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Reflection gratings in the visible region: efficiency in non-polarized light

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Numerical analysis of efficiency is made for holographic diffraction gratings with deep and very deep grooves (modulation depth up to 100%). The spectral interval with very high efficiency values could be shifted toward longer wavelengths away from the cut-off and plasmon anomalies, provided the grooves are very deep. In this case the efficiency becomes less polarizationally dependent.

1. Introduction

It is already well-known that the diffraction efficiency of a reflection grating supporting only two diffraction orders is a quasiperiodical function of its groove depth [1–4], strongly depending on the polarization of light. In particular, for TM polarized incident light (electric field vector perpendicular to the grooves) the −1st order efficiency η_{-1}^{TM} has a maximum at about 40% modulation depth (groove depth h to period d ratio), decreases for deeper gratings and reaches a second maximum at about 100% modulation.

Up to know all the detailed numerical and experimental investigations of holographic diffraction gratings efficiency are carried out for moderately deep grooves (modulation up to 50%), probably due to the commercial availability of such gratings and their high efficiency in TM polarized light. Unfortunately, the maximum efficiency in the other polarization (TE, or p, or s) for the same modulation values lies in the spectral region around $\lambda/d \sim 2/3$ (λ/d is the wavelength λ to period d ratio) where sharp anomalies appear due to higher order cut-off and surface wave excitation (see, for example, refs. [3] and [5]. Up to now the only commercially available gratings with high diffraction efficiency in non-polarized light (i.e., having simultaneously maximum efficiency for both fundamental cases of polarization) are the echelles–blazed gratings with large periods (several tens or hundreds wavelengths), working at high angles of incidence in order to increase their spectral selectivity [6,7]. Unfortunately, echelles require special filters to separate the adjacent orders which "eat" a significant part of the incident energy [8,9]. Holographic gratings have two undoubtful advantages: lack of ghosts and lower stray-light level [10], although it is not quite clear which type of gratings is preferable. For example, whereas Kielkopf [12] finds out that the usage of holographic gratings increases spectrometer efficiency in comparison with echelles, Tull [8] concludes just the opposite.

On the other hand, recent technologies allow manufacturing of holographic gratings with much deeper grooves, h/d exceeding 1 [6]. Although such gratings are not available commercially, yet, we hope that this restriction is just a matter of time to be solved after overcoming some production problems – deposition of smooth aluminum layer on the steep groove slopes and difficulties in separation of the replicas from the master in the replication process. The existence of these difficulties makes it especially important to investigate in detail the properties of very deep holographic gratings in order to know their advantages (or disadvantages) in comparison with commercially available gratings.

The aim of this paper is to present a detailed numerical study of sinusoidal aluminum gratings in the

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spectral interval where only two diffraction orders propagate. In particular, we are interested in the efficiency in non-polarized light in a large interval of groove depth values. If large modulation depth causes noticeable quality improvement, our results should stimulate the interest of fabrication of such gratings and their utilization in high resolution spectroscopy.

2. Groove depth dependence of holographic grating efficiency

As already mentioned, grating efficiency exhibits a quasi-periodical behaviour as a function of groove depth h, a fact that becomes absolutely obvious when the grating supports only two diffraction orders. As is shown recently [4] this behaviour is determined by the formation of curls in the energy flow distribution inside the grooves of deep and very deep gratings. Due to the different boundary conditions, the efficiency variation due to the groove depth changes differs significantly for the two fundamental polarizations (fig. 1). The TM efficiency, η_{-1}^{TM}, changes more rapidly than that of TE, η_{-1}^{TE}, and in the modulation interval from 0 to 120% η_{-1}^{TM} exhibits two maxima, whereas η_{-1}^{TE} only monotonically increases. The efficiency in non-polarized light, η_{-1}^{NP}, the averaged of the two efficiencies, has a maximum at a modulation $h/d \approx 40\%$ and a second one at $h/d \approx 100\%$. For further reference these two cases are distinguished as class I and II, respectively. In this example, we have chosen a grating with a period $d = 0.5$ µm. Of course, any other choice could be well motivated, but it would lead only to a corresponding shift in the spectral interval, as discussed in the next section.

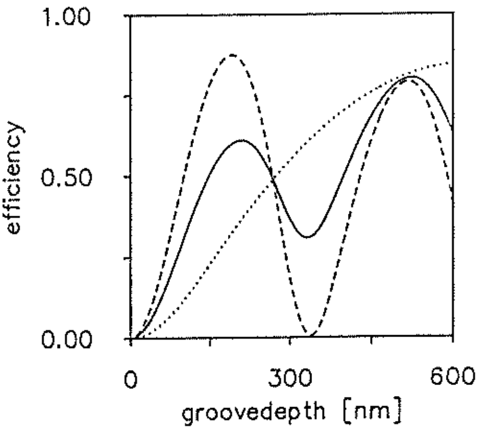

Fig. 1. Absolute efficiency in the −1st order of an aluminum sinusoidal diffraction grating as a function of groove depth in polarized and non-polarized light. Period $d = 0.5$ µm, wavelength $\lambda = 0.6328$ µm, Littrow mount. Dotted line – TE polarization, dashed line – TM polarization, solid line – non-polarized light.

The ratio between the values of η_{-1}^{NP} in cases I and II depends obviously on wavelength, therefore it is impossible to have a general conclusion which case is preferable. For that sake a detailed investigation in a large spectral interval is necessary and it is presented in the next section.

3. Spectral behaviour of −1st order efficiency

Typical spectral curves of efficiency in non-polarized light η_{-1}^{NP} for two representatives of classes I and II are drawn in fig. 2 with continuous lines. We are interested in their comparison at a level of $\eta_{-1}^{NP} \geq 60\%$ (high efficiency), but also at $\eta_{-1}^{NP} \geq 70\%$ (peak efficiency). For that sake we introduce the notion "interval of best performance" (IBP) – the spectral interval where the grating exhibits high efficiency, $\eta_{-1}^{NP} \geq 60\%$, in non-polarized light.

The first conclusion to be drawn from fig. 2 is that *the maximum efficiency cannot be improved significantly by simply increasing the modulation.* In both cases I and II it remains slightly above 75%. Secondly, the IBP has almost the same length for the two gratings, but *is shifted towards longer wavelengths in case* II: the IBP extends from 330 to 620 nm (centered at $\lambda = 475$ nm) for grating I, and from 520 to 740 nm in case II (centered at $\lambda = 630$ nm). The main difference between gratings I and II, however, could be found when returning again to the efficiency in polarized light. In case I two sharp TM anomalies exist inside the IBP: a strong one (A) just on the boundary of IBP and a weak one (B) inside the interval. In case II there is a strong TE anomaly (C) remote from the IBP and a weak TM anomaly (D) at its boundary. The existence of such anomalies and, in particular, the difference between the efficiencies in polarized and non-polarized light, $\Delta\eta = |\eta_{-1}^{TE} - \eta_{-1}^{NP}| = |\eta_{-1}^{TM} - \eta_{-1}^{NP}|$, could be undesirable for

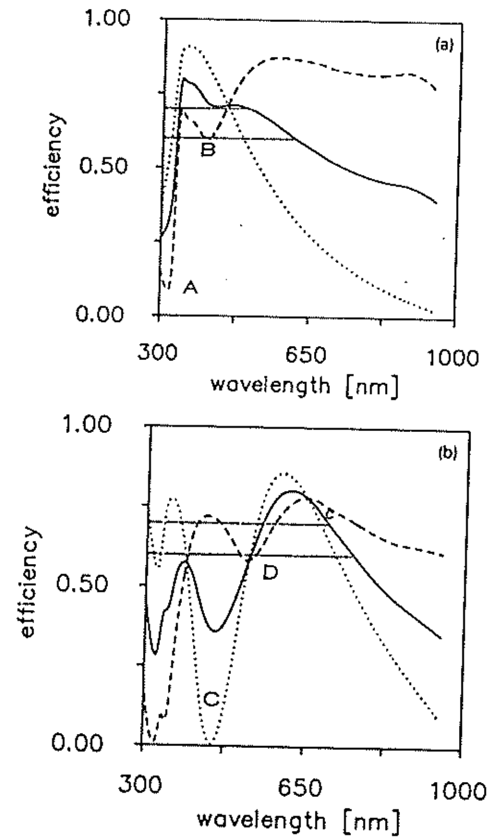

Fig. 2. Spectral behaviour of the −1st order absolute efficiency in a Littrow mount. Period $d=0.5$ μm. (a) $h/d=36\%$, (b) $h/d=104\%$. Dotted curve – TE polarization, dashed curve – TM polarization, and solid curve – non-polarized light. Different anomalies are marked from A to D. Horizontal dotted lines mark the 60% and 70% efficiency levels in non-polarized light.

practical spectroscopic reasons. In particular, for grating II $\Delta\eta$ does not exceed 10% inside the entire IBP, whereas for grating I $\Delta\eta$ increases up to 25% not only at the boundaries of the IBP, but also inside it, mainly due to the stronger anomalies. Therefore, *the behaviour of grating* II *is much less polarizationally dependent than grating* I.

The general conclusions about the performance of the two gratings, drawn at a particular groove depth or wavelength value are confirmed when a complete numerical investigation is carried out in the entire wavelength and groove depth interval. Varying λ and h, the regions of high ($\geqslant 60\%$) and very high ($\geqslant 70\%$) efficiency in non-polarized light are determined and plotted in fig. 3. The location of anomalies A–D in TE or TM polarized light is also shown. Whereas the width of IBP does not change significantly from case I to case II, there are two obvious differences: (i) for extremely deep gratings (II) the IBP is shifted toward longer wavelengths, (ii) diffraction efficiency anomalies lie inside the IBP for gratings of class I and outside it for case II.

Of course, the IBP could be changed simply by varying the period. An example of the properties of a grating with period $d=0.62$ μm is presented in the same fig. 3 (curve 9) to illustrate this possibility. Unfortunately, this change does not eliminate the TM anomaly inside the IBP (curve 10).

Another important question when gratings are utilized in spectroscopic devices is the influence of the angular departure from Littrow mount, as far as gratings only rarely work in autocollimation regime. Figure 4 presents angular dependencies of efficiencies of gratings I and II at different wavelength values. Evidently, gratings I and II have almost identical stability of their high Littrow mount efficiencies with respect to variation of angle of incidence.

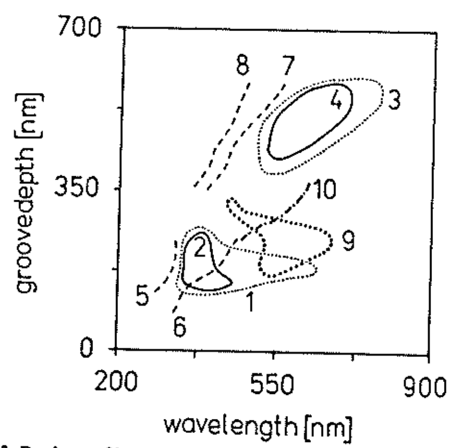

Fig. 3. Regions of best performance (non-polarized light) in the groovedepth–wavelength plane. Curves 1, 3, 9 are 60% efficiency contours, 2 and 4 are 70% efficiency contours (1, 3, 2 and 4 for period $d=0.5$ μm, 9 for $d=0.62$ m). Lines 5, 6, 7, 8, 10 represent the location of different anomalies (5, 6, 7, 8, anomalies A, B, D and C, respectively for $d=0.5$ μm, 10 TM anomaly for $d=0.62$ μm).

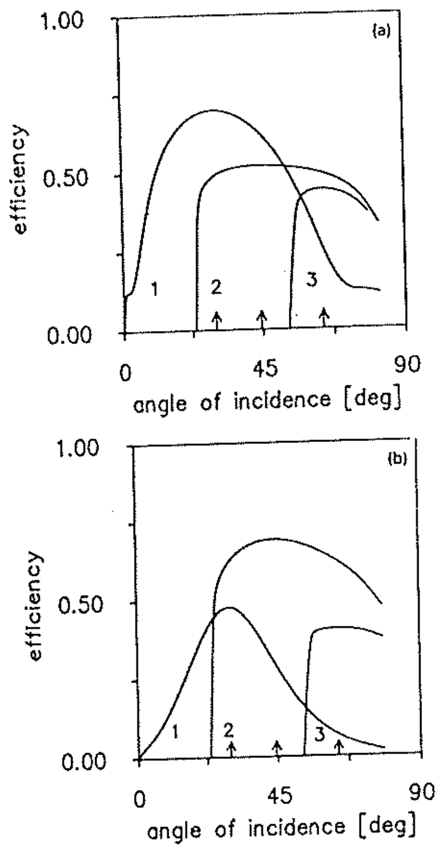

Fig. 4. Angular behaviour of the −1st order efficiency in non-polarized light. Period $d=0.5$ μm. Wavelength values: 1, 0.5 μm, 2, 0.7 μm; and 3, 0.9 μm. Exact Littrow angles are marked by arrows. (a) $h/d=36\%$, (b) $h/d=104\%$.

4. Conclusion

The following general conclusion could be made on the basis of the numerical results of the previous section: extremely deep sinusoidal diffraction gratings (modulation about 100) do not manifest a significant increase of efficiency nor a wider spectral interval with high diffraction efficiency in comparison with moderately deep gratings (modulation about 40). However, the spectral interval of best performance of the extremely deep gratings is free of anomalies and their properties are much less polarizationally dependent.

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