JOURNAL OF MODERN OPTICS, 1989, VOL. 36, NO. 5, 669–674

Total absorption of light in metallic gratings: a comparative analysis of spectral dependence for shallow and deep grooves

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

(*Received 16 August 1988 and accepted 29 September 1988*)

Abstract. A numerical analysis of the total absorption of light (TAL) in shallow and deep metallic gratings with a sinusoidal profile is made for different wavelengths λ of incident light. For shallow groves, TAL is exhibited within a very narrow range of values of groove-depth h which is practically independent of λ. For deep grooves, TAL can be observed over a much broader range of values of h, for example, at $\lambda = 580$ nm and groove separation $d = 500$ nm the reflectivity of the system could be less then 1% for $0{\cdot}79 \leqslant h/d \leqslant 0{\cdot}93$, provided the angle of incidence θ is properly chosen.

1. Introduction

TAL in metallic gratings is a significant phenomenon not only in the theoretical and experimental science of gratings but also in practical applications. During the short period since the discovery of Brewster's effect in shallow gratings by Maystre and Petit [1] in 1976 and its experimental verification by Hutley and Maystre [2] some important implications of TAL have been investigated:

(*a*) some of the experimental results for surface-enhanced Raman scattering (SERS) by gratings [3, 4] and rough surfaces [5] show the influence of the resonant nature of TAL which leads to very high values of the optical power density (that is electromagnetic field enhancement (FE)) in the near-vicinity of a corrugated surface [6, 7];
(*b*) FE, which has a maximum when the absorption is total, plays the major role in some nonlinear phenomena [8–12] and in surface-plasmon luminescence [13];
(*c*) some ideas have been proposed [14] on the use of TAL in solar absorbers.

Despite its high potential there exists a strong limitation on the application of this phenomenon: it is only exhibited within a very narrow range of values of the parameters. In particular, both TAL and FE are strongly sensitive to groove-depth and only exist within a fairly small range of values of h. However, it is difficult to produce a grating with a predetermined value of the groove-depth.

Very recently Mashev *et al.* [15] discovered that TAL can also occur in deep gratings. As in the case of shallow gratings it is accompanied by significant FE which, however, is localized to the *top* of the grooves [16].

In both shallow and deep gratings TAL occurs when the trajectory of the zero of specular order in the complex α plane ($\alpha = \sin\theta$) crosses the real axis as the groove-depth is being varied. This zero accompanies the existence of the pole of the

0950-0340/89 $3·00 © 1989 Taylor & Francis Ltd.

scattering matrix of the system, this pole corresponding to surface-plasmon excitation. A peculiar feature of the zero trajectory is that, for deep gratings, it forms a loop in the complex α plane (for more details see [15]). A natural question arises in connection with this loop (from a private communication with D. Maystre): is it possible to optimize the system parameters so as to shrink the loop and thus obtain high values of light absorption over a wider range of values of groove-depth? For, if there is a small loop in the zero trajectory lying close to the real axis, then, for all values of groove-depth corresponding to the loop, low reflectivity R will be obtained.

The aim of this paper is to present some results for the spectral dependence of Brewster's effect in shallow and deep gratings, that is the calculation of the groove-depth and incident angle values (h_B and θ_B) corresponding to TAL as a function of light wavelength. For shallow grooves h_B is almost independent of λ, while for deep grooves reducing λ shrinks the loop in the trajectory of the zero of specular order and consequently high absorption can be observed over a wider range of values of groove-depth.

2. Results and discussion

A sinusoidal aluminium grating with refractive index $n = 1{\cdot}378 + i17{\cdot}616$ is illuminated at an angle θ with TM-polarized light (that is with the electric-field vector perpendicular to the grooves). The upper medium is air. It can easily be shown that, provided

$$|\sin\theta| < \lambda/d - 1 \equiv \sin\theta_c, \qquad (1)$$

only specular order is propagating in the air, where $\theta = \theta_c$ corresponds to the -1st diffraction cut-off angle. In this case the diffraction efficiency of the zeroth reflected order is equal to the total reflectivity R of the system. In the calculations that follow $d = 500\,\text{nm}$. The groove-depth dependence of R is shown in figure 1 for $\theta = 14{\cdot}28°$ and $\lambda = 628{\cdot}1$ nm. The choice of these parameters is determined from the point of intersection of the three curves in figure 3 and provides near-TAL at the three minima shown in figure 1. These three minima are due to surface-wave excitation.

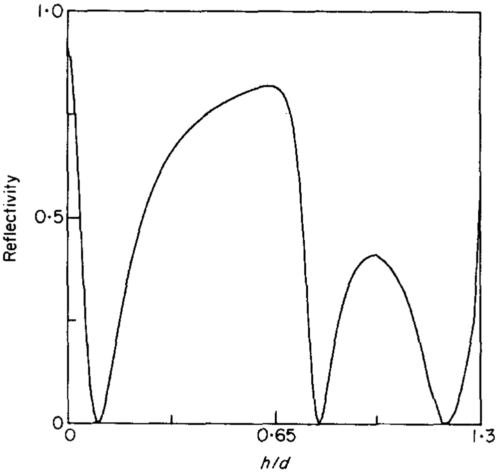

Figure 1. Groove-depth dependence of the reflectivity of a sinusoidal aluminium diffraction grating for $\theta = 14{\cdot}28°$ and $\lambda = 628{\cdot}1$ nm.

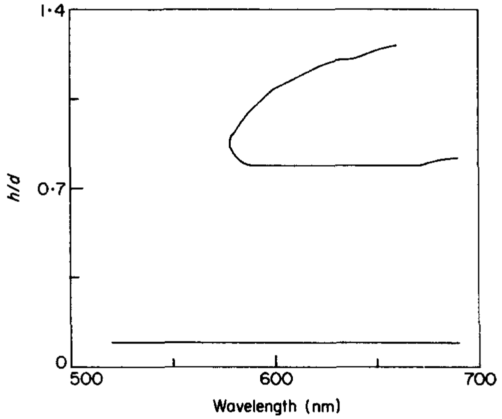

Figure 2. Spectral dependence of the values of the groove-depth for which total absorption of light occurs in a sinusoidal aluminium grating.

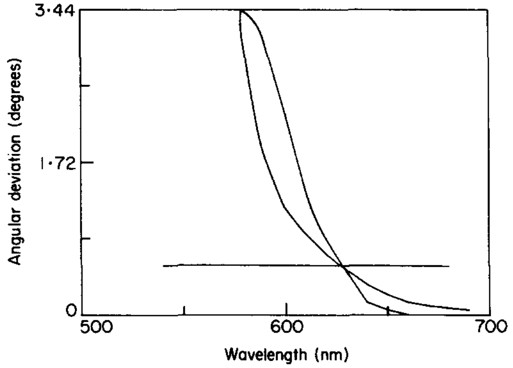

Figure 3. Corresponding to figure 2, spectral dependence of the optimum values of the angular deviation from the −1st diffraction order cut-off angle.

The first minimum appears at $h/d = 0{\cdot}1$ and becomes zero for $\theta = 14{\cdot}82°$, it represents the well known Brewster effect for shallow gratings. The other two minima (at $h/d = 0{\cdot}79$ and $1{\cdot}2$) represent the TAL recently discovered in deep and very deep gratings respectively.

2.1. *Shallow grooves*

The spectral dependence of h_B/d and of the angular deviation $\Delta\theta = \theta_c - \theta_B$ from the −1st order cut-off responsible for TAL (that is the zeros of R) are presented in figures 2 and 3 respectively. For shallow gratings the optimal values of h_B/d and $\Delta\theta$ are practically independent of λ over a wide spectral interval. A three-dimensional surface, representing the reflectivity R as a function of groove-depth and wavelength is shown in figure 4. The angular deviation $\Delta\theta = 0{\cdot}52°$ is kept fixed to provide TAL for small groove-depths. Thus TAL can be obtained in shallow gratings over a wide spectral interval provided the ratio h/d is the desired one. It is worth noting that

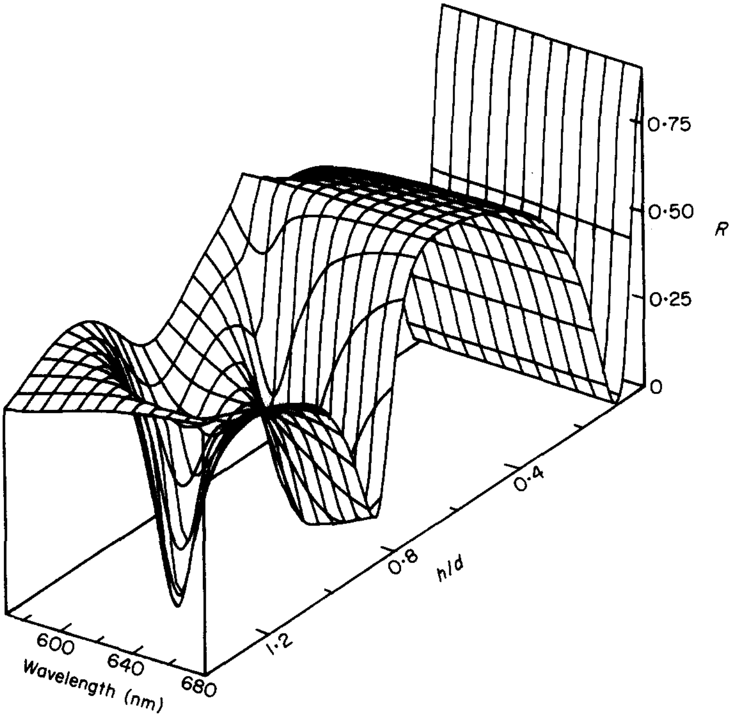

Figure 4. Reflectivity of a sinusoidal aluminium grating as a function of groove-depth and wavelength. Angular deviation from the -1st cut-off is 0·52°.

$\lambda/d>1$ is the necessary condition for equation (1), thus the investigated spectral interval begins at $\lambda=d$. On the other hand, since $\lambda\approx d$, TAL should be obtained close to normal incidence. In this case two surface-waves propagating in opposite directions are excited simultaneously and interactions occur between different zeros and poles (for more details see [17]). Consequently, the case $\lambda\approx d$ is not investigated in this paper.

2.2. *Deep grooves*

TAL is exhibited in deep gratings at two groove-depth values (figure 1). The lower value (which can be realized more easily experimentally) has an $h_B(\lambda)/d$ dependence similar to that for shallow gratings (figure 2). However the spectral dependence of its angular deviation (figure 3) differs greatly for shallow and deep grooves. Consequently, the constant angular deviation from the -1st order cut-off, chosen so as to provide optimal results for TAL in shallow gratings (figure 4), results in a very complicated pattern of $R(\lambda, h/d)$ for deep corrugation. Nevertheless, an appropriate choice of $\Delta\theta$ as a function of wavelength (corresponding to figure 3) can also optimize TAL in deep gratings.

As λ is reduced the loop in the trajectory of the zero of R in the complex α plane shrinks and its intersection points with the real α axis (responsible for TAL in deep gratings) move closer together. Below $\lambda\approx 578{\cdot}5$ nm the loop vanishes and the trajectory ceases to cross the real α axis, thus Brewster's effect ceases to exist in deep gratings below $\lambda \approx 578{\cdot}5$ nm. At this short-wavelength limit a peculiar behaviour in the spectral dependence of h_B/d (figure 2) is exhibited: it becomes tangential to the h/d axis and a high absorption value can be expected to exist over a relatively wide range of values of groove-depth. The dependence of R on h/d and θ for $\lambda = 580$ nm is shown in figure 5. The upper part of the figure corresponds to $R(h/d, \theta)$ whilst in the lower part the corresponding lines of equal reflectivity (expressed as a percentage) are given. As a result, provided θ is properly chosen, the reflectivity can be less than one percent over a wide interval $(0{\cdot}79 \leqslant h/d \leqslant 0{\cdot}93)$.

It is obvious from figure 3 that a long-wavelength limit to the investigated phenomenon also exists for deep gratings. As λ increases, the zero of R, corresponding to the highest h/d value, crosses (at $\lambda \approx 660$ nm) the 'cut' ($\Delta\theta = 0$) and then (above $\lambda \approx 660$ nm) its trajectory crosses the real α axis in the region where two diffraction orders are propagating. As λ increases beyond 700 nm, the second zero, corresponding to $h/d \approx 0{\cdot}8$, crosses θ_c (equation (1)) as well. Above θ_c the zero of specular-order efficiency is no longer responsible for TAL as the -1st order is now propagating as

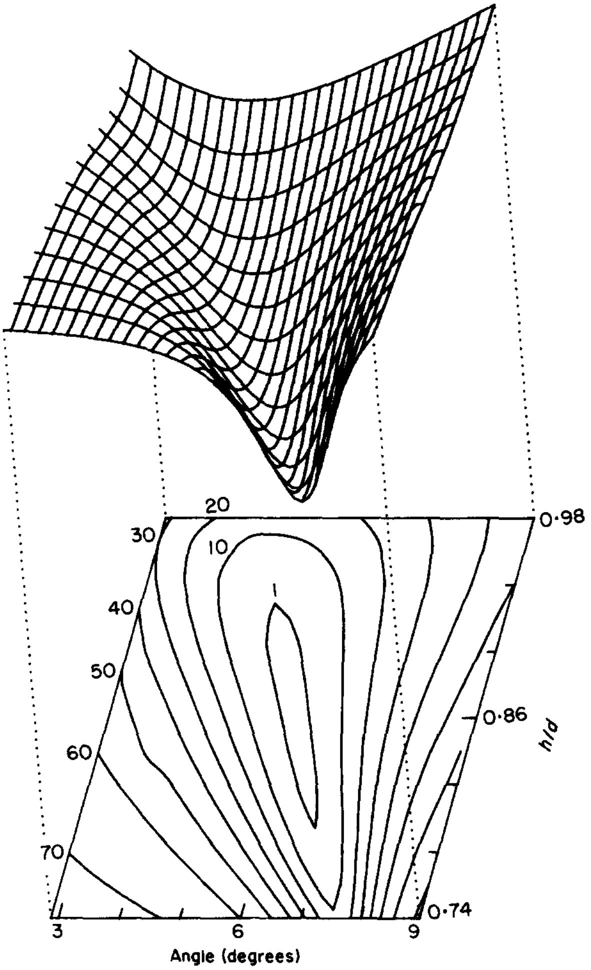

Figure 5. Reflectivity as a function of angle of incidence and wavelength (upper surface) and the corresponding lines of constant reflectivity as a percentage (lower part of figure) for $\lambda = 580$ nm.

well. If the system is lossless (for example, if instead of aluminium the substrate is a perfect conductor), all the energy of the incident light will be diffracted in the -1st order, thus perfect blazing will be achieved in a non-Littrow mount—a phenomenon of the type discovered some years ago [18–20].

3. Conclusions

A detailed numerical study of the spectral dependence of Brewster's effect in shallow and deep gratings could help to optimize the experimental investigation and practical usage of this phenomenon.

If an *equal* TAL and FE response of the system is required over a large spectral interval, and a grating of *desired* groove-depth to period ratio is available, it is best to use Brewster's effect in shallow gratings.

If a grating with a predetermined, constant groove-depth cannot easily be obtained then TAL (and the corresponding FE) can be realized using deep corrugations. It must be pointed out that by varying the period (which is easily done from a technical point of view) the optimum value of wavelength, resulting in TAL in deep gratings, can be tuned.

It is worth noting that the spectral dependence of the refractive index of aluminium has not been taken into account in the results presented in this paper. In fact, for the wavelength interval investigated, its dispersion is not very important. If the groove period were changed, it could be difficult to use these results directly as the variation of n with λ in another spectral region may become significant.

Acknowledgments

This work has been completed with the financial support of the Bulgarian Ministry of Culture, Science and Education under contract No. 648.

References

[1] Maystre, D., and Petit, R., 1976, *Optics Commun.*, **17,** 196.
[2] Hutley, M. C., and Maystre, D., 1976, *Optics Commun.*, **19,** 431.
[3] Metcalfe, K., and Hester, R., 1983, *Chem. Phys. Lett.*, **94,** 411.
[4] Yamashita, M., and Tsuji, M., 1983, *J. phys. Soc. Japan*, **52,** 2462.
[5] Reinisch, R., and Neviere, M., 1981, *Opt. Engng*, **20,** 629.
[6] Garsia, N., 1983, *J. Electron. Spectrosc.*, **29,** 421.
[7] Garsia, N., 1983, *Optics Commun.*, **45,** 307.
[8] Maystre, D., Neviere, M., Reinisch, R., and Coutaz, J. L., 1988, *J. opt. Soc. Am.* B, **5,** 338.
[9] Neviere, M., and Reinisch, R., 1983, *J. Phys., Paris*, **44,** 12, C10–349.
[10] Reinisch, R., Chartier, G., Neviere, M., Hutley, M. C., Clauss, G., Galaup, J. P., and Eloy, J. F., 1983, *Phys. Lett., Paris*, **44,** 1007.
[11] Coutaz, J. L., 1987, *J. opt. Soc. Am.* B, **4,** 105.
[12] Neviere, M., Akhouayri, H., Vincent, P., and Reinisch, R., 1987, *Application and Theory of Periodic Structures, Diffraction Gratings and Moiré Phenomena III, Proc. SPIE* (Bellingham: SPIE) Vol. 815, p. 146.
[13] Coutaz, J. L., and Reinisch, R., 1985, *Solid St. Commun.*, **56,** 545.
[14] See, for example, McPhedran, R. C., Derrick, G. H., and Botten, L. C., 1980, *Electromagnetic Theory of Gratings*, edited by R. Petit (Berlin: Springer), Chap. 7.
[15] Popov, E., Mashev, L., and Loewen, E., *Appl. Optics* (to be published).
[16] Popov, E., and Tsonev, L., 1989, *Optics Commun.*, **69,** 193.
[17] Popov, E., and Mashev, L., 1987, *Optics Commun.*, **61,** 176.
[18] Maystre, D., Cadilhac, M., and Chandezon, J., 1981, *Optica Acta*, **28,** 457.
[19] Maystre, D., and Cadilhac, M., 1981, *Radio Sci.*, **16,** 1003.
[20] Breidne, M., and Maystre, D., 1980, *Periodic Structures, Gratings, Moiré Patterns and Diffraction Phenomena, Proc. SPIE* Vol. 240, (Bellingham: SPIE), p. 165.