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Reflective diffraction with high efficiency and beam splitter by metal-mirror-based grating

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It is interesting and desirable to achieve two functions of high efficiency and two-port output with one reflective grating, which is not easy to acquire by multilayer coatings. We describe the reflective high efficiency element and the two-port beam splitter by the metal-mirror-based grating. By modal method, the design guideline is proposed according to the two-beam interference of the excited modes by incident TE and TM polarizations. Using rigorous coupled-wave analysis (RCWA), accurate grating parameters are optimized by numerical calculation. This indicates that wideband property can be achieved for such a reflective dual-function grating. Furthermore, the element can also be used for beam splitting for TE polarization with the predetermined angle of incidence. With merits of wideband and so many functions, the reflective elements presented should be useful in a variety of optical systems.

Keywords: modal method, rigorous coupled-wave analysis, metal-mirror-based grating, high efficiency, beam splitter.

1. Introduction

Binary gratings have attracted more and more attention in the resonance domain due to the various diffraction properties and practical applications [1–3]. With the development of the theoretical treatment and experimental method, novel phenomena continue to be discovered [4]. Based on the theoretical analysis, it is feasible to investigate new and useful diffraction. When the grating period can be comparable to the incident wavelength, the diffraction may depend on the incident polarized state. The widely used theories include rigorous coupled-wave analysis (RCWA) [5] and modal method [6]. Diffraction efficiency can be calculated by the numerical approach of RCWA [7] not only for a simple rectangular-groove but also for complicated multilevel gratings [8]. However, no physical mechanism can be provided by the numerical treatment. The modal method can give an intelligible explanation of the propagation process based on the two-beam interference in the grating region. Using experimental methods of lithographic and dry etching advances [9], it is possible to form grating patterns and obtain deep depth. Many high-density gratings have been optimized and fabricated as high-efficiency element [10], beam splitter [11] and polarizer [12].

High-efficiency gratings can be used for dense wavelength division multiplexing with advantages of parallel demultiplexing, low polarization-dependent loss, and the lowest cross-talk over thin-film filters, arrayed waveguide gratings, fiber Bragg gratings. By holographic recording and dry etching in optimized experimental conditions, efficiency of 87.1% can be reached at a wavelength of 1550 nm [13]. Furthermore, binary gratings can also work as beam splitters, which are widely used in optical information processing systems such as a coupler, an interferometer, and so on. Without multiple reflection and refraction of conventional beam splitters based on multilayer coatings, the efficiency can be improved greatly and good uniformity can be obtained between different ports. The optimized and fabricated grating can be used as a two-port beam splitter not only for TE or TM polarization but also for both the TE and TM polarizations [14]. Although binary gratings can work as high-efficiency elements and beam splitters, most reported gratings concentrate on one function. It is desirable that two functions be fulfilled by one grating. A dual-function grating has been presented to obtain high efficiency for TE polarization and two-port output for TM polarization with the transmissive structure of a simple grating [15].

In this paper, for the reflective diffraction, a metal-mirror-based grating is introduced to achieve a dual-function element of high efficiency and a beam splitter. The complicated grating structure involves the grating region to realize diffraction, the connecting layer to obtain wideband property, and metallic slab to reflect the incident wave. The grating parameters are optimized using physical insight of modal method and numerical calculation of RCWA in order to obtain high efficiency for TE polarization and uniformity for TM polarization. This indicates that the grating performance can be improved by novel grating structure.

2. Grating design

Figure 1 shows the schematic of a metal-mirror-based grating with period d and depth h_g, where an additional metal slab with thickness h_m is evaporated on the substrate to reflect the incident wave, as compared to conventional simple grating element. A connecting layer of thickness h_c is incorporated to obtain high efficiency with wideband property. The incident wave with wavelength λ illuminates the grating under the Littrow mounting at a Bragg angle $\theta_i = \sin^{-1}(\lambda/(2n_1d))$ with refractive index $n_1 = 1$. The grating can be etched in fused silica with refractive index $n_2 = 1.45$, and n_3 is the refractive index of Ag metal slab. As a dual-function grating element, high efficiency can be obtained in the –1st reflection order for TE polarization, while two-port output can be diffracted in the 0th and the –1st orders for TM polarization. Although the reflective dual-function element can be achieved by such a metal-mirror--based grating, there are too many parameters to be optimized compared to conventional transmissive simple binary grating. The additional parameters such as thickness of

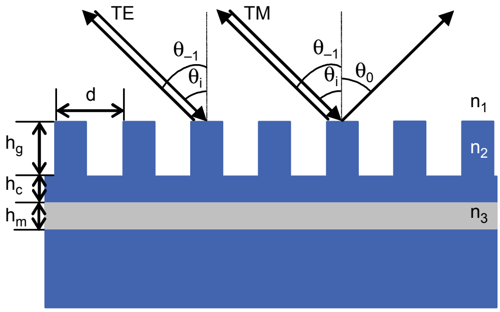


Fig. 1. Schematic of a reflective dual-function grating by a metal-mirror-based grating (refractive indices n_1 – air, n_2 – fused silica, n_3 – Ag; d – period; h_g – grating depth, h_c and h_m – thickness of the connecting layer and metal slab, respectively; θ_i – incident angle, θ_{-1} and θ_0 – diffraction angles of the –1st and 0th orders, respectively).

the connecting layer will greatly increase the numerical calculation of RCWA during optimization, which will take too much time. Most importantly, the design guideline cannot be indicated from so many numerical results. In this paper, physical mechanism of modal method is introduced for the metal-mirror-based grating, which makes it possible to obtain such a dual-function grating efficiently.

The number of the parameters that need to be optimized can be reduced to some extent based on the modal method. The grating is considered with usual duty cycle of 0.5 for easy fabrication. Two modes can be excited in the grating region when the incident wave illuminates the grating. For different effective indices of two modes, phase differences can be accumulated after propagating through the grating depth, which can determine the efficiency of diffracted orders because energies are coupled by the two-beam interference of excited modes. So, in order to obtain high efficiency for TE polarization, the phase difference should be an odd-numbered multiple of π, which should correspond to an odd-numbered multiple of π/2 for two-port output of TM polarization. The phase difference is formed by the effective index difference and propagating distance. Since propagating distances of grating depths are the same for the two polarizations. The effective index difference of TE polarization should be twice as many as that of TM polarization. A grating period of 1181 nm may be chosen to meet such a condition with the duty cycle of 0.5 for the incident wavelength of 1550 nm.

By physical analysis of the modal method, there are only the grating depth and thickness of the connecting layer to be optimized. The accurate results for those parameters can be achieved using RCWA. Figure 2 shows the reflection efficiency versus the grating depth and thickness of the connecting layer with usual duty cycle of 0.5 and period of 1181 nm for the incident wavelength of 1550 nm at a Bragg angle of incidence. In Figure 2, with the optimized depth of 0.90 μm and connecting layer thickness of 1.40 μm, reflective efficiency of 96.97% can be diffracted into the –1st order for TE polarization. And for TM polarization, the two-port output

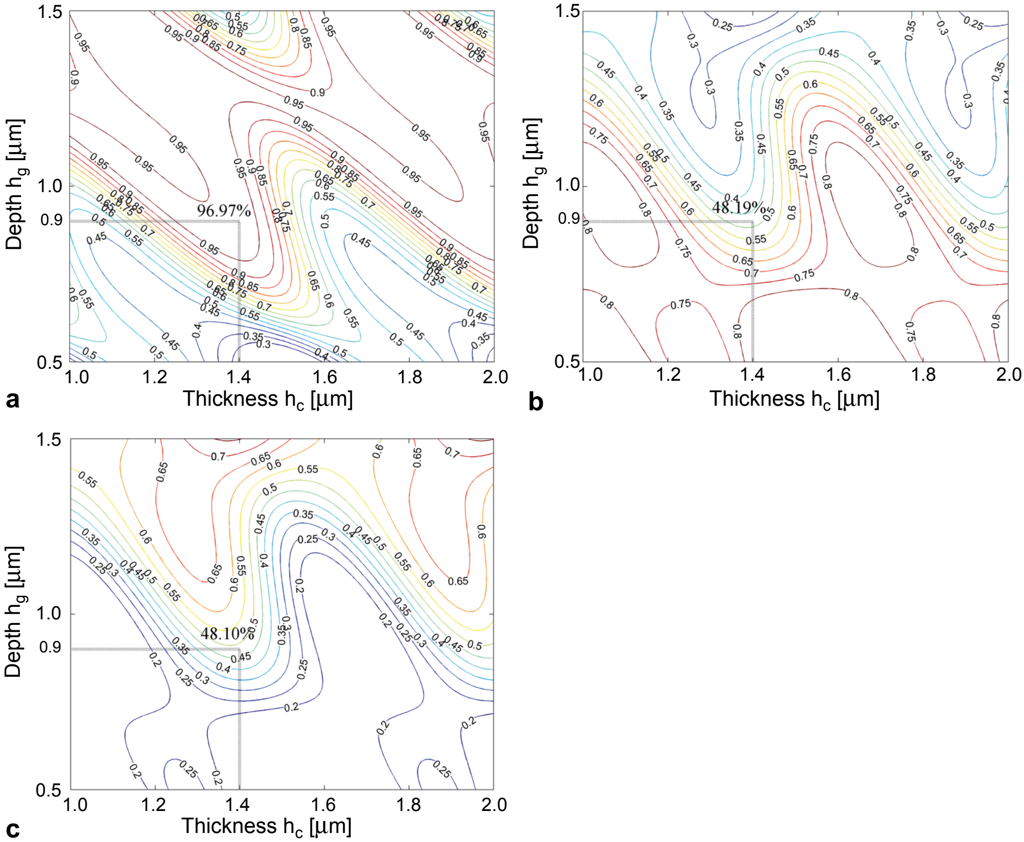


Fig. 2. Reflection efficiency versus grating depth and thickness of the connecting layer with the duty cycle of 0.5 and period of 1181 nm for the wavelength of 1550 nm: TE polarization diffracted into the –1st order (**a**), TM polarization diffracted into the 0th order (**b**), and TM polarization diffracted into the –1st order (**c**).

efficiency of 48.19% and 48.10% can be diffracted into the 0th and the –1st orders, respectively.

The connecting layer thickness can modulate the efficiency during propagation of the incident wave. Figure 3 shows the reflection efficiency with the different connecting layer thickness for the duty cycle of 0.5, the period of 1181 nm, and the grating depth of 0.90 µm. One can see that with the optimized connecting layer thickness of 1.40 µm, high efficiency and two-port output can be achieved for TE and TM polarizations, respectively.

3. Performance of the optimized gratings

The metal-mirror-based grating is different from the conventional simple binary grating, in which a connecting layer is introduced to improve the wideband

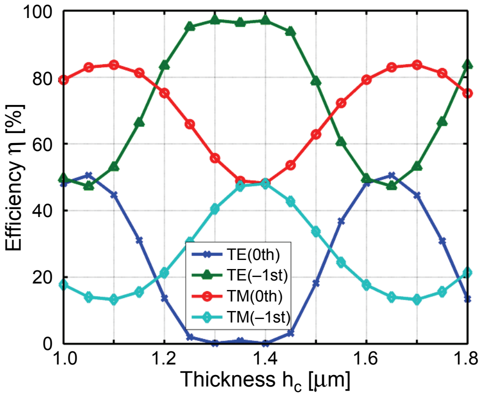
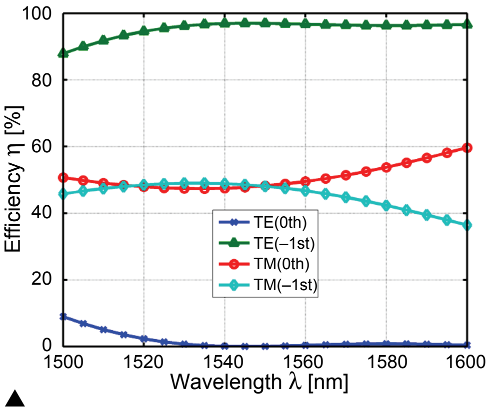


Fig. 3. Reflection efficiency versus thickness of the connecting layer with the duty cycle of 0.5, period of 1181 nm and depth of 0.90 μm for the wavelength of 1550 nm under the Littrow mounting.



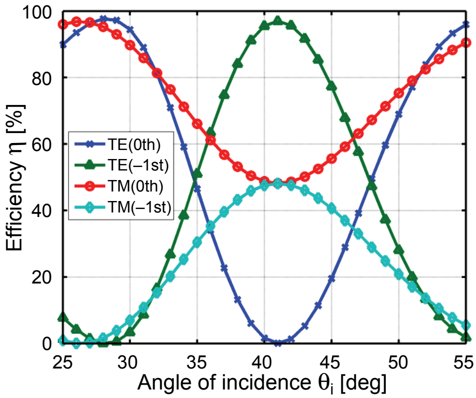


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Fig. 4. Reflection efficiency versus incident wavelength under the Littrow mounting with the optimized grating parameters.

Fig. 5. Reflection efficiency versus angle of incidence for the wavelength of 1550 nm with the optimized grating profile parameters.

property. Figure 4 shows the reflection efficiency with different incident wavelengths for the optimized grating parameters. In Figure 4, efficiencies of more than 90% for TE polarization diffracted into the –1st order and more than 45% for TM polarization diffracted into the 0th and the –1st orders can be obtained within the wavelength range of 1506–1569 nm. Figure 5 shows the efficiency at different angle of incidence for the optimized grating parameters. In Figure 5, a dual-function element can be achieved under the Littrow mounting by the metal-mirror-based grating. In addition, a two-port beam splitter can be obtained for TE polarization with the angle of incidence of 34.82° and 47.89°. Therefore, the metal-mirror-based grating can work as a high-efficiency element for TE polarization and beam splitter for both TE and TM polarizations.

4. Conclusions

In conclusion, a reflective element of high efficiency and a beam splitter are proposed by the metal-mirror-based grating. With usual duty cycle of 0.5 for easy fabrication, a grating period of 1181 nm can be chosen according to modal method. With the optimized grating depth of 0.90 μm and the connecting layer thickness of 1.40 μm using RCWA, efficiency of 96.97% can be diffracted into the –1st order for TE polarization, and for TM polarization, two-port output efficiency of 48.19% and 48.10% can be diffracted into the 0th and –1st orders, respectively. When the incident wavelength deviates from the wavelength of 1550 nm, efficiencies of more than 90% for TE polarization and more than 45% for TM polarization can be shown within the range of 1506–1569 nm. When deviating from the Littrow mounting, the reflective grating can work as a beam splitter at the angles of incidence of 34.82° and 47.89°. The presented metal-mirror-based grating should be very useful in numerous optical systems as a reflective high-efficiency element and a beam splitter with good performance.

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