Volume 65, number 2 OPTICS COMMUNICATIONS 15 January 1988

BACK-SIDE DIFFRACTION BY RELIEF GRATINGS

E. POPOV, L. MASHEV
Institute of Solid State Physics, Bulgarian Academy of Sciences, boul. Lenin 72, 1784 Sofia, Bulgaria

and

D. MAYSTRE
Laboratoire d'Optique Electromagnétique, Faculté des Sciences et Techniques de Saint-Jerôme, Université d'Aix-Marseille III, Rue Henri-Poincaré, F-13397 Marseille Cedex 13, France

Received 14 August 1987

A comparison is made between the efficiency of bare and aluminum coated dielectric diffraction gratings supporting only two propagating orders utilizing substrate side light incidence. A large dissimilarity between the two types of gratings is observed and a possibility to achieve a 100% value of the absolute diffraction efficiency in Littrow mount is discussed. An almost constant value of 80% of efficiency is preserved for the aluminum grating nearly in the entire visible region.

1. Introduction

The wishes of grating users are usually connected with the possibility to obtain the maximum diffraction efficiency in a large spectral interval. Blazed gratings can simply be designed with a 100% relative efficiency [1], but the value of the absolute efficiency is restricted by metal coating absorption [2]. On the other hand, it has been shown [3] that a dielectric grating can display a 100% absolute diffraction efficiency in the transmission regime, provided the groovedepth is large enough.

However, in a superior amount of spectroscopic devices the gratings are usually used in reflection in order to avoid the necessity of mirrors which can insert additional losses. From that point of view the following question arises naturally: is it possible to propose, at least theoretically, a grating such that a 100% value of the absolute efficiency in a Littrow mount in the visible region is reached? In this paper we are trying to answer partially this question by a drastical reduction of the number of propagating diffraction orders using total internal reflection (TIR) with light incident from the substrate side. This makes it possible to achieve perfect blazing in the case of a bare dielectric grating. For an aluminum grating the back-side diffraction enables us to expand the spectral interval of a maximum efficiency over the entire visible region.

For the sake of clarity and simplicity we have not taken into account the dispersion characteristic neither of the substrate nor of the aluminum refractive indices. The reflectance of the second uncorrugated substrate surface is neglected, too.

2. Dielectric grating

With light incident from the substrate side of a bare dielectric grating (fig. 1), above a given value of the angle of incidence TIR occurs. If the grating period is properly chosen, the number of propagating orders is reduced to two: only the zeroth and the −1st orders are reflected in the dielectric, no orders being allowed to be transmitted in these conditions, according to the grating formula (see the Appendix). In this mount it can be conjectured that the dielectric grating has similar properties as the perfectly conducting grating supporting the same number of diffraction orders: as the energy balance is retained

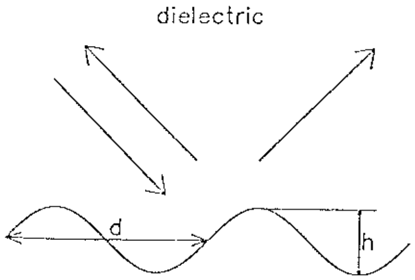

Fig. 1. Schematic representation of the system under consideration.

taking into account energy flow in the propagation orders only, the scattering matrix [4] of the diffraction system is unitary and the phenomenological approach [5] can be applied in a similar way for both types of gratings. As a consequence two main results can be expected: sinus square dependence on the modulation depth and an existence of a perfect blazing even for sinusoidal groove profiles. The second effect is the most interesting and useful one since we can not expect the existence of a blaze angle for triangular bare dielectric gratings, in contrast to the aluminum coated one (fig. 2).

The calculated diffraction efficiency curves versus the groovedepth h of a sinusoidal grating with a period $d=0.26$ μm are shown in fig. 3 for two wavelengths 550 nm and 650 nm, respectively. The calculations were performed using a computer code [6] based on the rigorous differential formalism of Chandezon et al. [7].

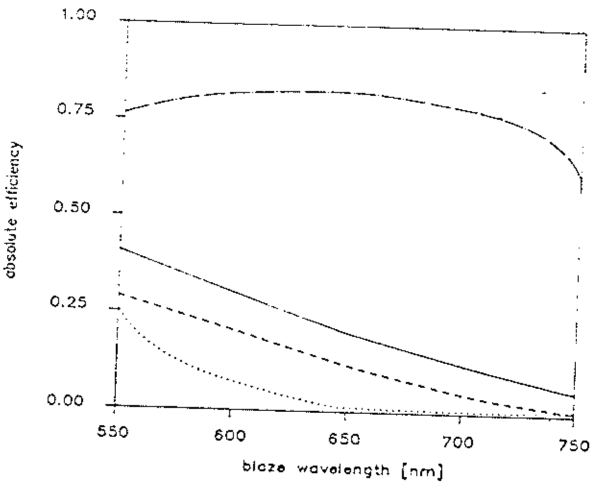

Fig. 2. Dependence of the −1st order absolute diffraction efficiency on the wavelength for gratings with triangular profile with 90° apex angle and blaze angle α such that $2\cos\alpha=\lambda/d$. Solid curve – dielectric grating, TE polarization; dotted curve – dielectric grating, TM polarization; dashed curve – aluminum grating, TE polarization; dotted-dashed curve – aluminum grating, TM polarization. Littrow mount. Dielectric refractive index $n=1.5$.

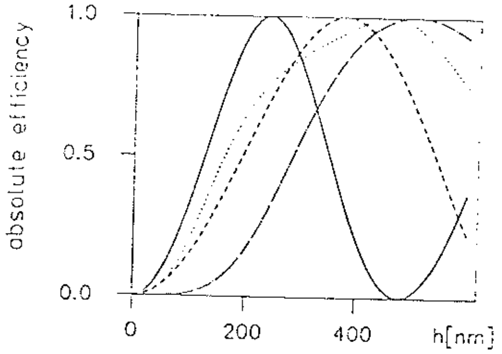

Fig. 3. Diffraction efficiency in the −1st order of dielectric grating with refractive index $n=1.5$ as a function of the groovedepth: solid line – Te polarization ($\lambda=550$ nm), dotted line – TM polarization ($\lambda=550$ nm), dashed line – TE polarization ($\lambda=650$ nm) and dotted-dashed line – TM polarization ($\lambda=650$ nm). Littrow mount.

For TE polarization (electric field vector parallel to the grooves) a 100% maximum is obtained for a reasonable and achievable experimentally groovedepth value of 240 nm. Furthermore, for unpolarized incident light the efficiency exceeds 85%. By increasing the wavelength, the location of the maximum is shifted towards greater groovedepths. Thus in the spectral dependence a peak with a halfwidth of about 100 nm exists at a fixed value of h (fig. 4). A sharp drop for shorter wavelength is due to the appearance of new orders in the air, carrying away a large amount of energy. Although the peak is relatively sharp, the perfect blazing of 100% can provide the possibility of very high performance for some practical applications like multiplexing for optical communications, at least if the wavelengths are lying not too far from each other.

3. Aluminum grating

The second set of curves in fig. 4 corresponds to the grating covered with an Al layer ($n_{Al}=1.23+16.95$). As long as the thickness of the metal exceeds 80–100 nm, it can be considered as infinite, thus the calculations have been performed

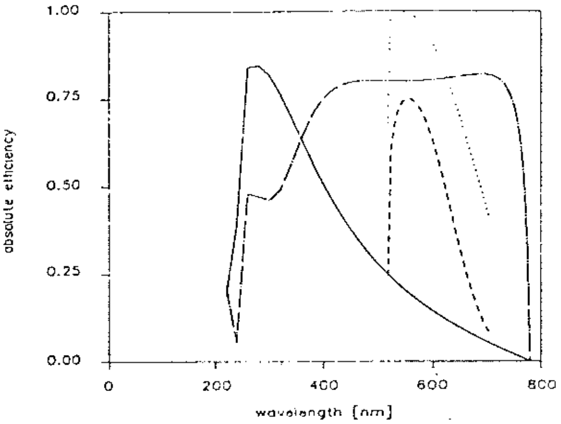

Fig. 4. Spectral dependences of diffraction efficiency for dielectric grating (dotted curve – TE polarization, dashed – TM; $h=240$ nm) and for aluminum grating (solid curve – TE, double-dashed – TM polarization; $h=92.6$ nm). Littrow mount.

assuming that the entire lower semispace is filled with aluminum. A quasiperiodicity [7] with respect to the groovedepth is observed, too (fig. 5), the maximum value for a TM polarization being achieved for ratio $h/d\approx 0.4$, the same value as in the classical mounting [8]. The spectral dependences (fig. 4) correspond to the case of $h=92.6$ nm. The main advantage is the possibility to obtain a nearly constant value of 80% of absolute diffraction efficiency for TM polarization in almost the entire visible region. When the upper medium is dielectric with refractive index $n=1.5$, the permitted wavelength interval in a Littrow mount is expanded up to three times the grating period rather that $2d$ for air-side incidence and the available spectral region is 1/3 times greater.

It must be pointed out, however, that the reflection on the second substrate boundary should insert a few percent losses for both the dielectric and metal grating, which must be taken into account in the grating optimization of the working conditions.

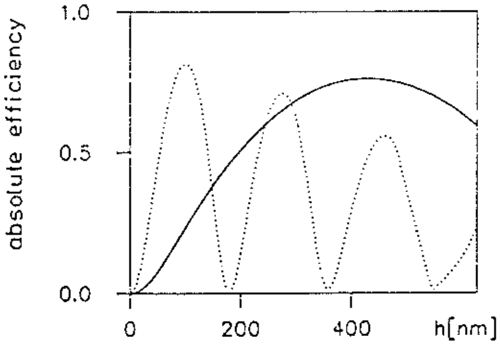

Fig. 5. Back-side difraction efficiency of aluminum grating as a function of groovedepth (solid line – TE polarization, dotted – TM). Wavelength $\lambda=550$ nm, Littrow mount.

Acknowledgement

E. Popov and L. Mashev acknowledge the financial support of the Committee for Science at the Council of Ministers under contract No. 648.

Appendix

If the upper medium is air and the refractive index of the dielectric is denoted with n, the conditions for TIR in the case of plane boundary is

$$n \sin\theta' > 1, \tag{1}$$

where θ' is the angle of incidence in the dielectric. Littrow mount is characterized by the equation

$$2n \sin\theta' = \lambda/d, \tag{2}$$

where λ is the wavelength in vacuum, and d is the grating period.

Eqs. (1) and (2) result in the following connection between λ and d:

$$\lambda > 2d. \tag{3}$$

The well-known grating formula gives the angles of propagation of diffraction orders in air (θ_a) and in the dielectric (θ_d):

$$n \sin\theta_{d,m} = n \sin\theta' + m\lambda/d, \tag{4a}$$

$$\sin\theta_{a,m} = n \sin\theta' + m\lambda/d, \tag{4b}$$

where $m=0, \pm 1, \pm 2, \ldots$.

If in the Littrow mount only the zeroth and -1st orders are propagating in the dielectric, then, according to eq. (4a):

$$3\lambda > 2nd. \tag{5}$$

Since $n>1$, from (4b) and (5) it follows that no propagation order can exist in air.

References

[1] See, for example:
R. Petit, ed., Electromagnetic theory of gratings (Springer, Berlin, Heidelberg, New York, 1980);
E.G. Loewen, Diffraction gratings, ruled and holographic, in: Applied optics and optical engineering, vol. IX, ch. 2.

[2] M.C. Hutley and V.M. Bird, Optica Acta 20 (1973) 771;
R.C. McPhedran and D. Maystre, J. Spectr. Soc. of Jap. 23, suppl. 1 (1974) 13.

[3] M.G. Moharam, T.K. Gaylord, G.T. Sincerbox, H. Werlich and B. Yung, Appl. Optics 23 (1984) 3214.

[4] D. Maystre, in: Electromagnetic surface modes, ed. A.D. Boardman (John Wiley, 1982) ch. 17.

[5] D. Maystre, M. Cadilhac and J. Chandezon, Optica Acta 28 (1981) 457.

[6] E. Popov and L. Mashev, Optica Acta 33 (1986) 593.

[7] J. Chandezon, M.T. Dupuis, G. Cornet and D. Maystre, J. Opt. Soc. Am. 72 (1982) 839.

[8] D. Mayste, M. Neviere and R. Petit, ed., in: Electromagnetic theory of gratings (Springer, Berlin, Heidelberg, New York, 1980) ch. 6.