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Sandwiched grating for high efficiency with wide bandwidth and polarization independence

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We describe novel sandwiched grating for high efficiency with polarization independence. The grating parameters can be optimized based on modal method and rigorous coupled-wave analysis (RCWA). According to modal method, grating period and duty cycle are prescribed for polarization independence by excited modes with different effective indices. Using RCWA, accurate grating depth and covering layer thickness are optimized by numerical calculation. The sandwiched grating can show high efficiency for both TE and TM polarizations with the optimized grating period, duty cycle, depth, and covering layer thickness. Most importantly, wideband property can be obtained for operation around the central wavelength of 800 nm. The presented novel sandwiched grating can have merits of high efficiency, polarization independence, and wideband property, which should be of great significance for numerous applications.

Keywords: modal method, rigorous coupled-wave analysis (RCWA), sandwiched grating, high efficiency, polarization independence.

1. Introduction

Diffraction gratings are useful elements in ultrashort high-power laser systems such as dynamic space shaping [1], ultrafast electron spectroscopy [2] and so on. It is desirable to achieve a high-efficiency grating with a wideband wavelength range and high damage threshold in numerous applications. However, for multilayer coatings, wideband properties are not easy to obtain. And metallic gratings are not suitable to stand with high power due to absorption. Therefore, dielectric phase gratings have attracted more and more attention with the development of vector diffraction theory [3, 4] and dry etching method [5]. Especially, fused silica is an excellent optical material with high optical quality: wideband transmitting spectrum and high damage threshold. A series of fused-silica gratings have been designed and fabricated with high efficiency and polarization independence [6, 7]. For example, an optimized fused silica grating with high efficiency for TE polarization can be used for a miniature pulse compressor in femtosecond laser systems [6]. Further investigation demonstrates that wideband property of high efficiency can be obtained for both TE and TM polarizations [7]. To the best of our knowledge, most fused-silica high-efficiency gratings reported are based on simple grating structures, which are directly etched in substrate [8–11].

In this paper, a novel sandwiched grating is introduced for high efficiency with polarization independence. Modal method [3] can be applied to analyze such a grating in order to obtain polarization independence from physical mechanism. And rigorous coupled-wave analysis (RCWA) [4] is used to optimize the accurate grating parameters to achieve high efficiency with numerical calculations. The diffraction property indicates that a wideband wavelength range can be shown for operation around central femtosecond laser wavelength of 800 nm. High efficiency with polarization independence can be achieved by such a new type of sandwiched grating.

2. Configuration of sandwiched grating for high efficiency

Figure 1 depicts a sandwiched grating, where d is the period and h_g is the depth. The grating is etched in fused silica with refractive index $n_2 = 1.45332$ for an incident wavelength of 800 nm. A covering layer with thickness of h_c is introduced over the grating. The incident beam illuminates the grating from air with refractive index of $n_1 = 1$ under Littrow mounting at a Bragg angle of $\theta_i = \sin^{-1}(\lambda/(2n_1 d))$. As a sandwiched grating with polarization independence, TE- and TM-polarized waves can be diffracted in the –1st order with high efficiency.

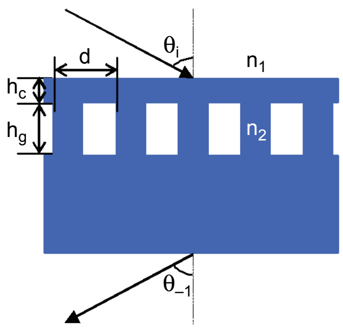

Fig. 1. Schematic of a sandwiched grating (refractive indices: n_1 – air, n_2 – fused silica; d – period; h_g – grating depth, h_c – thickness of the covering layer; θ_i – angle of incidence, θ_{-1} – diffraction angle of the –1st order).

For a conventional grating etched in fused silica, parameters of duty cycle, period, and depth need to be optimized to obtain high efficiency. If a covering layer is introduced for a sandwiched grating, the thickness will affect the efficiency for both TE and TM polarizations. Therefore, the thickness parameter of the covering layer should be added in the optimization. However, with modal method and RCWA, the optimization process will be easy, intelligible, and effective.

According to modal method, two modes may be excited by the incident wave in the grating region. Due to different effective indices of the excited modes, phase differences can be accumulated after propagating through the grating depth, which determines the diffraction efficiency based on the two-beam interference. For the phase difference of odd- and even-numbered multiple of π, high efficiency can be obtained in the −1st and 0th orders, respectively. Since the efficiency can be based on the phase difference, which should be the same for TE and TM polarizations to obtain polarization independence. In reference [7], for the period of 750 nm and duty cycle of 0.67, the effective index difference will be equal for TE and TM polarizations, which can result in the same phase difference. The next step is to optimize the grating depth and covering layer thickness using RCWA for high efficiency in the −1st order.

The grating depth and covering layer thickness can both modulate the efficiency for the sandwiched grating. Figure 2 shows the efficiency versus grating depth and covering layer thickness with period of 750 nm and duty cycle of 0.67 for the incident wavelength of 800 nm. It can be noted that the thickness of the connecting layer has different influence on TE and TM polarizations. The connecting layer can be divided into a stack of uniform homogeneous thin layers [4]. Different boundary conditions can be introduced with two orthogonal polarized light fields for each layer, which can lead to different efficiencies for TE and TM polarizations. Although the excited modes in the grating region are determined by the incident condition and the grating structure, the covering layer affects the efficiency of TE and TM polarizations after propagating such a thin layer which will further affect the efficiency of the sandwiched grating. In Fig. 2, efficiencies of 97.51% and 98.45% can be obtained in the −1st order with the optimized depth of 1.92 μm and covering layer thickness of 0.31 μm for TE and TM polarizations, respectively. With the prescribed grating period and duty cycle based on modal method and accurate optimized grating depth and covering layer thickness using RCWA, high efficiency with polarization independence can be achieved for the sandwiched grating. The grating depth can form the phase difference between two modes excited by the incident wave, which will affect the efficiency of

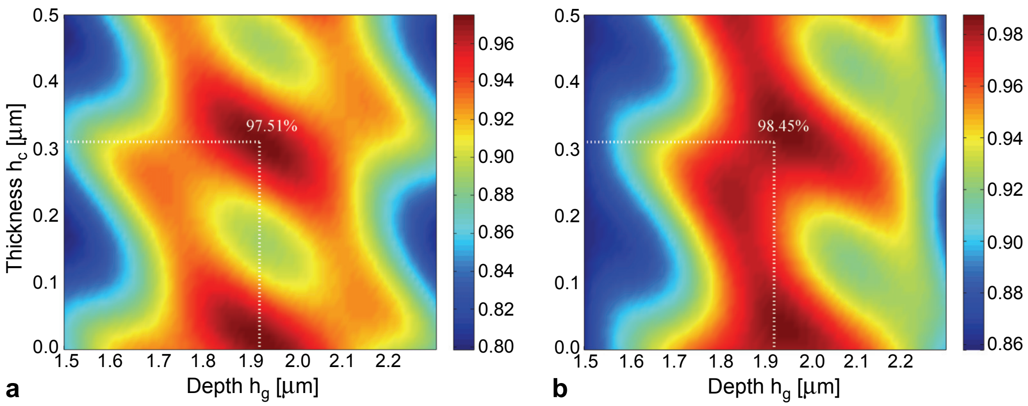

Fig. 2. Diffraction efficiency versus grating depth and thickness of the covering layer with the duty cycle of 0.67 and period of 750 nm for the incident wavelength of 800 nm under Littrow mounting: TE polarization (**a**), TM polarization (**b**).

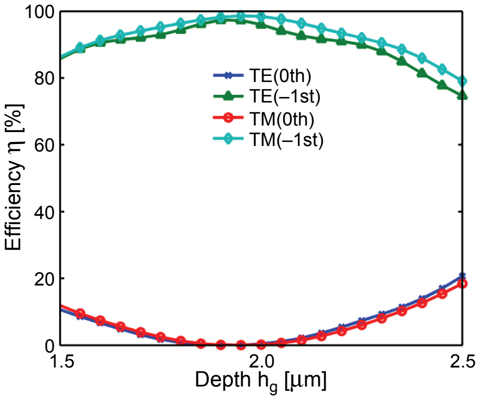

Fig. 3. Diffraction efficiency versus grating depth under Littrow mounting with the duty cycle of 0.67, period of 750 nm, covering layer depth of 0.31 μm for the incident wavelength of 800 nm.

the diffracted orders. Figure 3 shows the efficiency versus the grating depth with the covering layer thickness of 0.31 μm. Efficiencies larger than 97% can be obtained for the optimized sandwiched grating with the etched depth of 1.88 μm < h_g < 1.96 μm. With the deviation of the grating parameters from the optimized results during fabrication, the performance may fall to some extent. However, efficiencies larger than 97% can be obtained within the range of 0.30 μm < h_c < 0.32 μm and 1.90 μm < h_g < < 1.94 μm, which is a good guideline for fabricating such a sandwiched grating with high efficiency. Compared with simple binary grating reported in reference [7], efficiencies larger than 97% can be reached for not only the optimized grating parameters but also the moderate fabrication tolerance, which is of significance for practical applications.

The performance for 0-μm cover-layer thickness is lower. The efficiencies are 97.30% and 98.21% for TE and TM polarizations, respectively. In fact, during the optimization of gratings as micro-optical elements such as high-efficiency device, polarizing beam splitter and so on, the performance can be obtained with usually several regions which can refer to Fig. 3 in the reported reference [7]. For optimization, the optimum design region with better performance is chosen. The efficiencies and wideband properties for TE and TM polarizations are improved based on the sandwiched grating. Furthermore, moderate fabrication tolerance can be obtained.

3. Analysis of optimized results

For the optimized sandwiched grating, high efficiency can be achieved with polarization independence. It is attractive that a wideband property can be obtained based on such a sandwiched grating. Figure 4 shows the diffraction efficiency versus the incident wavelength at an incident Bragg angle for the optimized grating period, duty

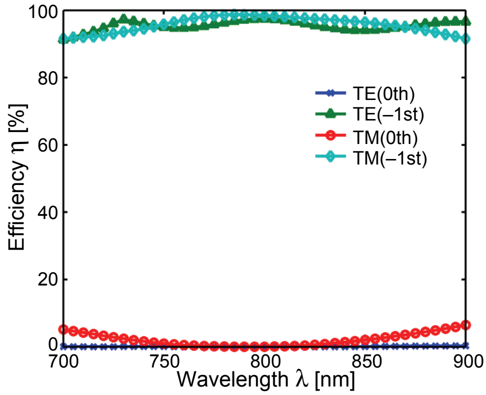

Fig. 4. Diffraction efficiency versus incident wavelength under Littrow mounting with the optimized grating parameters.

cycle, depth, and covering layer thickness. Efficiency will change with the deviation of the incident wavelength from the central 800 nm. As can be seen in Fig. 4, efficiencies larger than 90% can be obtained within the wavelength range of 700–900 nm. Compared with wavelength range of 750–850 nm [7], the efficiency larger than 92% can be obtained within 710–897 nm for the sandwiched grating. When the sandwiched grating is used in the laser systems, wide wavelength for operation can be applicable, which will be of great significance for the femtosecond laser.

Under Littrow mounting, high efficiency can be achieved for the optimized sandwiched grating. If the angle of incidence is not for the Bragg angle, efficiency will decrease to some extent. Figure 5 shows the efficiency versus the angle of incidence with the incident wavelength of 800 nm for the optimized sandwiched grating. In Fig. 5,

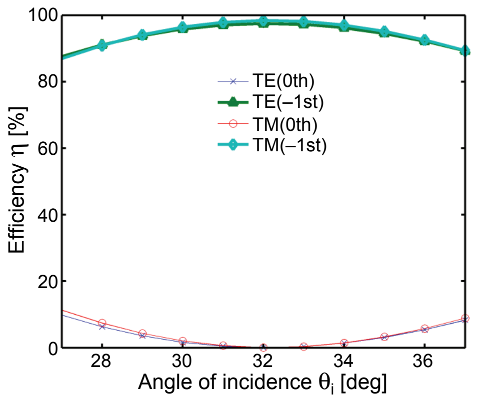

Fig. 5. Diffraction efficiency versus angle of incidence for the incident laser wavelength of 800 nm with the optimized grating parameters.

efficiencies larger than 92% can be achieved for the angle of incidence range of 27.76–36.76°, which is 28.43–35.96° by calculation for the simple binary parameters in [7]. Moreover, the efficiencies of TE and TM polarizations are nearly the same in the –1st order, which correspond well with predictions of modal method due to the same phase difference. From diffraction property, it can be seen that the sandwiched grating can have wider wavelength and angular bandwidth compared with the results in ref. [7].

4. Conclusions

In conclusion, a novel sandwiched grating is presented to work as a high-efficiency element with polarization independence. According to modal method, with the period of 750 nm and duty cycle of 0.67, polarization independence can be obtained for TE and TM polarizations. Using RCWA, with accurately optimized grating depth of 1.92 μm and covering layer of 0.31 μm, high efficiency can be achieved in the –1st order. Further analysis shows that wideband property can be indicated with such a sandwiched grating. Efficiencies larger than 90% can be obtained for the operation wavelength range of 700–900 nm. Moreover, the optimized sandwiched grating can have moderate angle of incidence for high efficiency. Efficiencies larger than 90% can be obtained with the angle of incidence range 27.76°–36.76° near Littrow mounting. The new and novel sandwiched grating can have advantages of high efficiency, polarization independence, and wideband property, which should be useful for various optical systems.

The performance for 0-μm cover-layer thickness is lower. The efficiencies are 97.30% and 98.21% for TE and TM polarizations, respectively. In fact, during the optimization of gratings as micro-optical elements such as a high-efficiency device, polarizing beam splitter and so on, the performance can be obtained with usually several regions which can refer to Fig. 3 in the reported reference [7]. For optimization, the optimum design region with better performance is chosen. The efficiencies and wideband properties for TE and TM polarizations are improved based on the sandwiched grating. Furthermore, moderate fabrication tolerance can be obtained.

The efficiencies and wideband properties for TE and TM polarizations are improved based on the sandwiched grating. Furthermore, moderate fabrication tolerance can be obtained. Reference [7] is based on the simple binary grating, while this manuscript is based on the sandwiched grating. In reference [7] efficiencies can reach 97%. In this manuscript, efficiencies of 97.51% and 98.45% can be obtained in the –1st order with the optimized results for TE and TM polarizations, respectively. Most importantly, efficiencies larger than 97% can be reached for not only the optimized grating parameters but also the moderate fabrication tolerance.

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