

Original research article

# Reverse design for diffraction gratings by modal method

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## ABSTRACT

A novel method for reverse design of the rectangular-groove dielectric surface-relief grating by modal method is presented. The principle of the reverse design method is the excitation and coupling between the propagating modes in grating. When the modes 0 and 1 are transmission through the grating, the phase difference is accumulated. By adjusting the cumulative phase difference between the modes 0 and 1, the energy can be reallocated between the  $-1$ st and 0th order diffraction light. Thereby the diffraction efficiency of the grating  $-1$ st and 0th order are adjusted. By using these reverse design method, we analyze the design of the beam splitter and blazed grating. As an example, a  $-1$ st transmitted order blazed grating has been designed by reverse design method. The comparative results have shown that the geometrical parameters of the grating calculated by modal method agree well with the results simulated by the rigorous couple-wave analysis (RCWA).

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## 1. Introduction

In optics, a diffraction grating is an optical component with a periodic structure, which splits and diffracts light into several beams travelling in different directions. The directions of these beams depend on the spacing of the grating and the wavelength of the light so that the grating acts as the dispersive element. Because of this, gratings are commonly used in monochromators and spectrometers. In the development of the past few decades, grating diffraction theory has formed a relatively perfect theoretical system, which is divided into positive solution and inverse solution. The method of the positive solution is need calculation the diffraction efficiency based on the physical and geometric parameters of the grating. However, the inverse problem algorithm is reverse calculate the geometric parameters of the grating based on its function. At present, the development of the positive solution of the grating is relatively perfect. The positive solution includes scalar diffraction theory and vector diffraction theory. However, the development of the inverse solution for the diffraction grating is relatively behind the positive solution. Inverse problem algorithm for the grating mainly include GS method [1], genetic method [2], simulated annealing method [3], effective medium theory [4] and modal method [5]. The former three methods use an iterative algorithm to find the optimal grating parameters. Also, they usually require a lot of computation time to find the optimum grating parameters. In addition, the effective medium theory is a kind of method that grating can be equivalent to a uniform dielectric film. Also, the thin-film optical method is used for calculation the diffraction efficiency for the grating [6]. In particular, the effective medium theory is mainly applied to the sub-wavelength grating. More specifically, in the case of dielectric transmission gratings with rectangular grooves, the modal method [7–10] has a simple physical understanding with the interference taking place in the grating. Furthermore, the modal method can reduce the difficult diffraction process to an easy and intelligible mechanism [11,12]. In this paper the modal method has applied to reverse design the beam splitting grating and blazed grating with a rectangular-groove dielectric surface-relief grating. The

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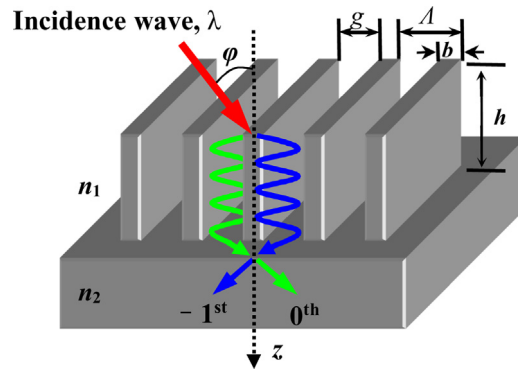


Fig. 1. Geometry of the rectangular-groove dielectric surface-relief gratings.

method of rigorous couple-wave analysis [13,14] has used to verify the grating geometrical parameters designed by modal method.

## 2. Modal method

The schematic of the rectangular-groove dielectric surface-relief grating structure is shown in Fig. 1, where  $\Lambda$  is the grating period;  $\lambda$  is the wavelength of the incident light;  $h$  and  $b$  is the depth and ridge widths of the grating;  $n_1$  ( $n_1 = 1$ ) and  $n_2$  ( $n_2 = 1.5$ ) is the refractive index of the air and the fused-silica, respectively;  $f$  is the fill factor. Since it is assumed that the grating profile is square, the fill factor is the ratio of opening to period. Here a plane wave incident on the surfaces of the gratings with Littrow mounting  $\varphi$  by the following

$$\varphi = \arcsin(\lambda/2\Lambda) \quad (1)$$

From the field continuity conditions at the boundaries between the ridges and grooves of the grating, the eigenvalue equation is [13]

$$\cos \alpha\Lambda = F(n_{\text{eff}}^2) \quad (2)$$

where  $F(n_{\text{eff}}^2)$  is the eigenvalue function. For the TE and TM polarization incident, it is

$$F(n_{\text{eff}}^2) = \cos(\beta b) \cos(\gamma g) - \frac{\beta^2 + \gamma^2}{2\beta\gamma} \sin(\beta b) \sin(\gamma g) \quad (3)$$

and

$$F(n_{\text{eff}}^2) = \cos(\beta b) \cos(\gamma g) - \frac{n_1\beta^2 + n_2\gamma^2}{2n_1n_2\beta\gamma} \sin(\beta b) \sin(\gamma g) \quad (4)$$

where  $\alpha = k_0 \sin \theta$ ,  $\beta = k_0 \sqrt{1 - n_{\text{eff}}^2}$ ,  $\gamma = k_0 \sqrt{1 - n_{\text{eff}}^2}$ ,  $k_0 = 2\pi/\lambda$ ,  $n_{\text{eff}}$  is the effective indices for the discrete modes,  $g$  ( $g = \Lambda - b$ ) is the grating groove width. The eigenvalue function  $F(n_{\text{eff}}^2)$  depends on the ridge width, the period, and the refractive indices. Here, the propagating modes with  $n_{\text{eff}}^2 > 0$  can propagate through the gratings. Those with  $n_{\text{eff}}^2 < 0$  are evanescent modes, since their effective refractive index  $n_{\text{eff}}$  is imaginary. The left part of the eigenvalue equation represents the incidence conditions, where  $\cos(\alpha\Lambda) = 1$  is the case of normal incidence.

When the discrete mode excited only transmission modes 0 and 1 in grating, there will be only  $-1$ st and 0th order diffraction. The coupling between the modes 0 and 1 is similar to that of the M-Z interference, and the process is shown in Fig. 1. When the transmission modes 0 and 1 excited in grating only, the grating period should satisfy [14]

$$\lambda/2 < \Lambda < 3\lambda/2n_2 \quad (5)$$

The relationship between effective refractive index and the eigenvalue function can be calculated by Eqs. (3) and (4) for different grating parameters. The grating eigenvalue function  $F(n_{\text{eff}}^2)$  as a function of the effective refractive index for TE and TM polarizations with  $f = 0.9$ ,  $\lambda = 850$  nm, and  $\Lambda = 600$  nm (or  $1.6 \mu\text{m}$ ) is shown in Fig. 2. The dotted line of  $\cos(\alpha\Lambda) = -1$  is the case of Littrow mounting incidence as shown in Fig. 2. The effective refractive index of the discrete mode is calculated by the point that the intersection of the Littrow mounting line and the characteristic function curves. More specifically, the intersection point is located on the right side of the vertical coordinate as the propagating modes, and the left side of the coordinate is the evanescent modes.

As shown in Fig. 2, when  $\Lambda = 600$  nm since the grating periods satisfying Eq. (5), there exist only two propagating modes 0 and 1 for the incident light of the TE and TM polarizations. When the grating period is  $1.6 \mu\text{m}$ , since the grating periods can

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