Optimization of the grating efficiency in grazing incidence

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A detailed numerical study of the sinusoidal and triangular groove shape grating efficiency behavior has been carried out in grazing incidence using rigorous electromagnetic theory. The optimized parameters for maximum efficiency have been found for both types of grating. The influence of the metal reflectance and the oxide layer are discussed, and some results of higher order efficiency are also presented.

I. Introduction

Reflection gratings are widely used in grazing incidence as a tuning element in dye lasers. Several cavity configurations utilizing grazing incidence have been proposed[1] to achieve a very narrow linewidth. Since grating efficiency rapidly decreases when the angle of incidence tends to 90°, the applications of grating tuners generally have been confined to relatively high-gain pulsed lasers that can tolerate higher losses. To take advantage of the higher dispersion in grazing incidence and ensure the single-mode operation of the cw laser systems, the grating efficiency must be as high as possible.

The first question arising in the use of diffraction gratings is what type, holographic or ruled, is preferred in grazing incidence. The second problem is what are the optimal grating parameters. While the properties of the diffraction gratings are generally well established over a wide spectral region,[2,3] less attention has been devoted to grazing incidence gratings in the visible region.

A partial answer of the above-mentioned problems is given in Ref. 4 where the influence of the groove profile and the angle of incidence on the efficiency behavior is discussed.

In the visible region, aluminum surface gratings are usually preferred. The oxidation of aluminum in air results in the formation of Al_2O_3 film, typically a few nanometers thick,[3] which is normally ignored in diffraction efficiency calculations. The purpose of this paper is to present the optimized diffraction efficiency in the visible region of both holographic and ruled gratings at grazing incidence. The effects of the grating parameters as well as the incident wave conditions are discussed in detail. Finally, the influence of the oxide layer on the grating efficiency is shown.

II. Presentation of the Problem

Certain processing conditions for holographic gratings lead to a groove profile close to sinusoidal.[3,5] At a fixed angle of incidence and wavelength, grating efficiency depends only on the modulation depth (ratio of groove depth h to period d). In the same conditions the efficiency of triangular groove gratings with 90° apex angle is described completely by the blaze angle α_B.

Once the optimized grating parameters are determined, the second most important step is to find the angular and wavelength efficiency dependence. This procedure gives a fairly good picture of the efficiency behavior of almost all practically interesting cases. The calculations were performed with a computer code based on a rigorous electromagnetic theory for multicoated diffraction gratings in conical diffraction mounting.[6] The advantages and restrictions of the method for the in-plane case are described in Ref. 7.

III. Sinusoidal Gratings

Diffraction efficiency of several gratings with 1000, 2000, and 3000 grooves/mm was calculated as a function of modulation depth. The results are shown in Figs. 1–3.

The efficiency maximum occurs at $h/d = 0.2$ and always in S-polarization (the electric field vector is perpendicular to the grooves) regardless of the grating period. The P-polarization efficiency is usually <1%; however, for very deep gratings it increases significantly in the presence of an oxide layer (Fig. 3). With increasing spatial frequency, efficiency increases and

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Received 9 April 1987.
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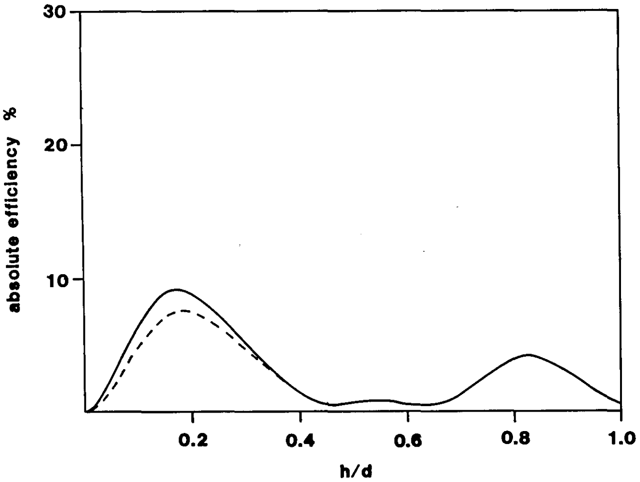

Fig. 1. First-order efficiency vs modulation depth h/d for sinusoidal grating with 1000 g/mm and S polarization. Solid line, bare aluminum grating; dashed line, aluminum grating with an oxide layer 50 Å thick; angle of incidence $\theta_i = 89°$; wavelength $\lambda = 0.6328$ μm.

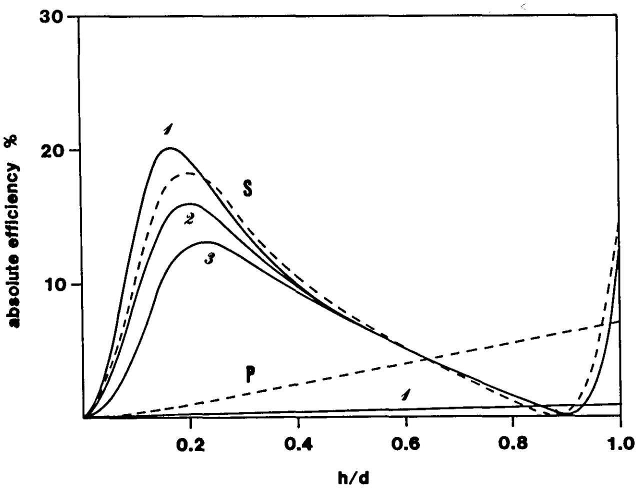

Fig. 3. Similar to Fig. 1 except that the groove frequency is tripled to 3000 g/mm and that P-plane results have been added for the primary data which are based on the complex index of aluminum $n = 1.378 + i7.616$ (curves 1). Curves 2 and 3 show what happens when the extinction coefficient is reduced to $i6.0$ and $i5.0$, respectively.

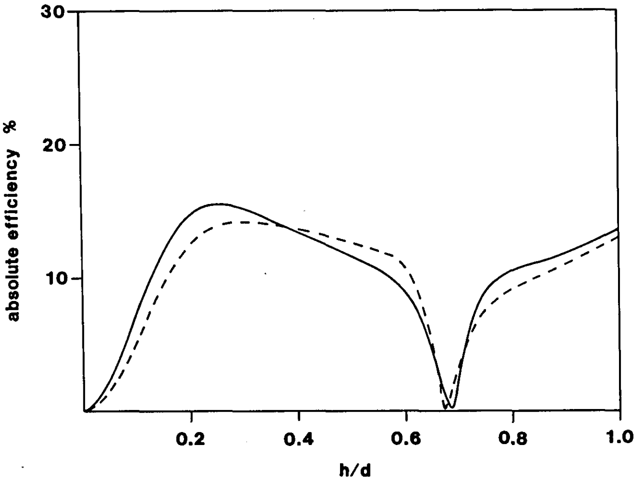

Fig. 2. Same as Fig. 1 except for a grating with 2000 g/mm.

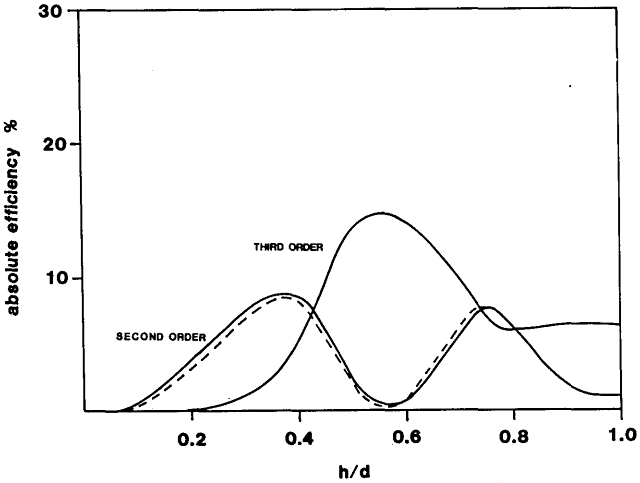

Fig. 4. Higher order efficiency as a function of h/d for S polarization and a grating with 1000 g/mm. Solid line, bare aluminum grating; dashed line, coated aluminum grating with 50-Å thick dielectric layer, $\theta_i = 89°$, $\lambda = 0.6328$ μm.

for $\lambda = 0.6328$ μm reaches a value of 20% for the grating with 3000 grooves/mm. The effect of an oxide layer is always to reduce the maximum of S-polarization efficiency. More surprising is that the location of that maximum remains practically the same for different metal coatings (Fig. 3).

In higher orders efficiency is much less sensitive to the presence of an oxide layer (Fig. 4), but the efficiency maximum is obtained for deeper gratings. Higher orders can evidently be used to increase the dispersion with an efficiency comparable to first order. It should be remembered, however, that the usable wavelength region is progressively narrower for higher orders.

The spectral dependence of efficiency, which is of prime interest for dye laser tuning applications, is shown in Fig. 5 for gratings with $h/d = 0.2$. In the domain $1.0 < \lambda/d < 2.0$, where only first order is propagated, the efficiency gradually increases with an increasing λ/d ratio and reaches a value of 20% for $\lambda/d = 1.9$. The presence of a 50-Å thick oxide layer causes a relative reduction in the efficiency of ~10%, and, in addition, the anomaly in the vicinity of passing-off −2 order is sharper. Although in practice oxide layers tend to stabilize at 40 Å, the value of 50 Å was chosen in these calculations to indicate an extreme boundary.

As can be expected, increasing the angle of incidence rapidly reduces efficiency (Fig. 6). The role of dielectric coatings remains the same.

IV. Triangular Gratings

Triangular groove gratings with the same groove frequencies of 1000, 2000, and 3000 grooves/mm had their efficiencies calculated as a function of the blaze angle (Figs. 7–9). We may assume that the optimum value is $\alpha_B = 12°$. The wavelength dependence of the

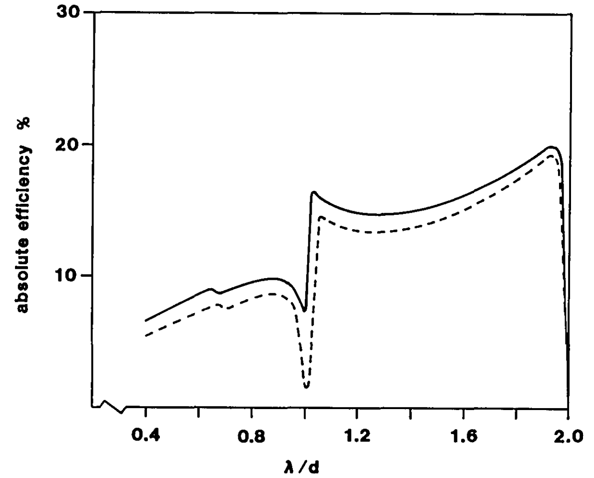

Fig. 5. First-order efficiency curves for $\theta_i = 89°$ and S polarization. Solid line, Al grating; dashed line, Al + Al_2O_3 (50 Å thick).

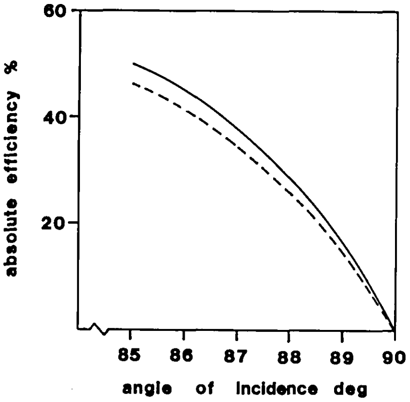

Fig. 6. Angular dependence of the efficiency for a grating with h/d-0.2, $\lambda/d = 1.05$, and S polarization. Solid curve, Al grating; dashed curve, Al + Al_2O_3 (50 Å thickness).

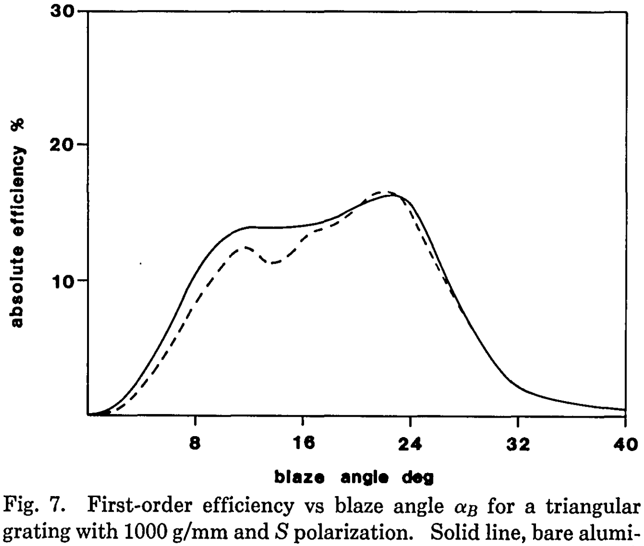

Fig. 7. First-order efficiency vs blaze angle α_B for a triangular grating with 1000 g/mm and S polarization. Solid line, bare aluminum grating; dashed line, aluminum grating with an oxide layer 50 Å thick. Angle of incidence $\theta_i = 89°$, wavelength $\lambda = 0.6328\ \mu m$.

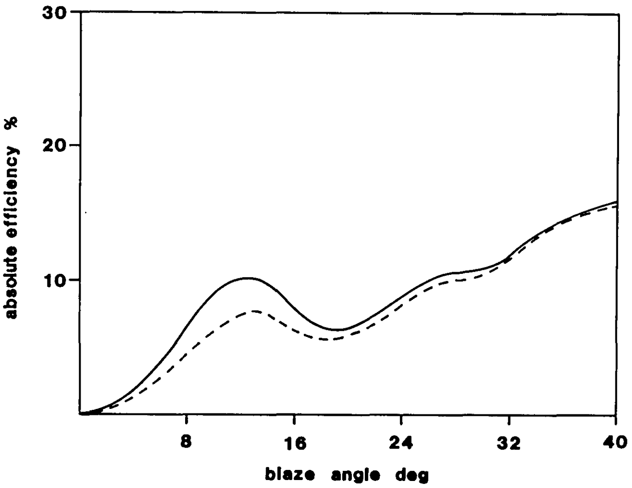

Fig. 8. Same as in Fig. 7 except for a grating with 2000 g/mm.

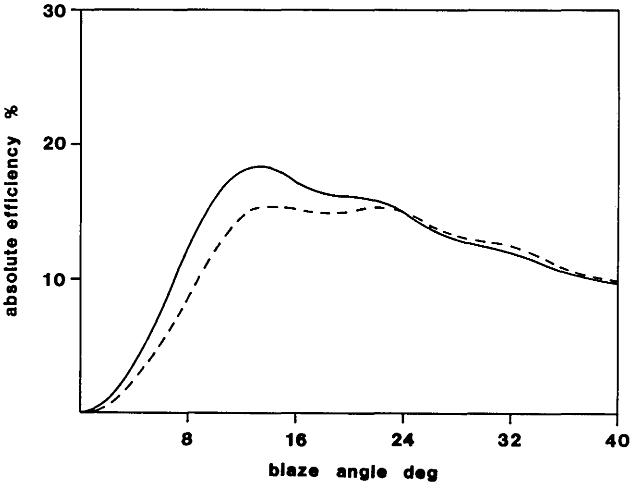

Fig. 9. Same as in Fig. 7 except for a grating with 3000 g/mm.

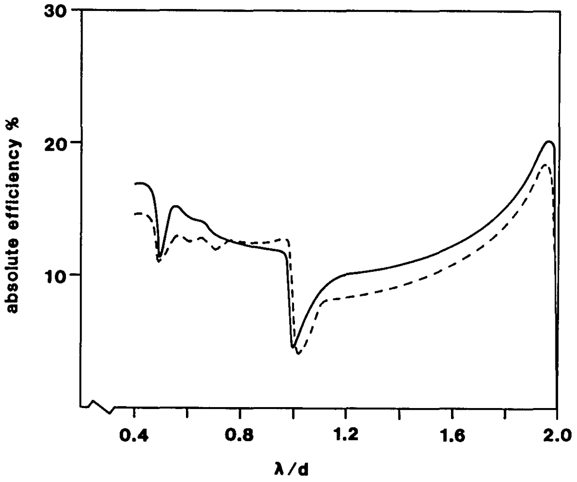

Fig. 10. First-order efficiency curves for $\theta_i = 89°$ and S polarization. Solid curve, Al grating; dashed curve, Al + Al_2O_3 (50 Å thick).

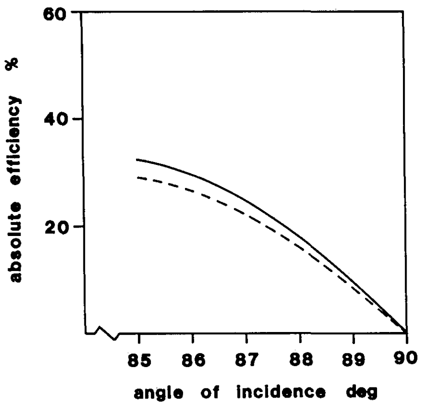

Fig. 11. Angular dependence of the efficiency for a grating with $\alpha_B = 12°$, $\lambda/d = 1.2$, and S polarization. Solid curve, Al grating; dashed curve, Al + Al_2O_3 layer (50 Å thick).

efficiency is presented in Fig. 10. Compared with sinusoidal gratings, blazed ones have higher efficiency when more than 1 order propagates; however, in the domain $1.0 < \lambda/d < 2.0$, their efficiency is considerably lower. The effect of the oxide layer is to reduce efficiency. Furthermore, the anomaly near $\lambda/d = 1.0$ is shifted toward longer wavelengths.

As can be seen from Fig. 11, at $\lambda/d > 1$, the blazed gratings have lower efficiency compared with the sinusoidal gratings of Fig. 6.

V. Influence of the Dielectric Layer Thickness

While aluminum oxide formation is self-limiting, it is interesting to calculate what happens as the thickness of a dielectric layer increases. The effect on grating efficiency is shown in Fig. 12. Blazed gratings seem to be much more sensitive to the presence of an oxide layer; a thickness of 200 Å would reduce efficiency by a factor of nearly 3.

VI. Conclusion

To achieve high efficiency in grazing incidence, a careful examination of the influence of the grating parameters and the incident wave conditions has to be carried out. We have shown that sinusoidal gratings are preferred when only first order exists, and an efficiency of 20% can be achieved for $h/d = 0.2$ and $\lambda/d = 1.9$

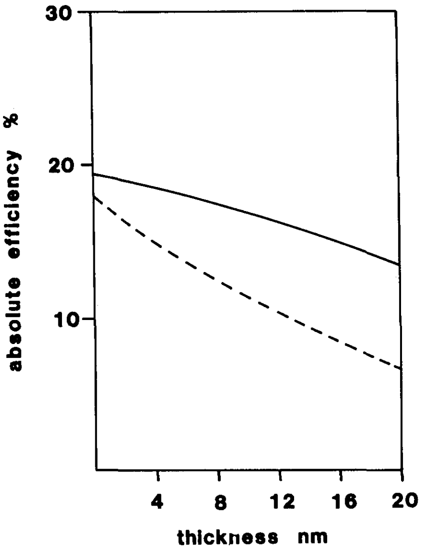

Fig. 12. First-order efficiency as a function of an oxide layer thickness for S polarization and grating with 3000 g/mm. Solid curve, sinusoidal profile with $h/d = 0.2$; dashed curve, triangular profile with $\alpha_B = 12°$, $\theta_i = 89°$, $\lambda = 0.6328$ μm.

The presence of the oxide layer on the metal coating reduces the efficiency of both kinds of grating and must be taken into account in calculations.

References

1. B. Racz, Zs. Bor, S. Szatmari, and G. Szabo, "Comparative Study of Beam Expanders used in Nitrogen Laser Pumped Dye Lasers," Opt. Commun. **36,** 399 (1981).
2. R. Petit, Ed., *Electromagnetic Theory of Gratings* (Springer-Verlag, Berlin, 1980).
3. M. C. Hutley, *Diffraction Gratings* (Academic, London, 1982).
4. I. Wilson, B. Brown, and E. Loewen, "Grazing Incidence Grating Efficiencies," Appl. Opt. **18,** 426 (1979).
5. L. Mashev and S. Tonchev, "Formation of Holographic Diffraction Gratings in Photoresist," Appl. Phys. A **26,** 143 (1981).
6. E. Popov and L. Mashev, "Conical Diffraction Mounting—Generalization of a Rigorous Differential Method," J. Opt. Paris **17,** 175 (1986).
7. E. Popov and L. Mashev, "Convergence of Rayleigh-Fourier Method and Rigorous Differential Method for Relief Diffraction Gratings," Opt. Acta **33,** 593 (1986).
8. G. Haas and R. E. Thun, Eds., *Physics of Thin Films, Advances in Research and Development, Vol. 2* (Academic, New York, 1964), Chap. 6.

This work was done during Lyuben Mashev's visit at the Analytical Products Division of the Milton Roy Co. as a postdoctoral fellow.