"ANTIBLAZING" OF GRATINGS

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Received 21 April 1988

A general property of diffraction gratings is established numerically: at a certain values of the groovedepth a grating supporting only two orders acts like a plane mirror – the efficiency of the non-specular order does not exceed 0.1% in a large angular region. This property is shown to be a direct consequence of the reciprocity theorem.

The development of rigorous electromagnetic theories [1] capable to deal with deep metal gratings [2] allows the prediction of a quite important property of the diffraction grating efficiency behavior: it groovedepth dependence is a quasiperiodical function for both TE and TM polarizations. In fig. 1 a typical example of the zeroth and −1st orders efficiencies dependence is shown for a perfectly conducting grating. The calculations were performed by a computer code [3,4] based on the rigorous differential formalism of Chandezon et al. [2].

Quite important from both theoretical and experimental point of view is the existence of the first maximum of the −1st order efficiency. This maximum, called "perfect blazing in Littrow mount" [5,6] or "Bragg type anomaly" [7] corresponds to a zero in the zeroth order efficiency.

Less attention has been paid to the minimum in the −1st order efficiency which occurs at high groovedepth values. This is not astonishing, since, at first, such a minimum is undesirable for grating users, and secondly it is manifested at groovedepth values not easy to be obtained experimentally. It was surprising to find numerically that for groovedepth to period h/d ratios corresponding to a zero in Littrow mount, the efficiency of the first order does not exceed 0.1% in the entire region of angles of incidence (fig. 2). Therefore a grating with a very high modulation depth behaves like a plane mirror. Moreover, this "antiblazing" effect appears to be a general property of gratings and it is a direct consequence of the reciprocity theorem:

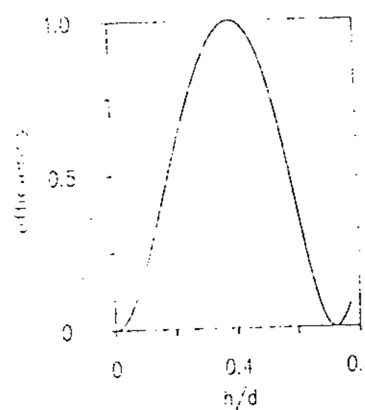

Fig. 1. Groovedepth dependence of the 0 th (solid curve) and −1st order (dotted line) efficiency of a perfectly conducting sinusoidal grating in the −1st order Littrow mount. $\lambda/d = 1.2656$. TM polarization.

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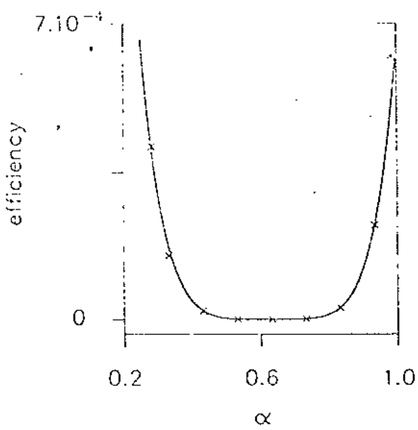

Fig. 2. The −1st order efficiency as a function of $\alpha=\sin\theta$ for a perfectly conducting sinusoidal grating. $\lambda/d=1.2656$, TM polarization, $h/d=0.72$. $C^0=C^2=0$, $C^4=0.00754$, $C^6=0.185$.

In the mth order Littrow mount for given values of λ and d of the wavelength and groovespacing, the particular value α^L of $\alpha=\sin\theta$ (θ being the angle of incidence) is given by

$$2\alpha^L=-m\lambda/d,\quad m=0,\pm1,\pm2,\ldots\qquad(1)$$

Around this mount, if a'_m and a''_m are the mth order amplitudes in the two cases, mutually symmetrical with respect to the mth order Littrow mount, i.e.

$$\alpha'+\alpha''=2\alpha^L,$$

reciprocity theorem [1] gives a connection between a'_m and a''_m:

$$\beta'_m a'_m=\beta''_m a''_m,\qquad(2)$$

where $\beta_m=k(1-\alpha_m^2)^{1/2}$, $\alpha_m=\alpha+m\lambda/d$ and $k=2\pi/\lambda$. Provided near Littrow mount no anomalies occur, $b_m=\beta_m a_m$ can be expanded in a Taylor series:

$$b_m=B_m^0+B_m^2(\alpha-\alpha^L)^2+B_m^4(\alpha-\alpha^L)^4+\ldots\qquad(3)$$

The odd members in (3) are omitted, due to the symmetry (2) of b_m with respect to α^L. The mth order efficiency $\eta_m=|b_m|^2/\beta_m$ can be represented as

$$\eta_m=C_m^0+C_m^2(\alpha-\alpha^L)^2+C_m^4(\alpha-\alpha^L)^4+\ldots,\qquad(4)$$

where

$$C_m^0=|B_m^0|^2/\beta_m,\quad C_m^2=\mathrm{Re}(B_m^0\bar{B}_m^2)/\beta,$$

$$C_m^4=[2\,\mathrm{Re}(B_m^0\bar{B}_m^4)+|B_m^2|^2]/\beta_m,\ldots,$$

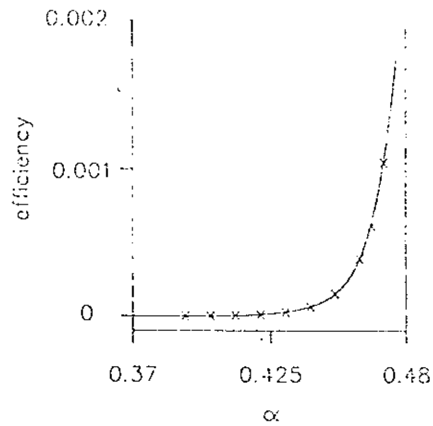

Fig. 3. The same as in fig. 2 but for $\lambda/d=0.74$, TE polarization, $h/d=0.7778$. $C^0=C^2=0$, $C^4=-0.151$, $C^6=1210$, $C^8=-2.5\times10^5$, $C^{10}=2.26\times10^7$.

and the overbar means complex conjugation.

The existence of a zero in Littrow mount requires $B^0=0$, i.e. $C^0=C^2=0$. Thus in the angular dependence of the efficiency the first non-zero term is proportional to $(\alpha-\alpha^L)^4$. Since C^4 is not very big, the efficiency is negligible in a large angular interval.

This conclusion is valid for arbitrary polarization and groove profile and in the next few examples is confirmed by rigorous numerical results. They cover perfectly conducting gratings with sinusoidal (fig. 2 and fig. 3) and symmetrical triangular (fig. 4) profiles, TE (fig. 3 and fig. 4) and TM (fig. 2) polarization and two different wavelength values ($\lambda/d=1.2656$ in fig. 2 and fig. 4 and $\lambda/d=0.72$ in

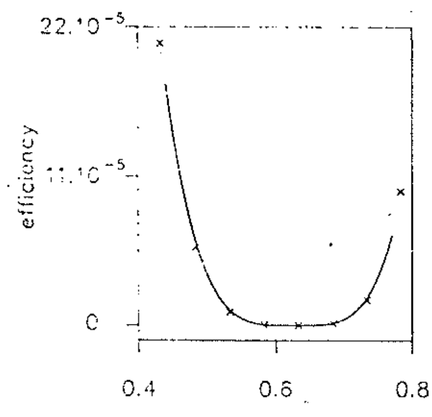

Fig. 4. The same as in fig. 2 but for symmetrical triangular profile with $h/d=0.84$, $C^0=C^2=0$, $C^4=0.152$.

fig. 3). The crosses correspond to numerical values, calculated using rigorous method and the curves - least square fit of eq. (4) with $C^0 = C^2 = 0$. The values of C^4 and C^6 are given in the figure captions. In all of the cases a very good agreement is observed.

Real metal gratings need a separate analysis. The conclusions concerning reciprocity theorem are still valid, but the minimum value in the efficiency dependence on the groovedepth in Littrow mount is not a perfect zero. Although C^0 and C^2 in eq. (4) do not vanish, the numerical calculations show that they remain negligible, thus the "antiblazing" effect can be observed for real metal gratings, too (fig. 5).

The same results are obtained for perfectly conducting gratings supporting more than two orders: although $\min(\eta_{-2}) > 0$, the -2nd order efficiency is very small in a large angular domain, provided the groovedepth is suitably chosen (fig. 6).

In the groovedepth dependence of the zeroth order efficiency (fig. 1) of grating supporting two propagating orders there exists a zero, too, corresponding to a perfect blazing in the -1st order. Unfortunately for grating users, the value of the zeroth order efficiency is much strongly influenced by the angular deviation from Littrow mount than the results shown in figs. 2–6, thus perfect blazing is obtained for relatively small interval of angles of incidence. Energy balance requires that

$$\eta_0 = 1 - \eta_{-1} \, . \qquad (5)$$

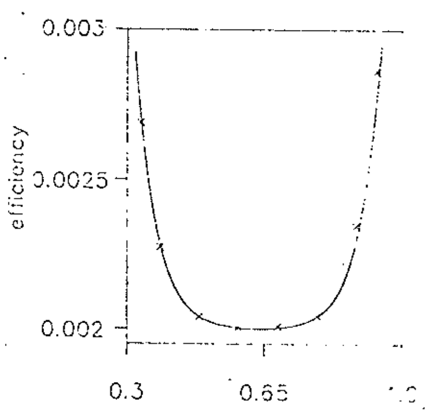

Fig. 5. The -1st order efficiency as a function of α for sinusoidal aluminium grating ($n_{Al} = 1.378 + i\,7.616$). $\lambda/d = 1.2656$. TM polarization. $h/d = 0.679$. $C^0 = 1.97 \times 10^{-9}$, $C^2 = 1.3 \times 10^{-9}$, $C^4 = 1.3 \times 10^{-2}$, $C^6 = 0.497$, $C^8 = 2.23$.

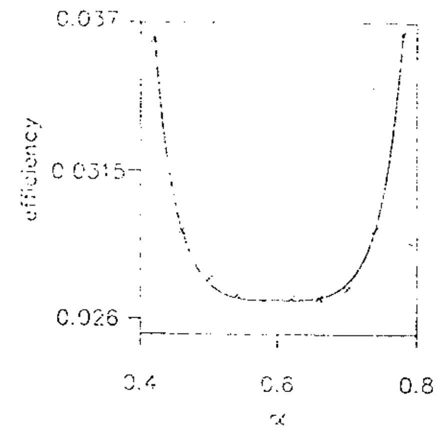

Fig. 6. The -2nd order efficiency as a function of α for a sinusoidal perfectly conducting grating. $\lambda/d = 0.6$. TM polarization, $h/d = 0.5745$. $C^0 = 0.0267$, $C^2 = 0$, $C^4 = 6.6$, $C^6 = -107$, $C^8 = 5920$.

If now $\eta_0(\alpha^L) = 0$ then the substitution of (4) expressed for the -1st order efficiency in the right hand side of eq. (5) shows that the first non-zero member in the expansion of η_0 in the vicinity of α^L is proportional to $(\alpha - \alpha^L)^2$. Least square fitting (solid line in fig. 7) confirms these considerations – the angular dependence of the zeroth order efficiency is proportional to the square of the deviation from Littrow mount, provided the groovedepth corresponds to a perfect blazing in Littrow mount.

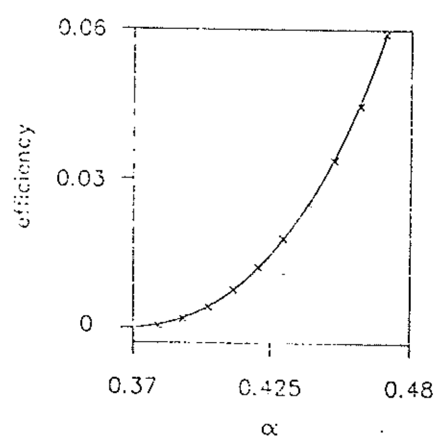

Fig. 7. The zeroth order efficiency as a function of α for a sinusoidal perfectly conducting grating. $\lambda/d = 0.74$. TE polarization. $h/d = 0.39$. $C^0 = 0$, $C^2 = 3.72$, $C^4 = 165$.

Acknowledgements

E. Popov acknowledge the financial support of the Committee for Science at the Council of the Ministers of Peoples Republic of Bulgaria under the contract No 648.

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