Total absorption of light by a sinusoidal grating near grazing incidence

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A heretofore unknown total absorption phenomenon on a diffraction grating has been demonstrated both theoretically and experimentally. It occurs only in a series of six special conditions, namely, groove shape, angle of incidence, groove frequency, depth modulation, polarization, and metal surface. None of the classical explanations for grating anomalous behavior seems to correspond to this case.

I. Introduction

Since 1902, when Wood discovered an abrupt change in the intensity in the spectrum of a continuous light source,[1] a great amount of theoretical and experimental work has been devoted to the anomalous behavior of diffraction gratings. Comprehensive introductions with an extensive bibliography on that subject are given in Refs. 2–5.

According to the classification of Hessel and Oliner,[5] two types of grating anomaly have to be distinguished:

(1) Wood anomalies, induced by energy redistribution of light in a new appearing order, which can be observed for both dielectric and metallic gratings at an angle of incidence θ_i given by

$$\sin\theta_i \pm m\lambda/d = 1, \tag{1}$$

where λ is the wavelength of the incident light, d is the grating period, and m is the diffraction-order number.

(2) Resonance types of anomaly, caused by excitation of surface waves on the air–grating interface. For bare metallic gratings, such waves are surface plasmons,[6] for metallic gratings with a dielectric overcoating leaky waves[7] and for monocoated and multicoated dielectric gratings, waveguide modes.[8,9] The general condition for the generation of that type of anomaly is

$$\sin\theta_i \pm \lambda/d = g, \tag{2}$$

where g is the propagation constant of the surface wave. Depending on the grating structure, the two anomalous effects may occur very close to each other and almost to superimpose (as in the case of aluminum gratings) or be separated (as in the case of corrugated waveguides).

In certain conditions resonance effects lead to total absorption of the incident light by high reflecting gratings. This phenomenon can be derived theoretically and is easily confirmed experimentally for bare metallic gratings and S-polarization (the electric field vector is perpendicular to the grooves[10,11]) and for dielectric overcoated metallic gratings and P-polarization. (The electric field vector is parallel to the grooves.[12]) In the latter case only zero-order reflectance was involved.

In this paper we describe an effect of total absorption of light which occurs only at specific grating and incident wave conditions and is not related to any of the above-mentioned mechanisms. Also, in contrast to Ref. 12, it applies to the S plane only, covers both zero and first orders simultaneously, and involves no dielectric overcoating. This totally unexpected behavior was discovered first in theoretical calculations and later fully confirmed by experiment.

II. Theoretical Results

The computer code from which the numerical results were derived was based on a rigorous electromagnetic theory for a conical diffraction mounting.[13] The program is applicable to both metallic and dielectric gratings with arbitrary groove profile and groove depth period ratios $h/d < 1$.[14]

The dependence of efficiency on the modulation depth h/d near grazing incidence is shown in Fig. 1. Total absorption of incident light occurs only for sinus-

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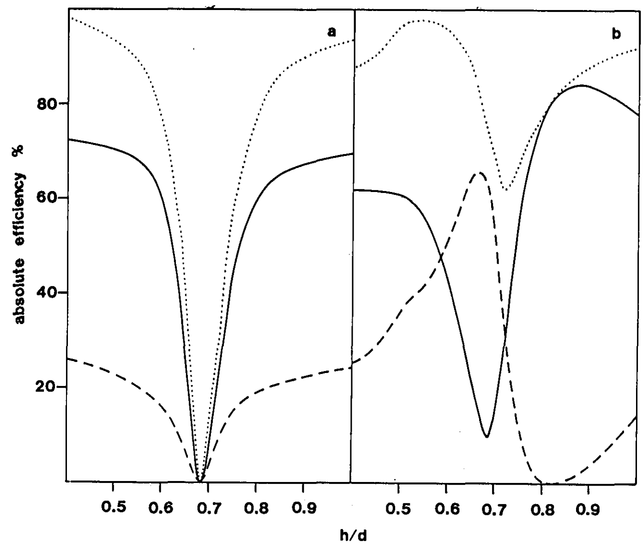

Fig. 1. Theoretical efficiency curves as a function of the modulation depth ratio h/d for an aluminum grating with $d = 0.5$ μm, $\lambda = 0.6328$ μm, $\theta = 87.85°$, and S-polarization: solid curves zero order; dashed line, first-order efficiency; dotted curve, total energy: (a) sinusoidal groove profile; (b) symmetrical triangular groove profile.

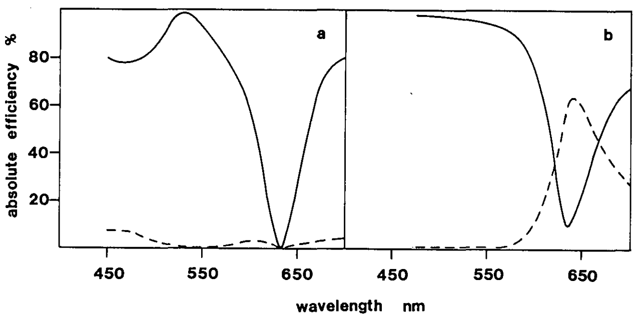

Fig. 2. Similar to Fig. 1 but with h/d constant at 0.69 and diffraction efficiency shown as a function of wavelength instead. The well-known Wood's anomaly would occur at a wavelength near 330 nm.

oidal gratings with $h/d \simeq 0.69$. Small deviations from the special conditions given in the captions of Fig. 1 are sufficient to cause a significant decrease in the light absorption. Particularly surprising is the role played by the groove shape.

In the same conditions as above, the efficiency behavior of symmetrical triangular gratings can be seen to be entirely different even though the physical dimensions of the groove do not differ by more than $\lambda/20$ from a sinusoid. The minimum of the zero-order efficiency for the V-groove is associated with an increase in the first order. In addition, the minimum of the total diffracted energy is 62% and shifted toward higher groove depths.

These features are similarly demonstrated by observing their dependence on wavelengths (Fig. 2). Note the significant enhancement at 640 nm of the first-order efficiency (up to 64%) for triangular V-groove gratings at grazing incidence (87°).

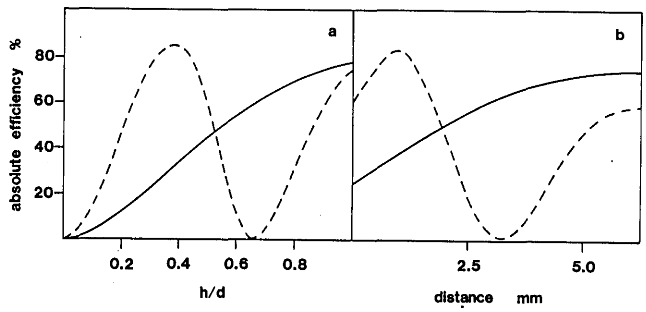

Fig. 3. Efficiency curves for a sinusoidal aluminum grating with $d = 0.5$ μm, A. D. = 2.77° (A. D. is the angular deviation or departure from Littrow), $\lambda = 0.6328$ μm: solid curve, P-polarization; dashed curve, S-polarization. (a) Theoretical efficiency values as a function of modulation depth ratio. (b) Efficiency measurements along the direction perpendicular to the grooves across the grating, as measured from a conveniently chosen reference point.

Such peculiar behavior is observed only in the case of S-polarization of the incident light. The P-polarization efficiency (not shown in the figures) is a slowly varying function for both the zero and first orders. In addition the values of the real and imaginary parts of the refractive index of the metal coating also play a significant role in this highly convoluted phenomenon, although not investigated in detail.

III. Experimental Results

To verify this unexpected phenomenon, a highly non uniform in-groove depth grating with a period $d = 0.5$ μm was produced interferometrically in Shipley AZ-1350 photoresist. After development, the grating was coated with a 2000-Å thick layer of aluminum. The exposure and development process were chosen to ensure a sinusoidal grating profile.[3,15]

The efficiency of the -1 reflected order as a function of the position of the beam from a He–Ne laser ($\lambda = 0.6328$ μm) was measured in the direction perpendicular to the grooves at 2.77° angular deviation between the incident and diffracted beams. The results are compared with the S and P theoretical efficiency as a function of the modulation depth in Fig. 3. The good agreement between two sets of curves allows us to estimate groove depth as a function of location and note that the maximum achieved modulation depth is ~90%.

At an angle of incidence of 87.85° a 1-mm diam laser beam covers ~26 mm of the grating width. According to Fig. 1, in this case only a small part of the laser spot hits the grating where the modulation has the critical depth of 69%. As a result a strong absorption line in the zero reflected order can be observed that corresponds to that modulation depth (Fig. 4).

The angular dependence of the efficiency is presented in Fig. 5. Very good agreement between the theoretical and experimental results is observed. The absorption maximum is located at an angle of incidence of 87°, very close to the theoretical value of 87.85°. While Fig. 5 shows zero-order behavior, the first-order image had exactly the same appearance.

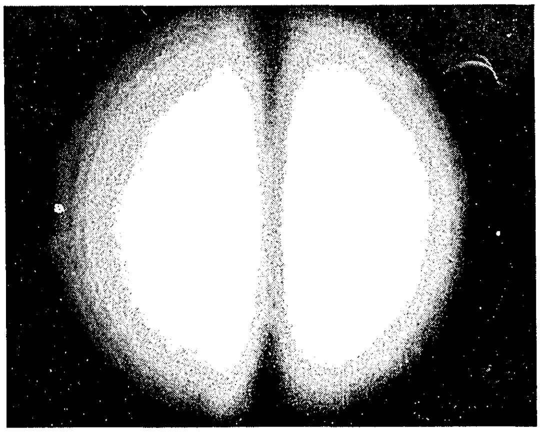

Fig. 4. Zero-order diffraction from a 2000-g/mm sinusoidal aluminum grating. It is illuminated by a 1-mm diam He–Ne laser beam, which has been focused with a 250-mm focal length lens at the 87° angle of incidence. Its divergence is small compared to the angles shown in Fig. 5. The center of the field is located at the point corresponding to 69% depth modulation, which explains the black line.

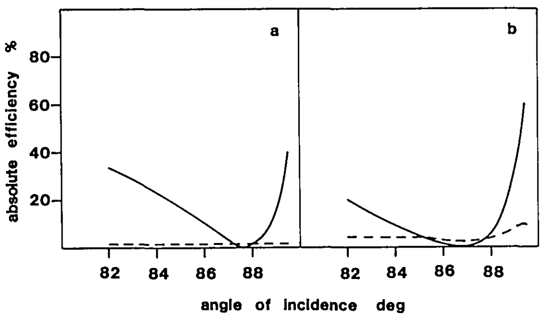

Fig. 5. Theoretical (a) and experimental (b) grating efficiency as a function of the angle of incidence. Solid curve, zero order; dashed line, first order; $d = 0.5\ \mu m$; $\lambda = 0.6328\ \mu m$; S-polarization.

IV. Discussion

In contrast to resonance anomalies where similar effects can be interpreted in terms of excitation of surface waves, we are not able to give in our case any simple physical explanation. Obviously, further developments are required to understand the nature of this phenomenon.

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