Optics Communications 392 (2017) 73–76

Contents lists available at ScienceDirect

Optics Communications

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

Mode suppression in a slanted grating

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ARTICLE INFO

Keywords:
Diffraction gratings
Diffractive theory
Diffractive optics

ABSTRACT

In this paper, we propose a novel method of mode suppression in a slanted grating; this can reveal the physical diffraction mechanism in the grating region. Analytical expressions are derived to illustrate the diffraction process based on the simplified modal method. Owing to the odd mode suppression, only two even grating modes determine the even symmetry field distribution at the output plane. In addition, a slanted grating is designed to make the oblique light mainly couple into the normal emission; this is notably different from a rectangular grating, which can never be used to realize this goal. Numerical simulation results verify the validity of the simplified modal method. We hope that this theoretical work can lay a solid foundation for potential applications of slanted gratings.

1. Introduction

With the rapid development of the lithography process and laser direct writing technology, the fabrication of surface relief grating has become a reality [1,2]. The slanted grating is investigated as novel optical device for special functions, such as ultrabroadband internal-reflection [3], coupling light into waveguide [4], which have attracted considerable interest for many scientists. For simulating a grating, the rigorous coupled wave analysis [5] is usually used as an accurate method to calculate diffraction efficiency. However, this pure numerical method cannot provide much physical insight for illustrating the diffraction process. It should be noted that a simplified modal method [6–8] offers a new approach to analyze the physical diffraction process. In our previous study [9], we presented a slanted grating that enables the normally incident light to be coupled into the −1 diffraction order. The diffraction efficiency is larger than 92.4% over a 100 nm bandwidth from 1500 to 1600 nm, covering a central wavelength of 1550 nm in the optical communication. In this situation, only even grating modes are excited in the first slice of the slanted grating and are coupled into odd grating modes at the output plane. However, in some real applications, a normal diffraction light is needed even for an oblique incident on the grating. In this paper, we demonstrate that the odd grating modes can also be coupled into the even grating modes for a slanted grating. In this case, only odd grating modes are excited in the first slice of the slanted grating and should be suppressed at the output plane; this is greatly different from the method of the previous study. Based on the simplified modal method, the process of the suppression of the odd grating mode is analyzed in detail. As an example, we design a slanted grating which can couple the light into the normal emission under the oblique incidence. The diffraction efficiencies of the slanted grating are higher than 92% transverse electric (TE) polarization over the bandwidth of 1260–1360 nm, including the central wavelength of 1310 nm in the optical communication. Analytical expressions are derived to illustrate the process of mode coupling and conversion in the slanted grating. The energy of the odd grating mode is converted into the even grating modes, leading to an even symmetrical field distribution at the output plane. The physical essential is that the oblique incidence can lead to normal emission. The simplified modal method, as a powerful tool, offers us a vividly physical image for illustrating diffraction process for slanted grating.

2. Grating design

Fig. 1 shows the slanted grating. A TE polarization plane wave with a central wavelength of 1310 nm is illuminated from the top substrate with the incident angle $\theta=\arcsin(\lambda/n_1 d)$, where d is the slanted grating period and λ is the central wavelength. The width of the slanted grating ridge is b; and the depth is h. The refractive index of the grating ridge is n_r. The duty cycle is represented as $f=b/d$. The variables n_1 and n_2 are the refractive index of air and the substrate, respectively.

In this study, a high diffraction efficiency slanted grating is designed. The −1 diffraction order carries the main energy of the incident light, indicating that the out plane wave is a normal emission. To obtain the high efficiency, the rigorous coupled-wave analysis (RCWA) and simulated annealing algorithms [10] are employed to optimize the slanted grating parameters. The objective is to realize high

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http://dx.doi.org/10.1016/j.optcom.2017.01.049
Received 23 November 2016; Received in revised form 19 January 2017; Accepted 24 January 2017
Available online 31 January 2017

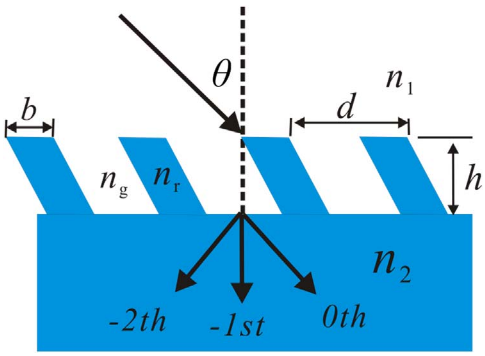

Fig. 1. Grating simulation geometry.

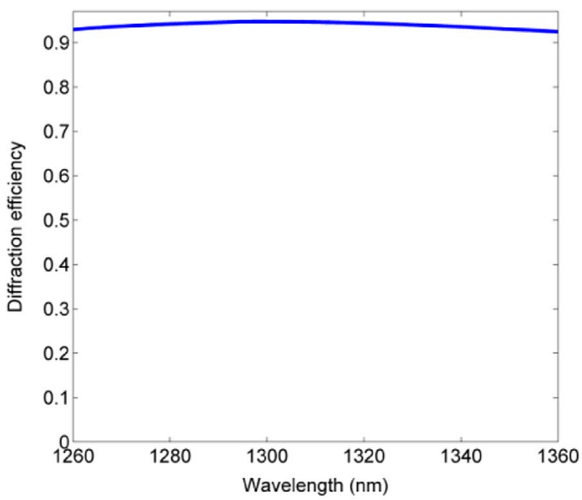

Fig. 2. Diffraction efficiencies for the −1 order versus the wavelength of 1260–1360 nm.

diffraction efficiencies from 1260 to 1360 nm, with a central wavelength of 1310 nm.

The optimized values are as follows: period 1774 nm, depth 200 nm, slanted angle 18°, and duty cycle=0.3.=0.3. Fig. 2 demonstrates the optimized results for the slanted grating. It can be seen that the diffraction efficiencies are higher than 92% for TE polarization over the bandwidth rang of 1260–1360 nm. This type of high diffraction efficiencies of slanted grating can be used in many optical systems, such as optical communications.

3. Mode analysis

In the modal theory, the electromagnetic fields above and under the grating region are expressed as a series of Rayleigh-Fourier modes. The fields in the grating region can be expressed as several grating modes. For the subwavelength grating, there are only a few grating modes that can be excited as propagating modes. Other higher order grating modes can hardly be excited as evanescent grating modes. Thus, the diffraction process in the grating region can be illustrated by only considering the propagating modes. Note the mode reflection at the interface is neglected because the grating is designed with high transmitted diffraction efficiency higher than 92%.

To analyze the diffraction process of the slanted grating, we slice the slanted grating into a series of rectangular gratings. In each rectangular grating region, a few of propagating grating modes are presented. The effective index of the propagating mode can be determined using the dispersion equation for TE polarization [11].

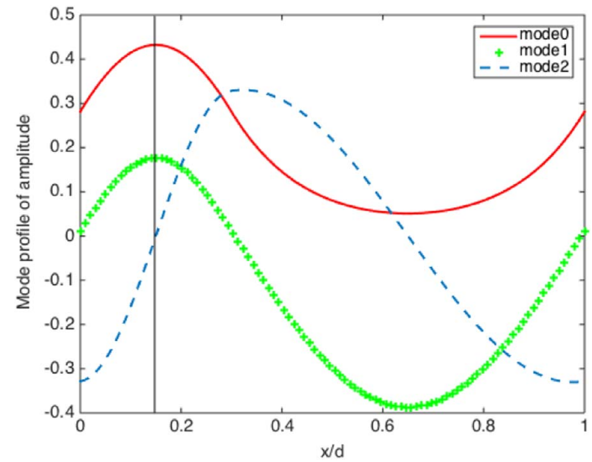

Fig. 3. Mode profiles of the three grating propagating modes for TE polarization.

$$F(n_{eff}^2) = \cos[k_1(1-f)d]\cos(k_2 f d_1) - \frac{k_1^2+k_2^2}{2k_1k_2}\sin[k_1(1-f)d]\sin(k_2 f d) = \cos(k_x d) \quad (1)$$

With

$$k_x = \frac{2\pi n_1}{\lambda}\sin\theta \quad (2)$$

$$k_1 = \frac{2\pi}{\lambda}\sqrt{n_1^2 - n_{eff}^2} \quad (3)$$

$$k_2 = \frac{2\pi}{\lambda}\sqrt{n_2^2 - n_{eff}^2} \quad (4)$$

where θ is the incident angle, and n_{eff} is the effective mode index. The propagating modes constants are n_{0eff}=1.283 for mode 0, n_{1eff}=0.843 for mode 1 and n_{2eff}=0.826 for mode 2. Fig. 3 illustrates the mode profiles, where modes 0 and 1 are seen as even symmetry, and mode 2 is an odd symmetry.

At the incident interface, only three propagating grating modes can be excited at the first layer (see Fig. 4). Thus, the electric fields distribution can be expanded as follows [12]:

$$E_{yin} = a_0u_0(x) + a_1u_1(x) + a_2u_2(x), \quad (5)$$

Here a_i is the excitation efficiency of the grating mode that can be obtained through the overlap integral:

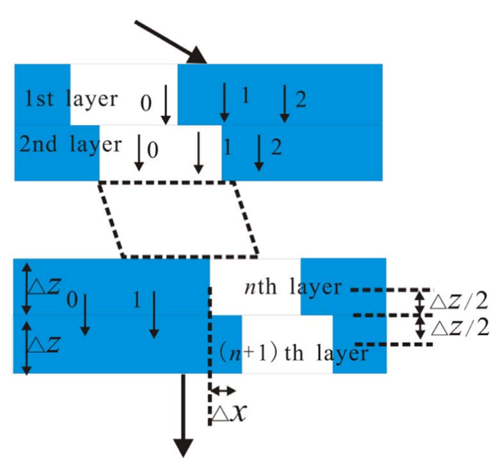

Fig. 4. Schematic of one period for the two adjacent lamellar grating. One offset from the other by Δx. Numbers 0, 1, and 2 stand for mode 0, mode 1 and mode 2, respectively. In the first layer, modes 0, 1 and 2 can be excited. In the grating end, mode 2 can be weakly excited.