between replica ruled gratings from two different manufacturers.

For these tests the gratings were mounted in Littrow condition, first order, as is common for their use as tuning elements in dye lasers. Using the single-shot-per-site mode, the samples were irradiated by 30-ps, 1064-nm pulses having a spot size of 0.5-mm radius.

It was found that holographic gratings have damage thresholds from 1.5 to 5 times higher than similar ruled gratings. For all but one of the gratings tested, thresholds for S-polarized light were substantially higher than for P-polarization, by factors ranging from 1.5 to 6.

For the same type grating, gold is a much better overcoat than aluminum at 1064-nm, as would be expected. Thresholds for gold-coated gratings were approximately 1.5 to 10 times higher than the threshold for aluminum-coated gratings.

2. Experimental Setup

The laser damage threshold measurements were made using a Nd:YAG oscillator-amplifier configuration. The laser was mode-locked, and a single 30-ps pulse was extracted from the mode-locked train. Care was used throughout the system to maintain a single transverse spatial mode.

This beam then entered the interaction area shown in figure 1. A 2-m focal-length lens focused the beam at a point beyond the sample (grating) so that the spot size radius at the sample was 0.5 mm (Gaussian parameter w). The spot size was measured on every shot using a Reticon linear-diode array.

Damage was detected in three ways: (1) visual observation during the shot; (2) photomultiplier observation of spark; and (3) comparative observation of the scattering of a He-Ne laser before and after the shot. The interaction room was completely darkened during the tests and an observer watched the sample through glasses highly shielded for the 1064-nm radiation. The observer saw a spark if substantial damage occurred, and was also able to detect very slight changes in the scattering from a coincident He-Ne beam. The primary damage detection was the signal from a photomultiplier viewing the spark at the interaction point. The photomultiplier was heavily filtered so that it could only see a narrow range of wavelengths centered at 4200 Å.

After each shot the sample was translated so that no site was irradiated more than once. An average of about 40 shots was used to establish the damage threshold for each test.

The gratings were mounted in Littrow condition, first order. Therefore gratings having different groove spacings were irradiated at different angles of incidence relative to the plane of the gratings. A half-wave plate was used to change the polarization of the incident laser beam. In order to avoid confusion over the terms S-plane and P-plane, we will explicitly refer to the electric vector parallel to the grooves, $E_{||}$, and the electric vector perpendicular to the grooves, $E_{\perp}$.

Figure 1. Experimental setup used to measure laser-induced damage thresholds.

3. Metallic Coatings

Four pairs of gratings were obtained such that, within a pair, the gratings were identical except for coating. One grating of each pair was coated with aluminum and one with gold. The damage threshold results are shown in table 1. In every case, the gold coated gratings had higher thresholds by a substantial ratio.

Table 1. Damage thresholds of gold and aluminum-coated gratings used at 1.06 microns.

Type	Grooves/mm	Damage Threshold (J/cm ²)				Threshold Ratio (Gold/Alum.)	
		E//Grooves		E⊥Grooves		E//Grooves	E⊥Grooves
		Gold	Alum.	Gold	Alum.		
Holog.	1800	2.6	0.32	1.2	0.14	8.1	8.6
Holog.	1800	1.0	0.28	0.87	0.09	3.6	9.7
Ruled	600	1.1	0.19	0.44	0.07	5.8	6.3
Ruled	300	0.49	0.32	0.07	0.05	1.5	1.4

This is reasonable at 1064 nm, since the reflectivity of gold is higher than that of aluminum, as shown in figure 2. Below 600 nm, however, the situation is reversed and one would expect that aluminum coatings would have higher damage thresholds than gold. Thresholds for both materials would be lower at 600 nm than those thresholds reported here, due to the increased absorption at shorter wavelengths.

Figure 2. Reflectance as a function of wavelength for aluminum and gold [1].

One might expect a relationship between the minimum coatings thickness that should be used and the laser pulse length (in time). For replica gratings, both ruled and holographic, the layer underneath the outer metallic layer is some form of epoxy (fig. 3). For master holographic gratings, the layer underneath the outer metallic layer is a photoresist material. These materials are thermal barriers, because of their low thermal conductivity, thus keeping most of the heat in the metallic layer. Since all of the absorption occurs in a thin (~200-300 Å) layer at the surface, increasing

the thickness of the coating decreases the maximum temperature attained by the coating. This is only true up to a point, however, since the heat must have time to diffuse into the metal. Once the laser pulse has turned off, further heat diffusion cannot reduce the (already attained) maximum temperature. Although they were not tested in this experiment, ruled masters may have some advantage for long pulse lengths in that they do not have the insulating epoxy layer. The use of metallic substrates could also help for high average power applications. The substrates used here were glass.

Figure 3. Cross-sectional view of ruled replica and holographic gratings showing metal deposited on epoxy or photoresist material.

4. Ruled Versus Holographic Gratings

Table 2 compares the damage thresholds of machine ruled and holographic gratings (both replicas). It can be seen that holographic gratings hold a clear and substantial advantage over ruled gratings.

Table 2. Damage thresholds of ruled and holographic gratings.

Grooves/mm	Coating	Damage Threshold (J/cm ²)				Threshold Ratio (Holog./Ruled)	
		E//Grooves		E⊥Grooves		E//Grooves	E⊥Grooves
		Ruled	Holog.	Ruled	Holog.		
1800	Gold	0.47	2.6	0.24	1.2	5.5	5.0
600	Gold	1.1	1.7	0.44	1.0	1.5	2.2

One possible explanation of the difference is the sharpness of the respective groove shapes, as demonstrated in figure 3. Ruled gratings are actually cut into the metal layer with a diamond tool, producing sharp corners and whiskers of metal. Electric-field enhancement at these sharp corners could account for lower thresholds. The ruled gratings used in these tests were actually replicas rather than masters, but it is presumed that the sharp features replicate faithfully.

Holographic gratings are made by irradiating a photosensitive surface with an optical interference pattern. The pattern etched into the surface is some truncated form of a sinusoid and is, therefore, smoother in shape than a ruled pattern. Figure 4 shows photomicrographs of two different holographic gratings. The reflective metal layer is deposited on top of the exposed and developed photoresist material.

All of the gratings in table 2 were tested in first order except the ruled 600 groove/mm grating, which was tested in second order. As will be seen in the next section, this may have had an adverse effect on the results. However, the results for the 1800 groove/mm gratings are clear and valid.

Figure 4. Photomicrographs of two holographic gratings illustrating groove profiles. Groove spacing on the left is 1800 ℓ/mm and on the right is 1200 ℓ/mm .

5. Higher Orders

One possible advantage of ruled gratings is their ability to go to higher orders efficiently. From a laser damage threshold viewpoint, however, using higher orders is not advantageous, as can be seen in table 3. Here, a holographic grating in first order is compared to ruled gratings in second and fourth orders. The groove spacing and order number are such that the Littrow angle is constant for the three cases. Each of the ruled gratings was blazed for use in the order listed in table 3 at 1064 nm. The use of higher orders reduces the damage threshold.

Table 3. Damage thresholds of holographic gratings used in first order compared to ruled gratings blazed for higher orders.

Type	Coating	Grooves/mm	Order	Damage Threshold (J/cm^2)	
				E//Grooves	E⊥Grooves
Holog.	Gold	1200	1	1.9	1.4
Ruled	Gold	600	2	1.1	0.44
Ruled	Gold	300	4	0.49	0.07

6. Effects of Polarization

Polarization of the incident beam had a substantial effect on the damage threshold of a grating, as seen in table 4. For all but one of the gratings tested, the threshold was higher for the electric vector E parallel to the grooves than for E perpendicular to the grooves. It is well known that the efficiency of diffraction gratings is different for the two different polarizations, and that the curves of efficiency versus wavelength vary from one grating to another [2]. This would imply that the details of the electric field distribution at the surface of the grating differ, perhaps accounting for the different damage thresholds. Typical grating efficiency curves are shown in figure 5. A simplistic approach of correlating the efficiency of a grating with its damage threshold for the two polarizations does not work at all. We have not attempted a detailed analysis of this area, but it can be seen from figure 6 that simple metal absorption theory would predict higher damage thresholds for S polarization (E parallel to grooves), in qualitative agreement with the data. Specifying the angle of incidence is more difficult, however, because of the angles involved in the grooves themselves. It is apparent that the higher efficiency configuration (E perpendicular to grooves) has the lower damage threshold.

Table 4. Effect of polarization on damage thresholds of gratings.

Type	Coating	Grooves/mm	Damage Threshold (J/cm ²)		Threshold Ratio $E_{//}/E_{\perp}$
			$E_{//}$ /Grooves	$E_{\perp}$ /Grooves	
Holog.	Gold	1800	2.6	1.2	2.2
Holog.	Alum.	1800	0.32	0.14	2.3
Holog.	Gold	600	1.7	1.0	1.7
Ruled	Gold	1300	0.47	0.24	2.0
Ruled	Alum.	830	0.26	0.35	0.7
Ruled	Alum.	300	0.22	0.05	6.4

Figure 5. Typical grating efficiency curves. Actual curves vary widely from one grating to another.

Figure 6. Ratio of absorptions for the two polarizations for Al and Au as a function of angle of incidence.

7. Groove Spacing

The dependence of damage threshold on groove spacing is not clear. In table 5, for holographic gratings and E parallel to the grooves, the threshold increases with the number of grooves per millimeter. However, for the same gratings and E perpendicular to the grooves, threshold increases from 600 to 1200 grooves/mm, then decreases from 1200 to 1800 grooves/mm. For the ruled gratings shown, the two different polarizations have opposite dependence on groove spacing. One can only conclude that other factors appear to be more important than groove spacing.

Table 5. Damage thresholds of gratings as a function of groove spacing (tested in first order).

Type	Coating	Grooves/mm	Damage Threshold (J/cm ²)	
			E//Grooves	E⊥Grooves
Holog.	Gold	1800	2.6	1.2
Holog.	Gold	1200	1.9	1.4
Holog.	Gold	600	1.7	1.0

Ruled	Alum.	830	0.26	0.35
Ruled	Alum.	300	0.32	0.05

8. Master versus Replica Gratings

Two master-replica pairs of holographic gratings were tested for relative damage thresholds. For both aluminum and gold coatings and for both polarizations the replica gratings had higher thresholds than the master gratings, as shown in table 6. One possible explanation is the different types of material layers used under the reflective coating, as discussed in Section 3. Holographic masters use a photoresist material so that the initial pattern can be "recorded." Replicas have no such requirement since they are merely taking the physical shape of the master by impression in an epoxy layer. Another possible explanation is that sharp points and corners may not replicate faithfully, but may come out more rounded. It should be noted that these replicas are actually second-generation or "positive" replicas so as to have the same phase as the master.

Similar tests on ruled gratings were not performed due to the considerable cost of ruled masters.

Table 6. Damage thresholds for master and replica holographic gratings.

Grooves/mm	Coating	Damage Threshold (J/cm ²)			
		E//Grooves		E⊥Grooves	
		Master	Replica	Master	Replica
1800	Alum.	0.28	0.37	0.90	0.14
1800	Gold	1.0	2.6	0.87	1.2

9. Two Manufacturers of Ruled Gratings

Table 7 gives the damage thresholds for two ruled gratings made by two different manufacturers but otherwise identical. Since the relative positions of the gratings changed between the two polarizations and the thresholds are close to one another, neither grating appears to be better than the other. This test was not performed on holographic gratings.

Table 7. Damage thresholds of ruled gratings from two manufacturers.

Manufacturer	Type	Coating	Grooves/mm	Damage Threshold* (J/cm ²)		Blaze λ
				E//Grooves	E⊥Grooves	
JY	Ruled	Alum.	600	0.19	0.07	2 μm, 1st order
B&L	Ruled	Alum.	600	0.18	0.12	2.5 μm, 1st order

* Damage thresholds for 1.06 μm irradiation, 2nd order

10. Conclusions

The thresholds for laser-induced damage to holographic and ruled gratings have been measured and compared for 30-ps pulses of 1.064 μm radiation. For these conditions, holographic gratings have higher damage thresholds than ruled (replica) gratings. Ruled master gratings were not tested. For both holographic and ruled gratings, gold coatings have higher damage thresholds than aluminum coatings, as would be expected at this wavelength. In general, the damage threshold was highest for the electric vector parallel to the grooves, by a substantial factor. Unfortunately, this orientation normally produces lower efficiency. Operating in lower orders gives the best damage resistance, where that is practical. Ruling density does not appear to have a clear effect on damage threshold. The holographic replica gratings tested in this series had higher damage thresholds than holographic master gratings. This is not fully understood. No significant difference was found between ruled replicas from two different vendors.

11. References

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