Optics Communications 383 (2017) 182–185

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Simplified modal method for slanted grating

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ARTICLE INFO

Article history:
Received 25 May 2016
Received in revised form
28 August 2016
Accepted 5 September 2016

Keywords:
Diffraction gratings
Diffractive theory
Diffractive optics

ABSTRACT

We report the simplified modal method for the slanted grating based on the accurate dispersion equation. The vividly physical insight is presented to interpret the diffraction process for slanted grating. We also present that the simplified modal method with the two-lowest mode condition is effective for a large slanted angle up to 26°. By examining the eignefunction, the mode index, and the two-lowest mode condition, we provide new evidences to verify the assumption that a slanted grating with subwavelength period can be analyzed as an equivalent rectangular grating using the simplified modal method, which is right and convenient to use for a small slanted angle up to 20°. Numerical simulations of the simplified modal method are coincident with rigorous coupled wave analysis for small slanted angle gratings. Thus the simplified modal method can be used for small slanted angle grating since the equivalence of slanted grating and rectangular grating is verified due to its vivid physical analysis.

1. Introduction

With the fast development of lithography process or laser direct writing technology, the slanted grating is investigated as novel devices for special functions, such as ultrabroadband internal-reflection, coupling the light into waveguide [1] etc. The low-contrast grating, such as fused-silica grating, can be used in pulse compression and high power laser system because of high laser induced damage threshold, which has attracted great attention. For simulating a slanted grating, the rigorous couple wave analysis [2] is an accurate way to calculate the diffraction efficiencies. However, this pure numerical method cannot provide much physical insight. Fortunately, the simplified modal method can illustrate the diffraction process. It should be noted that the simplified modal method has been applied in the rectangular grating [3], triangular grating [4], and slanted grating [5,6]. The simplified modal method presented in the Ref. [5] is an approximate method. In this paper we correct the eigenfunction according to the remarks in [7], which allows us to show that the equivalence is approximately correct according to a physical and mathematical analysis. In fact, numerical simulations demonstrated that it is still quite accurate to use the eigenfunction of the equivalent rectangular grating for the slanted grating up to 20°, which is not so close to zero degree. Therefore, we should explore the inside physics by comparing the difference between the eigenfunction of the equivalent rectangular grating and the accurate eigenfunction of the slanted grating.

In this paper, we will present the simplified modal method for the slanted grating based on the accurate eigenfunction. Without complicated numerical calculating, the diffraction process can be illustrated as a vividly physical image by the simplified modal method. We also present that the simplified modal method with the two-lowest mode condition is right for a large slanted angle up to 26°. Based on the accurate eigenfunction, we can illustrate that the two-lowest modes are not sensitive to slanted angle, thus this accurate equation can be approximate to the rectangular grating eigenfunction under small slanted angle. It is indeed that the two-lowest modes condition is right up to 26° where the third mode begins to occur, which is the essential physics of the equivalence between the slanted grating and rectangular grating. The equivalence has the beautiful property of even or odd grating mode symmetries, which can simplify the analysis for the slanted grating and it provides an effective tool for illustrating the overall performances of slanted grating.

2. Modal method

Fig. 1 shows the configuration of a slanted grating with parameters: period d, depth h, duty cycle f, and slanted angle φ_s. The refractive indices of top and substrate are n_1 and n_2, respectively. The indices of grating ridge and groove are n_r and n_g. For simplicity, the slanted grating will be treated as embedded inside a medium with averaged refractive index n_e, where $n_e{}^2 = n_r{}^2 + n_g{}^2(1-f)$. In this paper, we have assumed that the slanted grating has a subwavelength period, which is close to the wavelength.

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http://dx.doi.org/10.1016/j.optcom.2016.09.010
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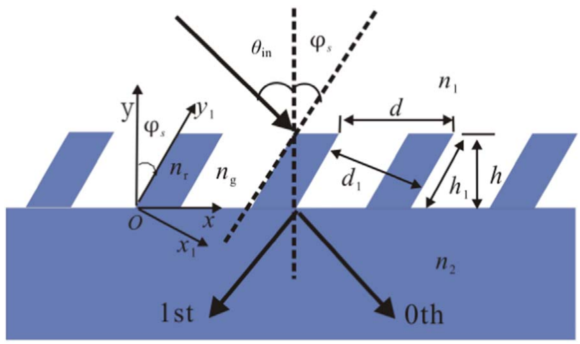

Fig. 1. Configuration of a slanted grating.

In the coordinate systems x_1oy_1, the TE polarized plane wave is incident on the slanted grating with the Bragg angle $\theta = \sin^{-1}(\lambda/2n_e d_1)$ [8], where $d_1 = d\cos\varphi_s$, $h_1 = h\cos\varphi_s$. According to [9], the electric distribution in the grating region can be expressed as:

$$U(x_1, y_1) = \exp(-j\beta y_1)v(x_1), \tag{1}$$

where

$$v(x_1) = \begin{cases} f_{1q}\exp(jk_{1q}x_1) + b_{1q}\exp(-jk_{1q}(x_1 - b_1)) \\ 0 \le x_1 \le b_1 \\ f_{2q}\exp(jk_{2q}(x_1 - b_1)) + b_{2q}\exp(-jk_{2q}(x_1 - d_1)) \\ b_1 \le x_1 \le d_1 \end{cases} \tag{2}$$

Here,

$$k_{1q} = \sqrt{k_0^2\varepsilon_1 - \beta^2} \tag{3}$$

$$k_{2q} = \sqrt{k_0^2\varepsilon_2 - \beta^2} \tag{4}$$

Where $\varepsilon_1 = n_r^2$, $\varepsilon_2 = n_g^2$, $q = 1, 2$, $b_1 = fd_1$ and $\beta = k_0 n_{eff}$. n_{eff} is the effective index of grating model. Based on the continuity of the electric and its derivative at the interface between grating ridge and grating groove, the dispersion equation for propagation constant β is [9]:

$$\cos(k_{1q}b_1)\cos(k_{2q}(d_1 - b_1)) - \frac{1}{2}\left(\frac{k_{1q}}{k_{2q}} + \frac{k_{2q}}{k_{1q}}\right)\sin(k_{1q}b_1)\sin(k_{2q}(d_1 - b_1))$$
$$= \cos(k_{x0}d + \beta\sin\varphi_s d) \tag{5}$$

In this paper, only the first two propagating modes are considered and other higher grating modes are evanescent under the Bragg angle, the diffraction process is very similar to a Mach–Zehnder interferometer (Fig. 2). The incident light excites two equal waves which propagate with different effective indices. According to the simple two beam interference mechanism, the diffraction efficiencies of the transmitted orders are mainly determined by the accumulated phase difference of the first two grating propagating modes and the efficiency of two transmitted orders can be calculated by [3]:

$$\eta_{-1} = \sin^2(\Delta\varphi/2) \tag{6a}$$

$$\eta_0 = \cos^2(\Delta\varphi/2) \tag{6b}$$

where $\Delta\varphi = (n_{0neff} - n_{1neff})k_0 h_1$. k_0 is the wavenumber in vacuum. Here n_{0eff} and n_{1eff} are the corresponding grating modes effective indices which can be easily obtained by solving the dispersion equation Eq. (5). In order to test the validity of accuracy of the simplified modal method, we compare the diffraction

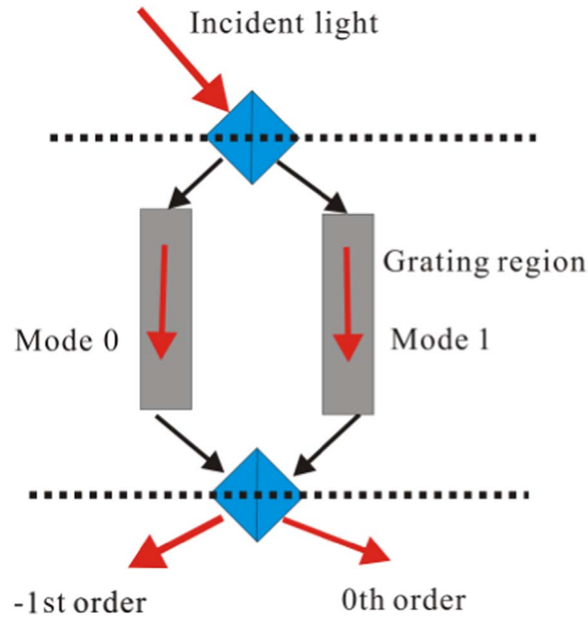

Fig. 2. Illustration of the diffraction process inside a slanted grating. The diffraction process is very similar to a Mach–Zehnder interferometer.

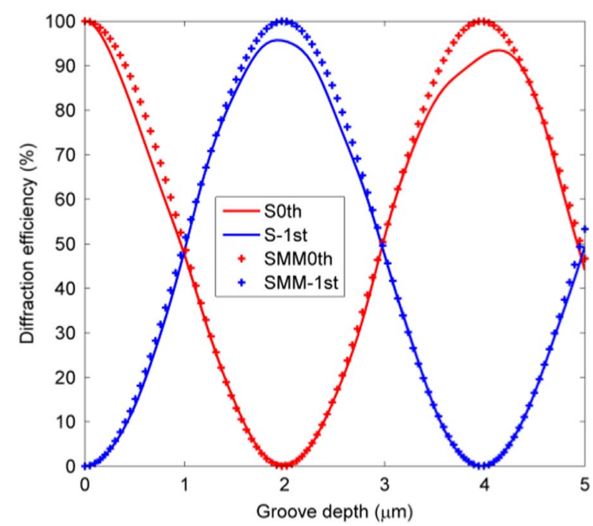

Fig. 3. Comparison of diffraction efficiencies between RCWA and modified simplified modal method (SMM) for slanted grating with 25° slanted angle. '+'stands for the simplified modal method (SMM).

efficiencies obtained by RCWA and the simplified modal method (Eq. (6)) in Fig. 3. The grating parameters are: period $d = 1216$ nm, duty cycle $f = 0.5$, $n_r = 1.44462$, $\lambda = 1550$ nm, $n_g = 1$, $n_1 = n_2 = n_e$. The incident angle, Bragg angle, is the function of slanted angle φ_s which can be obtained from Eq. (4) in Ref. [5]. The diffraction efficiencies for slanted grating calculated by RCWA are well predicted by the simplified modal method for slanted gratings. Thus, the simplified modal method can be used as an effective tool to interpret the diffraction process in the slanted grating region. The analytic equations cannot be analyzed by a pure numerical method RCWA.

If we define the left side of Eq. (5) as:

$$F[M_q(\varphi_s)] = \cos(k_{1q}b\cos(\varphi_s))\cos(k_{2q}(d - b)\cos(\varphi_s))$$
$$-\frac{1}{2}\left(\frac{k_{1q}}{k_{2q}} + \frac{k_{2q}}{k_{1q}}\right)\sin(k_{1q}b\cos(\varphi_s))\sin(k_{2q}(d - b)\cos(\varphi_s)) \tag{7}$$

while the eigenfunction for a slanted grating is: