Accuracy analysis of lamellar diffraction gratings by means of simplified theories

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Summary

The validity of both the scalar diffraction theory and the effective medium theory is evaluated by the comparison of the diffraction efficiencies predicted from both simplified theories to accurate results calculated by the finite-difference time-domain method.

Introduction

The Scalar Diffraction Theory (SDT) and the Effective Medium Theory (EMT) are considered as a good alternative for predicting diffraction efficiency of Diffractive Optical Elements (DOEs). These simplified theories are valid under several conditions related with the physical parameters of the DOE. In Jing et al. [1] a full analysis of the accuracy of both methods is detailed with the Fourier Modal Method (FMM) as reference. Although the FMM is classified inside the group of rigorous electromagnetic vector theories, the accuracy of this method depends on the number of spatial harmonics used to represent the periodic electromagnetic field. In addition, it is known that the convergence of FMM, as the Rigorous Coupled Wave Theory (RCWT), is high for TE polarization, but it exhibits poor convergence for TM polarization. The Finite-Difference Time Domain (FDTD) method is considered here as the reference instead of FMM. The FDTD method also belongs to the rigorous EM theories, and it is frequently applied to yield exact predictions of DOEs. However, the FDTD method has been considered difficult to use and it is computationally intensive. Because of that, in this work a parallel FDTD approach has been considered and accelerated by Graphic Processing Units (GPUs), avoiding the disadvantage of the time costs related with the finite difference methods. Moreover, the application of this numerical method gives us the opportunity to analyze higher orders and manufacturing deficiencies in the DOE.

Discussion

In Fig1 a schematic diagram of a lamellar diffraction grating is shown. Λ and h represent the period and groove depth, respectively, and n_0 and n_g are the refractive indices of the incident medium and grating, respectively. Here, we choose n_0 = 1.00 and n_g = 1.50.

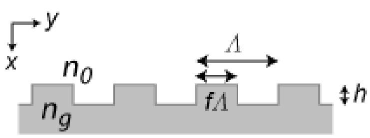

Figure 1: Schematic diagram of a lamellar diffraction grating

The plane wave propagates from air through the surface into the substrate material at normal incidence and the absorption loss and the dispersion of the medium are ignored for our analysis.

The transmission diffraction efficiency is computed by means of the SDT and the EMT. Both results are compared with the numerical curves obtained by means of FDTD method. The SDT method computes the diffraction efficiency utilizing the scalar Kirchhoff diffraction theory, which neglects the vectorial, polarized nature of light and is independent of the period of the surface profile. The EMT is based on considering a subwavelength grating as an anisotropic optical thin film with effective

refractive index. The second-order EMT expands the expressions for the effective optical properties asymptotically in terms of Λ/λ. As Λ/λ becomes greater, more higher-order terms from the series expansions must be included in the analysis. As Jing et al. in [1] we considered the zeroth-order and the second-order EMT to predict the diffraction efficiencies. As regards to the FDTD method here implemented, it must be said, that only the bidimensional scheme and TE polarization were considered. This method is well known and fully detailed in [2, 3]. The FDTD method solves the Maxwell equations by means of the approximation of the time and spatial derivatives by the central differences expressions.
The accuracy of the SDT and EMT are shown in Fig. 2. Concerning the accuracy of SDT, it has been verified that the scalar approximation is valid for Λ/λ > 2 and it is insensitive to the fill factor [1]. The EMT has been used for estimating the diffraction efficiency only when the zeroth-order diffraction wave exists (normalized period of the DOE much smaller than the wavelength). In Fig. 2c can be identified how the similarity between FDTD and both approximations of EMT behaves quite closer. The accuracy of EMT drops dramatically beyond Λ/λ = 0.64 because of the higher-order diffraction waves.

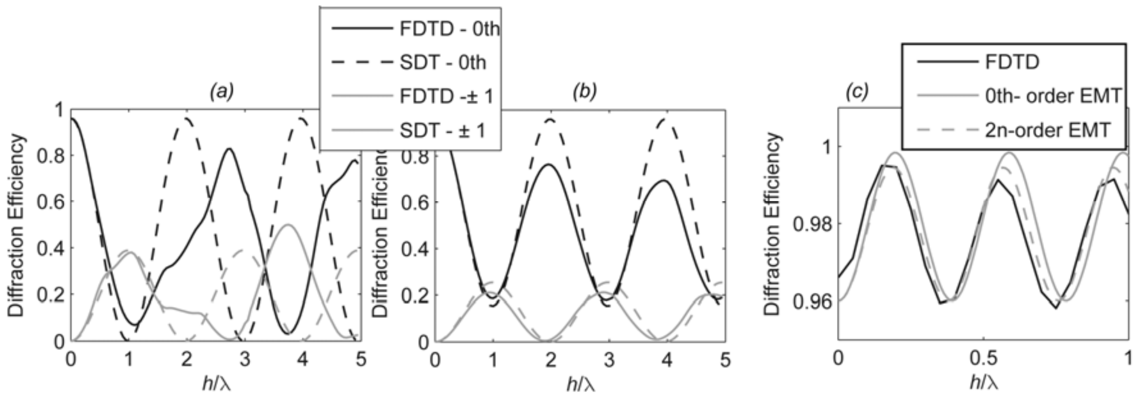

Figure 2: Comparison of transmittance characteristic between the simplified methods and FDTD as a function of normalized groove depth at normal incidence: (a)-(b) SDT for the zeroth order and ±1 orders : (a) Λ/λ = 2 and *f* = 0.5, (b) Λ/λ = 8 and *f* = 0.7. (c) Zeroth-order and second-order EMT Λ/λ = 0.6 and *f* = 0.5.

Conclusions

The accuracy of two simplified theories used for the analysis of the transmission diffracted orders for DOE has been analyzed. Specifically, the results obtained by Jing et al. [1] have been corroborated using the FDTD method instead of the FMM. The authors believe that the precision of the FDTD in some cases can be higher than the FMM, such as considering surface artifacts in manufacturing or non-periodical variations of the DOE characteristics. In addition, the computational drawbacks related with the FDTD have been avoided by means of the acceleration with GPU computing.

Acknowledgements

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