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Period interaction on diffraction efficiency of blazed transmission gratings

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Abstract

The period interaction on diffraction of the blazed transmission gratings is analyzed with a modified extended scalar theory. For one certain period, the lights reflected from the neighboring structures can be refracted by the grating facets and form two extra fields on the bottom facet of blazed transmission gratings. The effects of this period interaction versus several diffraction orders for a fixed fabrication error of blazed transmission gratings with intermediate structures are discussed for both TE and TM polarizations. The results have been compared with those obtained with finite-difference time-domain method.

Keywords: Period interaction; Blazed transmission grating; Diffraction efficiency

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1. Introduction

The interest of diffractive optical elements has been triggered by the higher precision fabrication technologies of micrometer and nanometer sized structures of almost arbitrary shape, such as laser direct writing [1], electric beam writing [2] and ion-beam etching [3]. Already along the transition from refractive to diffractive micro-optical components, this issue poses an enormous challenge for both the analysis and design. Diffraction efficiency is definitely a crucial parameter of blazed transmission gratings, which is related to comprehensive factors, such as grating material, the ratio of structure period to illumination wavelength (Λ/λ), fabrication error of inclination angles and height, shadowing effects [4], etc. Fabrication error is inevitable in any fabrication process and thus ideal sawtooth relief is not available, which results in the enhancement of the period interaction deriving from the increased lights reflected by both of the blaze and passive facets of the neighboring structures.

Rigorous coupled wave analysis [5] and finite-difference time-domain (FDTD) [6–8] which are both essentially based on Maxwell's equations can obtain the exact electric and magnetic fields. The FDTD has been used extensively in calculating various electromagnetic problems, and its popularity continues to grow as computing cost continues to decline. These two approaches adopt boundary conditions at the interface and can afford the exact final results, e.g. diffraction field and efficiency, but on the other hand, the calculation process of the individual diffractive component generally provides little insight for understanding the covered physical mechanism and hardly gives a comprehensive explanation of the period interaction. A modified extended scalar theory (MEST) is proposed to interpret the diffraction of blazed transmission gratings with moderate structure period [9], in which the diffraction field is considered to be the interference of

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four subfields investigated in the problem of diffraction of a plane wave by an infinite half-plane. It is observed that MEST gives more reliable diffraction efficiency than that of extended scalar theory, and that the light reflected from neighboring structures is a factor to be reckoned with in the distribution of the diffraction energy.

In this work we are interested in this period interaction, another factor concerned to the diffraction efficiency. Both TE and TM polarizations are considered. The problem is quantitatively and qualitatively studied and the results have been compared with FDTD approach.

2. Theory of period interaction

In the actual diffraction process, in our opinion, any of the structure of one certain period of the grating does not exert independently, as shown in Fig. 1. Refractive index of the air is n_1, and the index of grating substrate is $n_{Grating}$. The grating is with period Λ, height h, blaze angle θ and passive angle β. According to the lights which have contribution on the diffraction field on the bottom facet of the grating, we figure four subfields which are derived in detail in Ref. [9]. On the bottom facet of the grating the diffraction field is the interference of the four fields: two direct transmission fields E_l and E_r; and two extra fields, E_{la} and E_{ra}, formed by lights reflected from the grating facets of the left and right neighboring structures, respectively. These two extra fields are thought to be the headstream of the period interaction to participate in the modulation of the intensity of the diffraction field and subsequently influence diffraction efficiency.

In our method, field E_r is treated completely different from that in the extended scalar theory in which it is thought to be the critical reason of the efficiency reduction because of a direct geometrical shadow or a dead zone at the passive facet, known as the shadowing effect [4]. We take E_r as one of the two direct transmission fields in that in this intermediate structure it does possess indispensable contribution to the diffraction field, even part of the incident energy is lost via reflection on the passive facet.

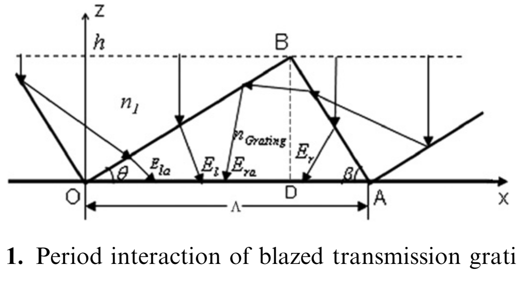

Fig. 1. Period interaction of blazed transmission gratings.

The total diffraction field and the field without period interaction are expressed as

$$E(x) = E_l + E_r + E_{la} + E_{ra} \tag{1}$$

and

$$E'(x) = E_l + E_r. \tag{2}$$

According to the scalar theory, the diffraction efficiency can be written as

$$\eta_m = \left| \frac{1}{\Lambda} \int_0^{\Lambda} E(x) \exp[-im(2\pi/d)\,x]\mathrm{d}x \right|^2, \tag{3}$$

where m is the diffraction order and Λ the grating period.

3. Results of the calculation

We analyzed three blazed transmission gratings with the ratio $\Lambda/\lambda = 13$, 9 and 5. In the fabrication process, structure period and height can be controlled exactly, making $\beta = 90^\circ$ is a hard task. We take $|\mathrm{OD}| = 0.95\Lambda$ as a fixed fabrication error, which can be easily achieved. For each case we calculated three groups of diffraction efficiency: the first group is η_0, obtained by substituting (1) into (3); and the second group is η, obtained when period interaction is excluded, namely substituting (2) into (3); for comparison, the last group η_{FDTD} is the rigorous results of FDTD.

The grating is assumed to be illuminated normally with a monochromatic plane beam. The optimal grating depth is chosen according to extended scalar theory $h = \lambda/(n_{Grating} - 1)$, $h = 1.266\,\mu\mathrm{m}$ when $\lambda = 0.6328\,\mu\mathrm{m}$, $n_{Grating} = 1.5$. These parameters are quoted in the following calculation. Fig. 2(a) gives the diffraction efficiency of the grating with ratio $\Lambda/\lambda = 13$. We can find that the results of MEST are basically consistent with the results of FDTD, showing the validity of MEST. The first order has the highest efficiency ($\eta_{0+1} = 83.11\%$, $\eta_{+1} = 84.29\%$, $\eta_{FDTD+1} = 88.37\%$) and the other orders are almost overlapping below 5%, i.e. the grating diffracts the majority of input energy into the first order.

To make the case more compendious and clear, Fig. 2(b) from which we may get more detailed information shows the corresponding logarithmic-scale values of η_0 and η, η_{FDTD} is omitted because its function to testify the validity of MEST is shown in Fig. 2(a). Differences that cannot be distinguished in linear scale definitely exist, though imperceptible in the linear scale, between η_0 and η in that the integrals are based on different fields. When the period interaction is considered, the efficiency of the first order decreases from 84.29% to 83.11%, and meanwhile the efficiencies of all the other diffraction orders change slightly, which means that the energy of the diffraction field experiences a process of redistribution.