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Metal-mirror-based grating for high-efficiency element in dense wavelength division multiplexing

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ABSTRACT

It is desirable to obtain high efficiency with polarization-independence and wideband properties for incident wavelength. A metal-mirror-based grating is presented to diffract the incident wave into reflection orders with high efficiency for TE and TM polarization. The modal method and rigorous coupled-wave analysis (RCWA) are used together to optimize a metal-mirror-based grating effectively. From the analysis of the modal method, it is feasible to realize such a grating with the prescribed grating duty cycle and period. Accurate parameters of the grating depth and thickness of the connecting layer are optimized using RCWA. Compared with the reported binary simple grating, high efficiency can be improved greatly for the incident wavelength of 1550 nm in dense wavelength division multiplexing. The diffraction investigation indicates that a wideband property for incident wavelength can be obtained for such a novel metal-mirror-based grating.

1. Introduction

Diffraction gratings have an advantage of compact size, which are suitable for miniaturization and integration compared with conventional optical elements. For high-density gratings whose periods can be comparable to the incident wavelength, only several diffraction orders may be remained according to the grating equation. High efficiency can be obtained for such a grating in the resonance domain. Optimized grating with high density can be used in numerous optical systems [1–3] such as interferometer [4], beam splitter [5] and so on. Based on the vector grating theory, diffraction properties can be not only numerically calculated using rigorous coupled-wave analysis (RCWA) [6] but also well explained by the modal method [7] for their physical mechanisms. Moreover, experimental progress makes it feasible to fabricate high-density gratings easily and effectively [8]. Thus, the study of high-density gratings with high efficiency as novel optical elements has attracted more and more attention in recent years [9–11].

Much theoretical and experimental work has been conducted on the design and fabrication of high-density gratings as novel optical elements. Néauport et al. suggested a new design of gratings with high efficiency more than 90% for TM polarization. By recording with holographic technology and etching in fused silica, such gratings can be used for the laser integration line and laser megajoule facilities due to high damage threshold of substrate [12]. Clausnitzer et al. reported highly efficient transmission gratings with efficiency of 95% achieved at the wavelength of 1060 nm for TE polarization, which are key elements for chirped-pulse amplification systems [13]. High-efficiency gratings have also found wide use in optical communications [14]. Wang et al. described the performance of optimized transmission gratings at a wavelength of 1550 nm which should be very suitable for dense wavelength division multiplexing instead of thin-film filters and arrayed waveguide gratings. Although efficiency of 95% for TE polarization can be exhibited, only 80% can be reached for TM polarization within the fabrication tolerance [15].

Although high efficiency can be obtained for either TE or TM polarization, the efficiency still needs to be enhanced for polarization-independent incidence. The reported work mostly is based on transmission or simple binary grating structure [16–18]. Zheng et al. presented a novel metal-mirror-based grating to act as a polarizing beam splitter with high efficiency and wideband properties, which was polarization-dependent for splitting different polarized beams [19]. In this paper, a metal-mirror-based grating is presented for polarization-independent diffraction with high efficiency. Such a structure includes grating region, connecting layer, metallic layer and substrate. The parameters are optimized using the modal method and rigorous coupled-wave analysis. High efficiency and wideband property for incident wavlength can be obtained from the diffraction investigation based on the novel grating structure compared with the reported simple binary grating [15].

2. Metal-mirror-based grating with high efficiency for different polarizations

Fig. 1 shows the schematic of a metal-mirror-based grating with period of d, which is incident upon by a plane wave with

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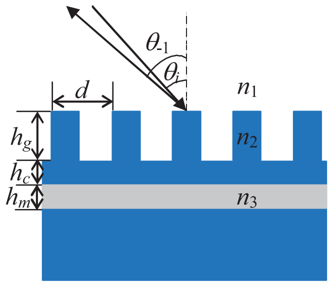

Fig. 1. Schematic of a metal-mirror-based grating for high-efficiency element (refractive indices n_1: air, n_2: fused silica, n_3: Ag; d: period; h_g: grating depth, h_c and h_m: thickness of the connecting layer and metal slab, respectively; θ_i: incident angle,θ_{-1}: diffraction angles of the −1st order). The diffracted angle of θ_{-1} is within the range of 45.88–49.32° to achieve high efficiency with the optimized grating parameters.

wavelength of λ from air with refractive index of $n_1=1$ under the Littrow mounting at a Bragg angle of $\theta_i=\sin^{-1}(\lambda/(2n_1d))$. The grating is etched in fused silica with refractive index $n_2=1.45$ for an incident wavelength of 1550 nm and grating depth of h_g. As a reflection element, the incident wave will propagate through the grating region and the connecting layer with thickness of h_c and be reflected by the Ag slab with refractive index of n_3 and thickness of h_m to obtain high efficiency in the −1st order. Generally speaking, a lot of numerical results should be calculated with much time to optimize the grating parameters: duty cycle, period, depth, the thickness of connecting layer and metal slab. Mostly important, it is not easy to obtain the desired structure through calculated results with so many parameters. If the modal method and RCWA are used together, optimization will be intelligible, easy and effective.

According to the modal method, the incident wave may excite two modes in the grating region. After propagating through the grating depth, the phase difference can be accumulated due to different effective indices between two modes. The efficiency can be determined by the phase difference based on the two-beam interference. In order to obtain high efficiency in the −1st order, the phase difference should be an odd-numbered multiple of π. Effective indices of excited modes satisfy the equation [7]

$$\cos\beta b\times\cos\gamma g-\frac{\beta^2+\gamma^2}{2\beta\gamma}\sin\beta b\times\sin\gamma g=\cos\alpha d \tag{1}$$

for TE-polarized wave, and

$$\cos\beta b\times\cos\gamma g-\frac{\varepsilon_1^2\beta^2+\varepsilon_2^2\gamma^2}{2\varepsilon_2\varepsilon_1\beta\gamma}\sin\beta b\times\sin\gamma g=\cos\alpha d \tag{2}$$

for TM-polarized wave, where

$$\alpha=k_0\sin\theta_i,\ \beta=k_0\sqrt{\varepsilon_2-n_{eff}^2},\ \gamma=k_0\sqrt{\varepsilon_1-n_{eff}^2},\ k_0=2\pi/\lambda \tag{3}$$

where $\varepsilon_2=n_2^2$ and $\varepsilon_1=n_1^2$ are dielectric permittivities of the ridge with width of b and groove with width of g, respectively. The usual grating duty cycle of 0.5 can be chosen for easy fabrication. According to Eqs. (1)–(3) of the modal method [7], the grating period should be 1050 nm to obtain that the ratio of the effective index difference of TE to TM polarization is 3. For proper depth, the phase difference for TE and TM polarizations can meet 3π and π, respectively. Therefore, high efficiency can be achieved for both polarizations in the −1st order.

The stable implementation of RCWA for surface relief gratings has been described in reference [6], which can be realized by the developed program in this paper. RCWA is used to optimize the accurate depth and thickness of connecting layer. Fig. 2 shows the diffraction efficiency versus the grating depth and thickness of the connecting layer with a duty cycle of 0.5, period of 1050 nm and metal layer thickness of 100 nm for the incident wavelength

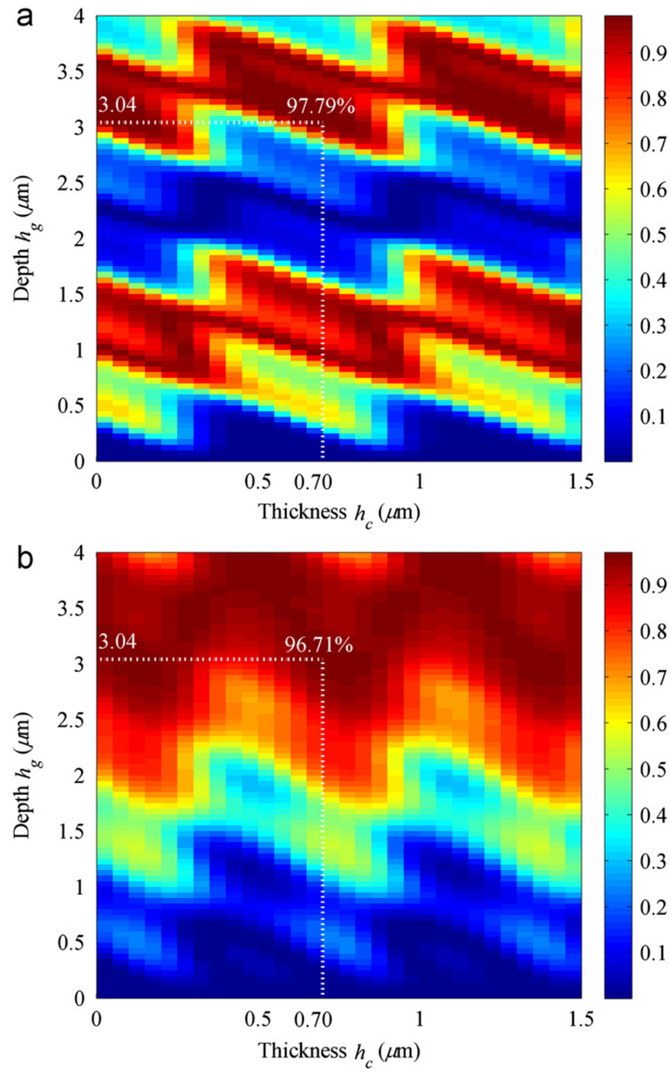

Fig. 2. Diffraction efficiency in the −1st order versus grating depth and thickness of the connecting layer with the duty cycle of 0.5 and the period of 1050 nm for the wavelength of 1550 nm and the incident Bragg angle of 47.57°: (a) TE polarization and (b) TM polarization.

of 1550 nm under Littrow mounting. It indicates that in Fig. 2, high efficiency of 97.79% and 96.71% can be obtained for TE and TM polarizations in the −1st order, respectively, with the optimized grating depth of 3.04 μm and connecting layer thickness of 0.70 μm. During fabrication, with the grating depth and connecting layer thickness varying around the optimized grating parameters, the efficiency will be affected to some extent. However, within the range of 2.94 μm $<h_g<$ 3.22 μm and 0.66 μm $<h_c<$ 0.76 μm, efficiencies more than 90% can be achieved for both TE and TM polarizations. Furthermore, a much wider fabrication tolerance is desirable for practical applications. Within the range of 3.10 μm $<h_g<$ 3.50 μm and 0.50 μm $<h_c<$ 0.71 μm, efficiencies more than 90% can be achieved for both TE and TM polarizations. So, such a design should be very significant for easy fabrication with moderate tolerance for high efficiency.

3. Investigation for diffraction

With the thickness of the connecting layer, the efficiency may be enhanced with wideband property for incident wavelength compared with the conventional binary grating. Fig. 3 shows the