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Comment on 'Resonant electric field enhancement in the vicinity of a bare metallic grating exposed to s-polarized light by A.A. Maradudin and A. Wirgin'

Anomalous light absorption by lamellar metallic gratings

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Anomalously high light absorption by deep lamellar metallic gratings in TE polarization (electric field vector parallel to the grooves) is found numerically. When the grating period is small enough to support only the specular reflected order, almost the entire amount of incident light can be absorbed, provided that the grooves are deep and the lamellae are thin.

1. Introduction

In 1976 it was discovered [1;2] that under certain conditions bare metallic gratings can totally absorb the incident light in the case of TM polarization (magnetic vector parallel to the grooves), although the mirror plane of the same metal reflects it strongly. This phenomenon, sometimes called Brewster's effect in metallic gratings has since then been thoroughly investigated and its connection with the surface wave excitation along the corrugated air–metal interface is clearly revealed [3].

The interest in light absorption by highly reflecting surfaces could be explained by two main reasons. First, reduction of reflectivity is important in solar absorbers or for military purposes. Second, this phenomenon is accompanied by a significant (several orders of magnitude) electromagnetic field enhancement near the grating surface [4], a fact that plays a major role in surface enhanced Raman scattering [5–7] and non-linear optical excitation [8–11].

Andrewartha et al. [12] investigated mode excitations inside the grooves of perfectly conducting lamellar gratings and found that it could result in strong redistribution of diffracted light into different propagating orders for both the TE and TM polarization. Maradudin and Wirgin [13] in 1985 predicted theoretically that if the losses of the grating material are taken into account, mode excitation could lead to some interesting phenomena (and, in particular, resonance field enhancement inside the grooves), even when only the specular order propagates. For that purpose the grooves have to be wide enough (that is, the width of the lamellae has to be very small) to ensure mode resonance. Unfortunately, the authors of ref. [13] used an approximate theoretical method in their investigation. They assume that the tangential electric field component is zero on the side walls of the grooves, thus neglecting the losses through those walls. In fact, it was the study of Maradudin and Wirgin that provoked our interest in the lamellar grating anomalies and that initiated the present work.

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The aim of this paper is to present rigorous numerical results of light reflection by a deep metallic lamellar grating that supports only a specular reflected order. These results are obtained using the rigorous modal method [14,15] for lossy lamellar gratings with some modifications, which should be a topic of a separate paper. In the region of grating parameters where Maradudin and Wirgin [13] predicted that groove mode excitation should cause resonance field enhancement we observe strong light absorption that could reach almost 100%.

2. Reflection by metallic lamellar gratings

Let us consider a lamellar grating of period d. The width of the lamellae is equal to w, and that of the grooves to c, so that $c + w = d$. Upper medium and the medium inside the grooves is assumed to be air with refractive index $n_1 = 1$. Lower medium and the material of the lamellae is one and the same lossy metal with complex refractive index n_2. Throughout this paper, for simplicity, we assume that $n_2 = 0.4 + i4.4$, independent of the wavelength in the investigated spectral region from 400 to 800 nm. This last assumption is not a limitation of the method and of the results and is taken for convenience only. Following the grating parameters of ref. [13], we take $d = 0.38$ μm, $w = 0.03$ μm, and TE polarized light illuminates the grating surface under normal incidence. These parameters in the spectral domain $\lambda > 0.38$ μm ensure that only the specular order propagates in the upper medium. Thus, its efficiency is equal to the total energy

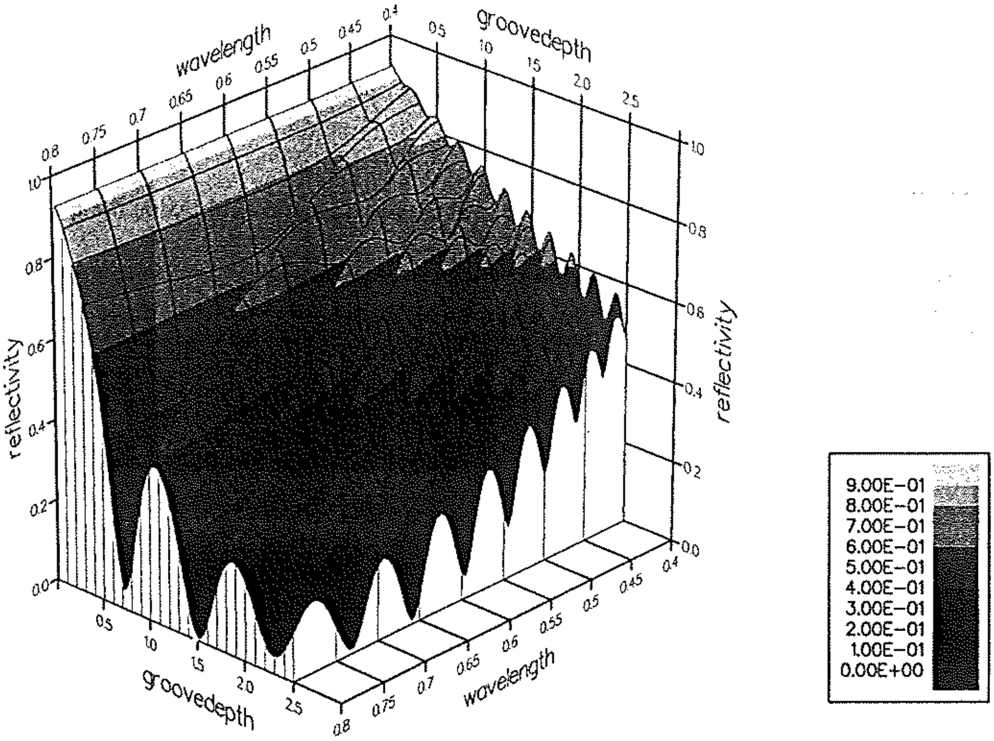


Fig. 1. Groove depth and wavelength dependence of reflectivity of a metallic lamellar diffraction grating with a period $d = 0.38$ μm, lamella width $w = 0.03$ μm, under normal incidence of TE polarized light. Wavelength and groove depth are given in microns. Metal refractive index is equal to $n = 0.4 + i4.4$.

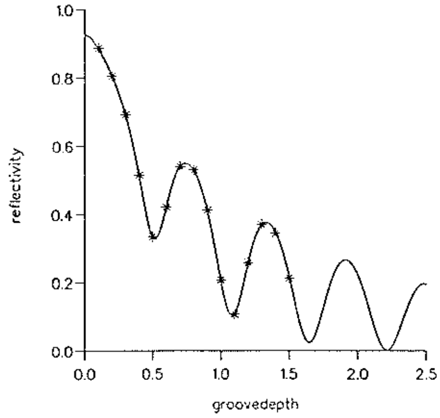


Fig. 2. Groove depth (in μm) dependence of the reflectivity of the grating discussed in fig. 1 for wavelength $\lambda = 0.694$ μm. Solid line – rigorous modal method results, asterisk – integral method results [17].

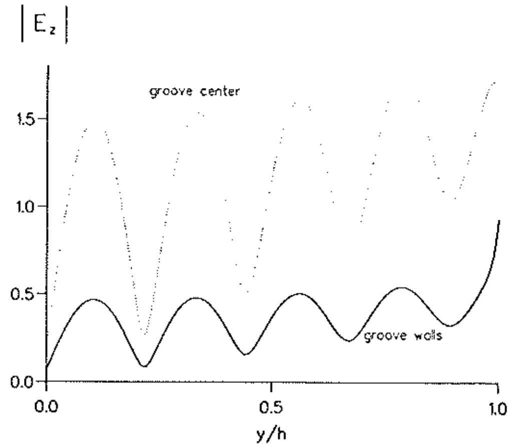


Fig. 3. Modulus of tangential electric field vector inside the groove as a function of relative height from the groove bottom. $d = 0.38$ μm, $w = 0.03$ μm, $\lambda = 0.694$ μm, $h = 2.5$ μm. TE polarization, normal incidence. Solid line – on the side wall, dotted curve – in the middle of the groove.

diffracted in air and is referred to further on as a "reflectivity".

A three-dimensional representation of the spectral and groove depth dependence of the reflectivity is presented in fig. 1. The wavelength λ and groove depth h are given in microns. For gratings not so very deep ($h < d$) a gradual smooth decrease of the reflectivity is observed in the total spectral interval under consideration. When the groove depth becomes large compared to the period, rapid oscillations with decreasing amplitudes are observed, strongly pronounced for longer wavelength.

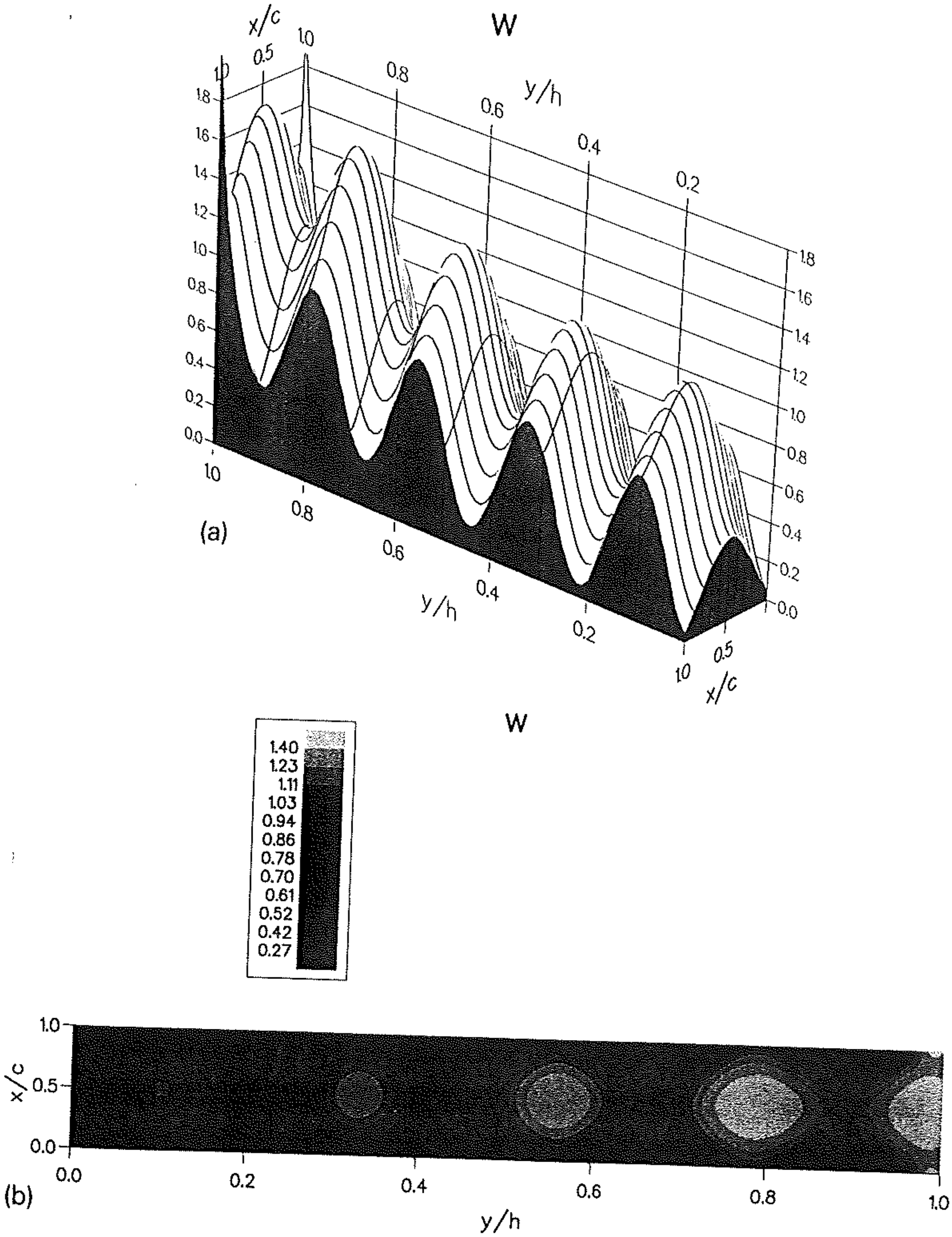
A typical cross-section for $\lambda = 0.694$ μm is shown in fig. 2. The wavelength value is chosen to provide the strongest resonance predicted by Maradudin and Wirgin [13]. For clarity, we presented it with an asterisk in the same figure as the results obtained by the rigorous integral formalism [16], that were placed at our disposal by D. Maystre [17]. A perfect coincidence is observed which could ensure us the validity of our numerical results and in the existence of this new anomaly. As an additional test, we checked the continuity of *all* the field components along the groove opening where there is no physical boundary.

3. Electromagnetic field inside the grooves

As mentioned in the introduction, the authors of ref. [13] neglected the tangential component of electric field vector E_z on the side walls of the grooves. In that case, there is no energy flow across these walls, thus no contribution to the total losses could be expected from the side walls. While in the case of shallow gratings this may be true, it is surely no more valid for deep and very deep grooves, when the area of the side walls is much larger than the bottoms and tops of the lamellae.

Fig. 3 represents the values of $|E_z|$ along the vertical coordinate y which is perpendicular to the grating plane. The origin $y/h = 0$ corre-

Fig. 4. Map of the normalized electromagnetic energy density w inside the groove for the grating presented in fig. 3. x/c is the relative coordinate along the groove bottom (c is equal to the groove width). (a) a 3D surface of the values of w, (b) isolines of constant values of w.


W
x/c
0.5
1.0
y/h
0.8
0.6
0.4
0.2
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
(a)
W
1.40
1.23
1.11
1.03
0.94
0.86
0.78
0.70
0.61
0.52
0.42
0.27
x/c
1.0
0.5
0.0
0.0
0.2
0.4
0.6
0.8
1.0
y/h
(b)

sponds to the groove bottom, and the plane $y/h = 1$ corresponds to the groove top. For comparison, we have presented the values of $|E_z|$ along the groove walls and in the middle of the groove, where it is maximal for a fixed height y. It is obvious that $|E_z|$ along the walls can by no means be neglected – it is comparable, and even in some points exceeding the minimal values in the middle of the grooves.

It was astonishing to find that the anomalously high light absorption in lamellar gratings in TE polarization was not accompanied by a significant electromagnetic field enhancement inside the grooves, in contrast to the total absorption in TM polarization. A map of the normalized electromagnetic energy density inside the groove of the grating discussed in fig. 3 is presented in fig. 4. Normalization is done with respect to the field energy of the incident wave that is taken to be equal to unity. Obviously no field enhancement is observed.

4. Conclusion

A new anomaly in the reflectivity of a lamellar metallic grating in TE polarized light is predicted theoretically using a rigorous model method and confirmed by integral formalism. The anomaly consists of strong light absorption by deep and very deep gratings supporting a single diffraction order. It appears in the region where mode excitation inside the grooves was predicted by Maradudin and Wirgin [13], but is not accompanied by a significant electromagnetic field enhancement inside the grooves.

The connections between this anomaly and other known phenomena like leaky wave excitation along lossy waveguides are now under study and should become a topic of a separate publication.

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