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TOTAL ABSORPTION OF LIGHT BY METALLIC GRATINGS AND ENERGY FLOW DISTRIBUTION

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Resonance and non-resonance types of total absorption of light by metallic gratings are discussed in connection with the energy flow distribution. Above the grooves the energy flow distribution for shallow and deep gratings is very similar, while in the grooves curls of flow exist. The resonance type of total absorption is accompanied by a strong compression of flow lines resulting in large electromagnetic enhancement, while for the non-resonance type the flow density near the grooves is not enlarged.

1. Introduction

A decade ago a very interesting property of metallic diffraction gratings was predicted [1] and confirmed experimentally [2]: under specific conditions a shallow grating supporting only a specular diffraction order can absorb incident monochromatic light totally. Later on it was shown that this phenomenon is accompanied by large electromagnetic field enhancement in the near vicinity of the corrugated surface, utilized in surface enhanced Raman spectroscopy [3–5], nonlinear optics and second harmonic generation [6–10].

Very recently total absorption of light was discovered at grazing incidence for gratings supporting two diffraction orders [11]. For deep and very deep gratings a phenomenon quite similar to the total absorption of light in shallow gratings [1,2] was shown to exist, too [12], accompanied by electromagnetic field enhancement [13] having some peculiarities (large electromagnetic field enhancement above the top of the grooves, an order greater then inside the grooves). Moreover, total absorptioh of light (and electromagnetic field enhancement) in shallow and deep gratings is exhibited at almost the same angle of incidence just below the cut-off of the first diffracted order.

A typical groove-depth dependence of reflectivity (equal to the zeroth reflected order efficiency, as far as only this order is propagating) of an aluminum grating is shown in fig. 1 for monochromatic TM polarized light with wavelength $\lambda = 0.6328$ μm at an angle of incidence $\theta = 14.8°$. The grating period is equal to $d = 0.5$ μm and the

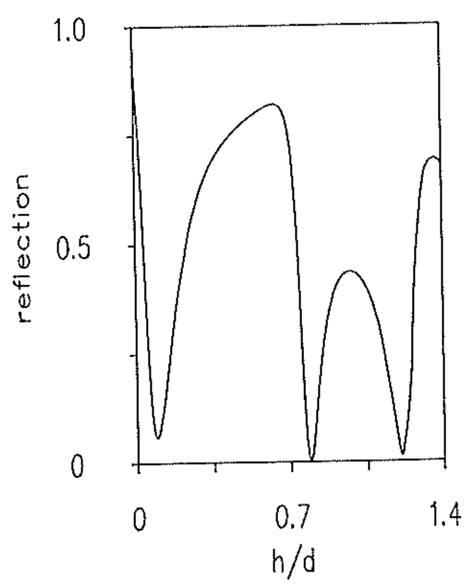

Fig. 1. Groove-depth dependence of reflectivity for aluminum grating (TM polarization, wavelength 0.6328 μm, angle of incidence $\theta = 14.8°$, grating period 0.5 μm).

refractive index of aluminum is taken to be $n_{Al} = 1.378 + i7.616$.

As has been shown in ref. [12], these three cases of total absorption of light are connected with surface plasmon excitation of the corrugated aluminum–air interface. On the contrary, total absorption of light in the grazing regime [11] happens to be a result of the intersection of two separate non-resonance phenomena – zero of the zeroth reflection order [14] and a very small value of first order in the entire interval of angles of incidence [15]; this type of total absorption of light does not lead to surface plasmon excitation and is of the non-resonance type – it is not accompanied by electromagnetic field enhancement.

However, a question of greatest importance remains unsolved: what is the reason, or physical interpretation of such peculiarities of the field density distribution and how can it be explained that there is a quasiperiodicity in the groove-depth dependence of properties not only with regard to the Littrow mount [16], but also concerning the total absorption of light (fig. 1).

Very recently [17] it was shown by Popov et al. that quasiperiodicity of groove-depth dependence of grating properties in Littrow mount is connected with the formation of curls in the energy flow distribution. In particular, there are groove-depth values, for which the energy flow distribution above the grooves is almost the same as above a flat surface; totally hidden inside the grooves one, two or more curls exist.

It is the aim of this paper to answer the above-stated question. For this sake we are investigating the energy flow distribution above and in the grooves for different cases of total absorption of light.

2. Energy flow distribution and resonance total absorption of light

Numerical results were obtained using a computer code based on the rigorous differential formalism of Chandezon et al. [18] and adapted to obtain a field and flow distribution in the near and far-field zone.

Figs. 2a–2f represent the picture of lines along which energy is flowing Away from the grating surface (approximately above 10λ), the picture is equivalent to the far-zone energy flow distribution, i.e. the evanescent orders have no influence above a distance of 10λ. As total absorption of light occurs, the far zone is characterized by a uniform energy flow towards the grating, corresponding to the incident wave. As the surface is approached, flow lines are turned to the left and the line density is increased. The near-zone energy flow distribution above the grooves represents a surface wave propagating to the left (the surface plasmon is excited through the first diffraction order). The increase in the flow line density leads to electromagnetic field enhancement. Some of the lines at the very near vicinity of the surface are turning downwards and end at the metal surface. The energy flow through the grating boundary is exactly equal to the energy flow of the incident wave. Comparing figs. 2a, 2c and 2e it can be observed that above the top of the grooves the energy flow distribution is almost one and the same for the total absorption of light in shallow, deep and very deep gratings. The second set of figures (2b, 2d and 2f) shows the peculiarities of each different case:

(1) Shallow gratings ($h/d = 0.1$): flow lines are following the grating surface. They are almost parallel to the metal–air boundary. Of course, separate lines are ending at the surface, as the metal is not perfectly conducting. The line density above the top of the grooves is slightly greater than above the bottom, as it can be expected – above the top there is "less space" than above the bottom. This results in a slight difference between the electromagnetic field enhancement values along the groove.

(2) Deep gratings ($h/d = 0.79$ and $h/d = 1.2$): inside the grooves one or two curls are formed which separate the main energy flow from the bottom of the grooves. The existence of these curls is typical for deep gratings. The process of their formation for metallic gratings supporting one or two diffraction orders is discussed in detail in ref. [17].

The separation of energy flow above the grooves from their bottom by these curls has two direct

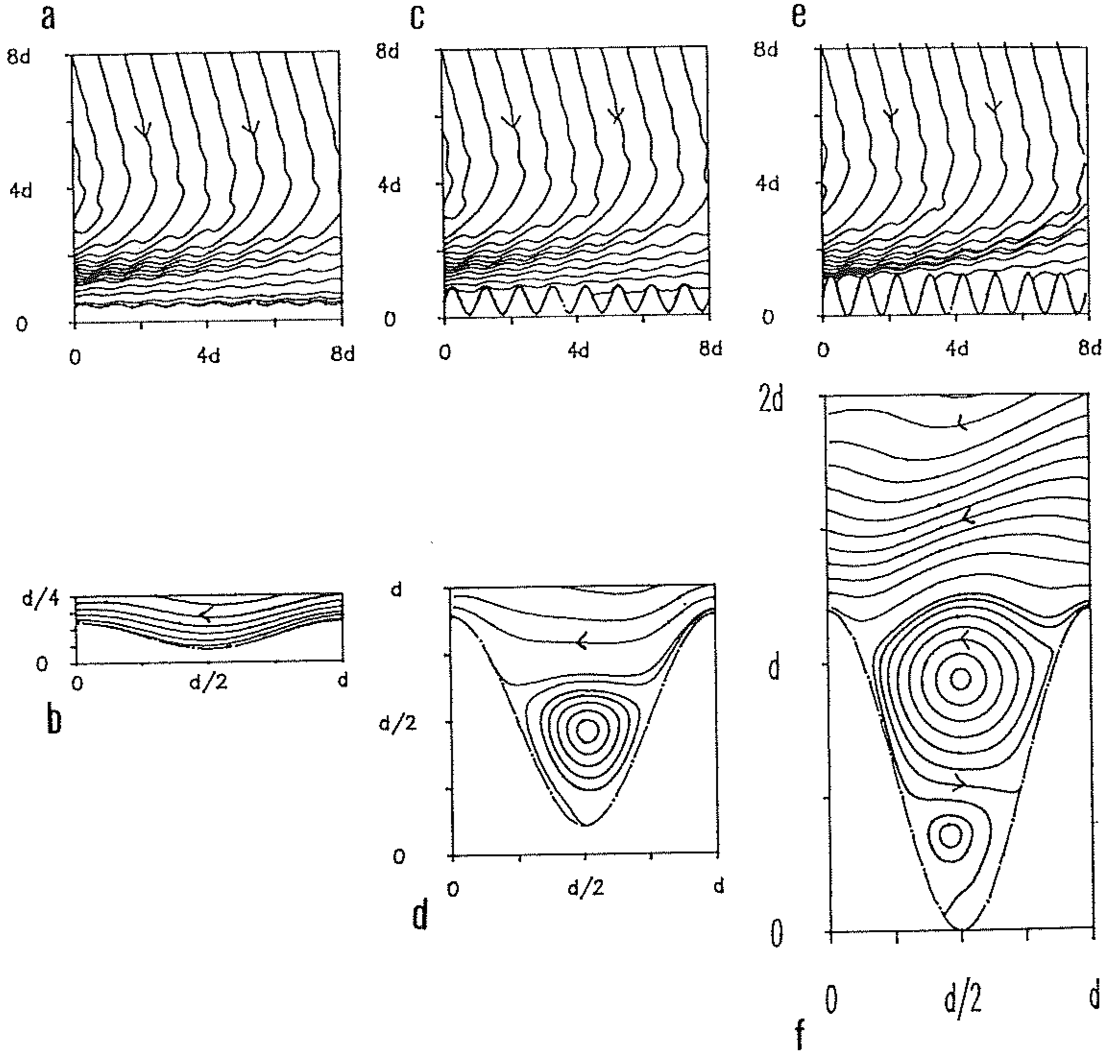

Fig. 2. Energy flow distribution at resonance total absorption of light above the groove top (a, c, e) and inside the groove (b, d, f). The grating is described in fig. 1 and has groove-depth 0.05 μm (a, b), 0.395 μm (c, d), and 0.60 μm (e, f).

consequences: (i) the energy flow distribution above the grooves (and in the far-field zone) is quite similar for total absorption of light in shallow and in deep gratings, and (ii) electromagnetic field enhancement which accompanies total absorption of light is exhibited only on the tops but not in the bottoms of deep grooves, contrary to the case of shallow gratings.

3. Non-resonance total absorption of light

Figs. 3a and 3b correspond to the energy flow distribution above and inside the grooves for the case of non-resonance total absorption of light in grazing incidence ($h/d = 0.69$, $\theta = 87.86°$). It must be pointed out that this phenomenon is not

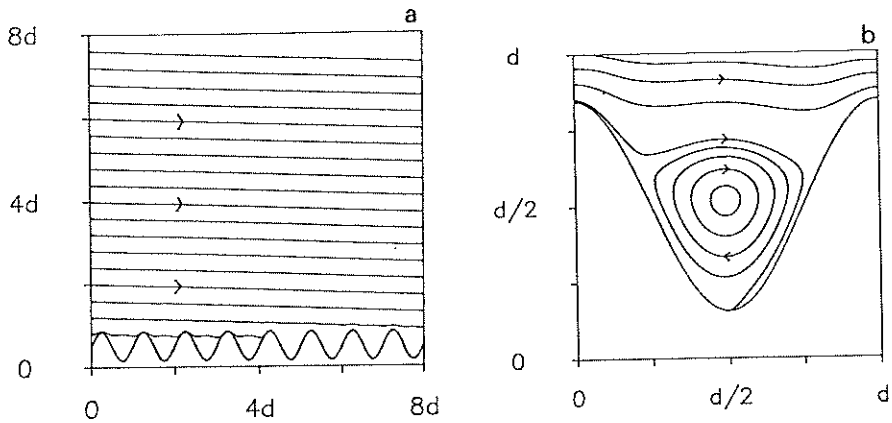

Fig. 3. Energy flow distribution at non-resonance total absorption of light in grazing incidence ($\theta = 87.86°$). Grating period $d = 0.5$ μm and groove-depth $h = 0.345$ μm; TM polarization, $\lambda = 0.6328$ μm: (a) above groove top, (b) inside the groove.

rigorously a total absorption of light: while the zeroth order efficiency is exactly zero, the first order efficiency is of order of 10^{-3}, but from a practical point of view we can speak of total absorption of light.

The energy flow distribution up to the closed vicinity of grating surface is almost the same as in the far-field zone – no turning of the flow lines in direction parallel to the surface is observed, contrary to figs. 2a, 2c, and 2e, as no surface wave is excited in this case. As a result, line density enlargement and electromagnetic field enhancement do not occur. The total change of direction in fig. 3a in comparison with figs. 2a, 2c, and 2e is due to the difference in angles of incidence. Inside the grooves (fig. 3b) the energy flow distribution picture is similar to the one in fig. 2d – groove-depth values are not so much different (in fig. 2d $h/d = 0.79$ and in fig. 3 $h/d = 0.69$). There is a curl totally hidden inside each groove.

In the previous section a similarity exists between the energy flow distribution above the grooves, while inside them the energy flow distribution is quite different. Now, comparing between fig. 2 and fig. 3 the opposite occurs: pictures inside the grooves are quite similar, while above them there is no similarity at all.

4. Conclusion

Calculating the energy flow distribution for different cases of total absorption of light in shallow and deep metallic grating, the following conclusions can be drawn:

(1) Similar physical phenomena (e.g. resonance type total absorption of light in shallow, deep and very deep gratings) are accompanied by similar energy flow distribution pictures above the grooves: flow lines are almost parallel to the grating plane in the region of 10 λ above the grooves. The turning up of flow lines of an incident wave in that direction results in increasing their density and thus field enhancement occurs. For non-resonance total absorption of light the direction of flow lines in the far and near-field zone is almost the same.

(2) Quasiperiodicity of properties of gratings as a function of groove-depth and, in particular, total absorption of light are due to formation of a definite number of curls inside each groove of deep grating. These curls separate the bottom of the grooves from the energy flow above the grooves. Thus deep grating can become equivalent to a shallow one with respect to the energy flow distribution above the grooves.

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