

# Highly-efficient element and two-port beam splitter of multilayer-based grating

BO WANG\*, LI CHEN, LIANG LEI, JINYUN ZHOU

*School of Physics and Optoelectronic Engineering, Guangdong University of Technology, Guangzhou 510006, China*

Highly-efficient element and two-port beam splitter are key elements in various optical systems. We describe that such functions can be fulfilled by one multilayer-based grating. Based on the effective indices of the modes excited in the grating region, grating duty cycle and period are chosen so that the design is feasible. Exact grating depth and thickness of the connecting layer are optimized using rigorous coupled-wave analysis (RCWA). The numerical calculation using RCWA coincides well with predictions of modal method. In the novel design, efficiency of TE polarization is improved greatly compared with the reported dual-function element for the transmission structure.

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*Keywords:* Modal method, Rigorous coupled-wave analysis, Multilayer-based grating, High efficiency, Beam splitter

## 1. Introduction

Gratings are key elements in various optical information processing systems [1-3]. Conventional gratings are low density, whose diffraction properties are based on scalar theory. However, when the grating period can be comparable to the incident wavelength, the diffraction properties must be investigated by vector theory [4-6]. Further study indicates that such high-density gratings can show various novel optical phenomena. For example, for subwavelength gratings, two orders of the 0th and -1st orders may be remained, therefore, the diffraction can be highly efficient [7]. Furthermore, efficiencies of diffraction orders can be modulated by the grating parameters to act as beam splitters [8]. Moreover, polarization-dependent properties make high-density gratings possible to be useful polarizing beam splitters to separate two orthogonal polarized beams into different directions [9, 10].

For the binary rectangular-groove grating, the rigorous coupled-wave analysis (RCWA) can give the formulation by directly solving Maxwell's equation to obtain the exact solutions [4]. Modal method may give the intelligible explanation of propagation process by the two-beam interference in the grating region [5]. With theoretical RCWA and modal method, high-density gratings are widely investigated in the resonance domain. Jia *et al.* proposed a high-efficiency grating of 98% diffraction efficiency in the -1st order for TE polarization and an incident wavelength of 800 nm, which could be used to compress femtosecond pulse instead of prism pairs. Compact cavity can be obtained to tune laser easily due to small size of gratings [11].

Cao *et al.* presented a polarization-independent fused-silica grating using RCWA, whose wideband property could be well explained by modal method. Such a high-efficiency grating can be used for chirp-pulse-amplification and high-laser power systems for high damage threshold of fused silica. High-density gratings can also work as two-port beam splitters [12]. Feng *et al.* presented the design of two-port beam splitter using RCWA and modal method for both TE and TM polarizations, which could be used in optical computing, holography and metrology [13].

High-density gratings can be optimized as novel devices such as high-efficiency elements, two-port beam splitters and so on. However, many investigations are concentrated on only one function. If several functions can be fulfilled by one simple grating, such an element will be greatly desirable. Although a dual-function grating element is proposed with rectangular-groove grating [14], the efficiency of TE polarization can be improved to some extent by the novel grating structure [15].

In this paper, we introduced multilayer-based grating to be high-efficiency element and two-port beam splitter. The diffraction property of such a novel grating can be analyzed using stable implementation of RCWA [5], which is different from the reported gratings of mostly simple binary rectangular-groove structure. Using modal method and RCWA, the grating parameters are optimized, including duty cycle, period, depth and thickness of the connecting layer. From diffraction properties, it indicates that efficiency of TE polarization can be improved based on the novel structure of multilayer-based grating.

## 2. Multilayer-based grating for high-efficiency element and two-port beam splitter

The multilayer-based grating structure is shown in Fig. 1, where  $d$  is the period,  $h_g$  and  $h_c$  are depth and thickness of the connecting layer, respectively. The cover medium is air with refractive index  $n_1 = 1$ ,  $n_2 = 2$  is the refractive index of the substrate. The grating is etched in fused silica for high optical quality with refractive index  $n_2 = 1.45332$  for an incident wavelength of  $\lambda = 800$  nm. A monochromatic plane wave is incident from air under Littrow mounting at an incident Bragg angle of  $\theta_i = \sin^{-1}(\lambda/(2n_1d))$ . For TE polarization, high efficiency can be obtained in the -1st order. For TM polarization, the incident wave is diffracted with two-port output in the 0th and -1st orders.

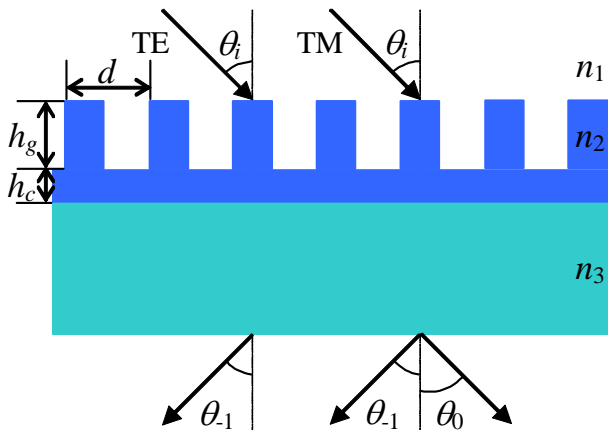


Fig. 1. (Color online) Schematic of a high-efficiency element and two-port beam splitter based on multilayer-based grating (refractive indices  $n_1$ : air,  $n_2$ : fused silica,  $n_3$ : substrate;  $d$ : period;  $h_g$ : grating depth,  $h_c$ : thickness of the connecting layer;  $\theta_i$ : incident angle,  $\theta_1$  and  $\theta_0$ : diffraction angles of the -1st and 0th orders, respectively).

By modal method and RCWA, the multilayer-based

grating can be optimized as highly-efficient element and two-port beam splitter. To begin with, for simplicity during fabrication, the grating duty cycle of 0.5 can be chosen. Furthermore, the incident wave will excite two modes with different effective indices in the grating region according to modal method. Phase differences can be accumulated after propagating through the grating depth. On the one hand, in order to obtain high efficiency for TE polarization, the phase difference should be an odd-numbered multiple of  $\pi$ . On the other hand, for two-port output of TM polarization, an odd-numbered multiple of  $\pi/2$  should be met. Since there is the same grating depth for TE and TM polarizations, the effective indices difference ratio of TE polarization to TM polarization should be 2. Theoretical investigation indicates that a grating period of 607 nm can be prescribed given the conditions above. Moreover, exact optimization of grating depth and thickness of the connecting layer can be obtained using RCWA [5]. The grating with a covering layer can be divided into a large number of sufficiently thin slabs. The electromagnetic fields are determined by the coupled-wave approach in each slab. And the boundary conditions can be applied in sequence at the interfaces among the slabs to obtain the diffraction efficiencies [5]. Fig. 2 shows the diffraction efficiency versus the grating depth and thickness of the connecting layer with duty cycle of 0.5 and period of 607 nm for the incident wavelength of 800 nm under Littrow mounting using RCWA [5].

In Fig. 2, high efficiency of 99.15% can be obtained for TE polarization and two-port output can be achieved with 48.18% in the 0th order and 48.16% in the -1st order for TM polarization for the optimized grating depth of  $1.26 \mu\text{m}$  and connecting layer thickness of  $0.19 \mu\text{m}$ . For a reported dual-function beam splitter [14], the theoretical efficiency of TE polarization is 95.15% for the optimized simple binary rectangular grating, which has been demonstrated in experiments with measured efficiency of 84.70%. The efficiency of 99.15% for TE polarization in this paper indicates that such a performance can be improved based on the novel grating structure with a connecting layer.

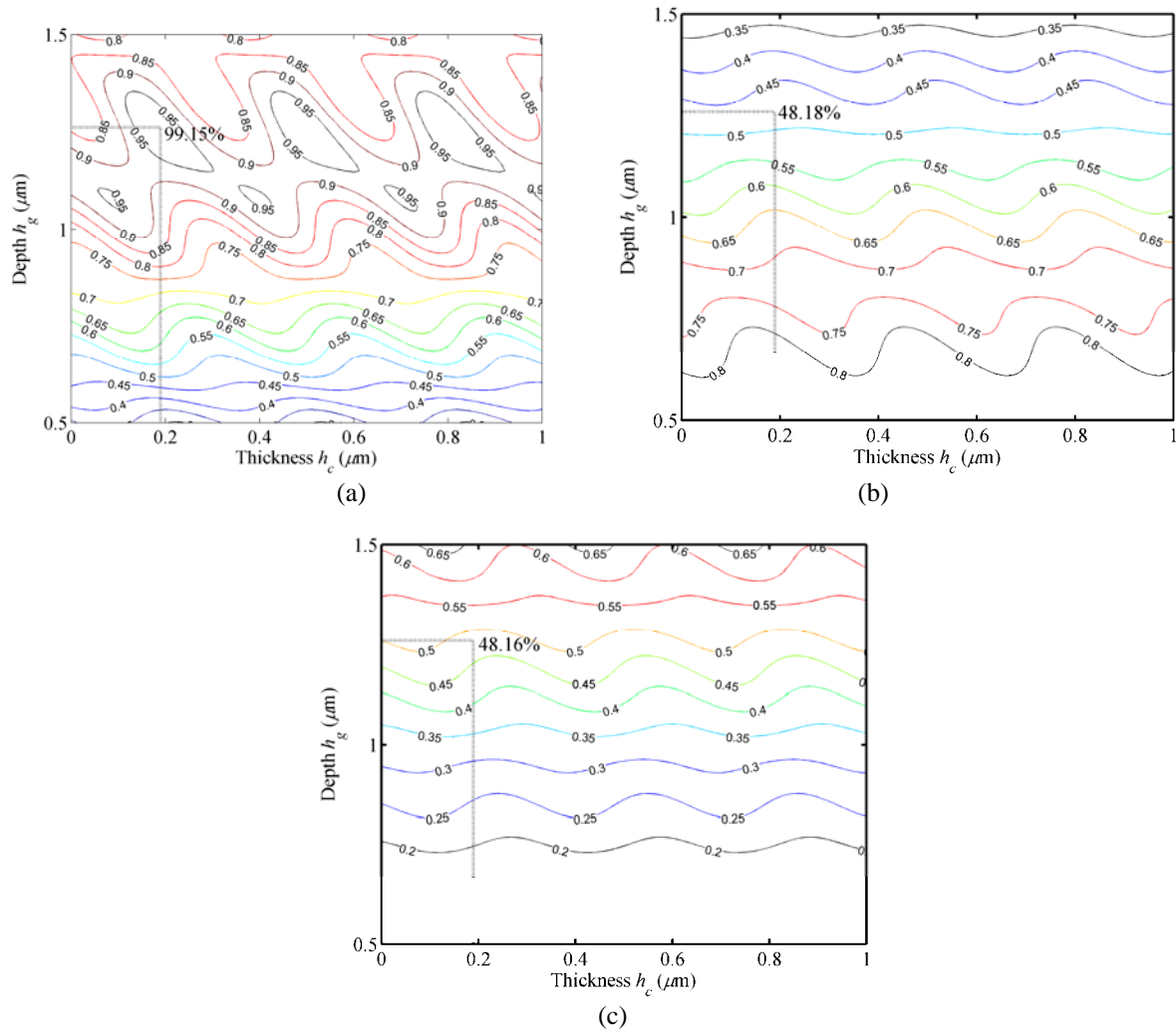


Fig. 2. (Color online) Diffraction efficiency versus grating depth and thickness of the connecting layer with the duty cycle of 0.5 and period of 607 nm for the wavelength of 800 nm: (a) TE polarization in the -1st order; (b) TM polarization in the 0th order; (c) TM polarization in the -1st order.

### 3. Diffraction properties

Compared with the conventional transmission grating, the connecting layer is introduced, which can modulate the efficiency. Fig. 3 shows the diffraction efficiency versus the thickness of the connecting layer with duty cycle of 0.5 and period of 607 nm for the optimized grating depth of 1.26  $\mu\text{m}$  using RCWA [5]. In Fig. 3, the efficiency changes with the thickness of the connecting layer for both TE and TM polarizations. It indicates that TE polarization is diffracted in the -1st order with very relatively high efficiency and TM polarization is diffracted with efficiency of near 50% with variation of the connecting layer thickness. With the optimized  $h_c = 0.19 \mu\text{m}$ , high efficiency and two-port output can be obtained for TE and TM polarizations, respectively.

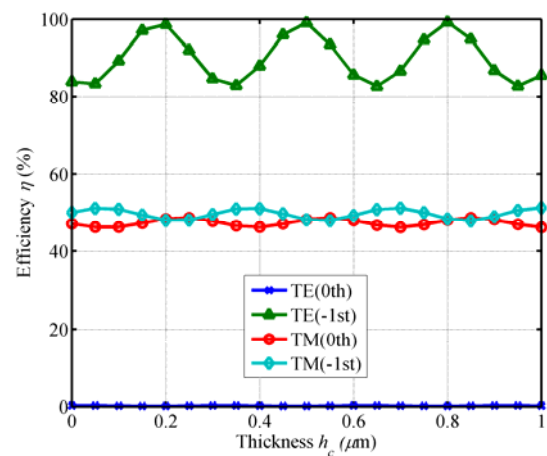


Fig. 3. (Color online) Diffraction efficiency versus thickness of the connecting layer with the duty cycle of 0.5, period of 607 nm and depth of 1.26  $\mu\text{m}$  for the wavelength of 800 nm under Littrow mounting.

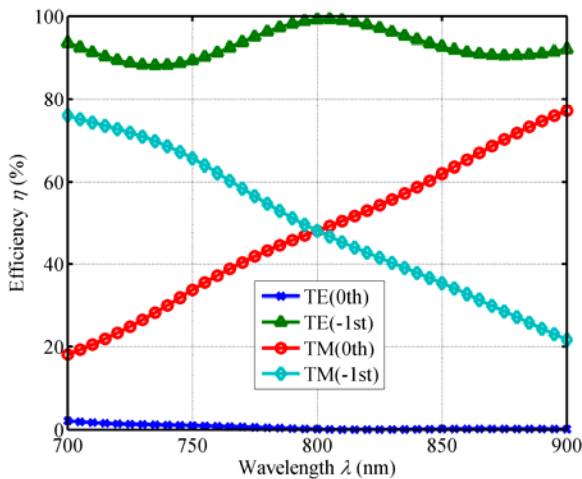


Fig. 4. (Color online) Diffraction efficiency versus incident wavelength under Littrow mounting with the optimized grating parameters.

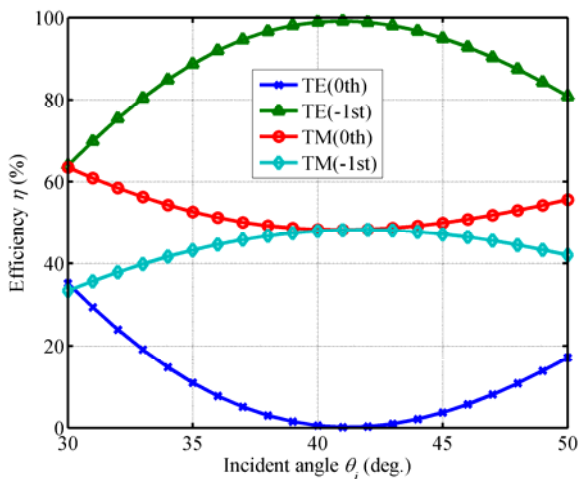


Fig. 5. (Color online) Diffraction efficiency versus incident angle for a wavelength of 800 nm with the optimized grating profile parameters.

For practical use, it is necessary to investigate the properties for the incident wavelength and angle. The excited modes will change with different of illumination conditions, which will affect the diffraction efficiency according to two-beam interference of modal method. Fig. 4 shows the efficiency with different incident wavelength for the optimized grating parameters using RCWA [5]. For the central wavelength of 800 nm, such highly-efficient element and two-port beam splitter can be obtained by the multilayer-based grating. Wideband property can be achieved for TE polarization with efficiency higher than 88.23% for the incident wavelength range of 700-900 nm.

Fig. 5 shows the efficiency with different incident angle for the optimized grating parameters using [5]. Under Littrow mounting which corresponds to a Bragg angle of 41.22°, high efficiency for TE polarization and two-port output for TM polarization can be achieved. And a moderate incident angle tolerance can be achieved for TM polarization.

#### 4. Conclusions

To our knowledge, it is the first time to present multilayer-based grating to be high-efficiency element and two-port beam splitter. The diffraction property of such a novel grating can be analyzed using stable implementation of rigorous coupled-wave analysis (RCWA), which is different from the reported gratings of mostly simple binary rectangular-groove structure. For the optimized grating parameters using modal method and RCWA, TE polarization is diffracted in the -1st order with high efficiency and TM polarization is divided into two with good uniformity in the -1st and 0th orders. Especially, efficiency of TE polarization can reach 99.15% in the novel design, which is improved greatly compared with the reported dual-function element for the transmission structure. The presented highly-efficient element and two-port beam splitter has novel structure of multilayer-based grating and advantage of improved efficiency for TE polarization, which should be useful in numerous optical systems with several functions in one device.

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\*Corresponding author: wb\_wsx@yahoo.com.cn