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Binary-phase metal-based sandwiched grating with high efficiency

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We describe a novel high efficiency element based on a binary-phase metal-based sandwiched grating, where the binary grating is covered by a dielectric layer and connected by a metal slab on the fused-silica substrate. The modal method is used to optimize the grating duty cycle and period to analyze the feasibility to achieve high efficiency for TE and TM polarizations by effective indices of the modes excited in the grating region. Rigorous coupled-wave analysis (RCWA) is employed to optimize the grating depth and to cover the layer thickness accurately by numerical calculations. It is not easy for the conventional binary grating with a usual duty cycle to achieve high efficiency in the –1st order for TM polarization. For the binary-phase metal-based sandwiched grating, high efficiency can be diffracted into the –1st order for not only TE polarization but also TM polarization. Moreover, the wide fabrication tolerance, the wideband property and the flat surface of easy cleaning should be significant for practical applications in a variety of optical systems.

Keywords: binary phase, metal layer, sandwiched grating.

1. Introduction

Binary-phase surface-relief gratings [1–3] are widely investigated in the resonance domain, where grating periods can be comparable to the incident wavelength. There may be only two diffraction orders left for such high-density gratings [4–6], which are different from conventional low-density gratings. By optimization, using vector grating theories such as the modal method [7] and the rigorous coupled-wave analysis (RCWA) [8], the incident energy can be diffracted in the –1st order by cancellation of the 0th order. Designed binary-phase gratings can be used in optics communications [9, 10] and ultrashort laser pulse systems [11]. And experimental progress can make it impossible to etch effectively such designed gratings with high efficiency by inductively coupled plasma dry etching [12]. For a good performance of fused silica [13] with a high damage threshold, a stable performance and wide transmitting spectrum, a series of binary-phase gratings have been optimized and fabricated with high efficiency based on fused silica. A transmission grating was etched in fused silica for high efficiency at a wavelength of 1550 nm, which can be used for dense wavelength division multiplexing [10]. Calculated efficiency, of more than 95% for TE polarization, can be exhibited within the fabrication tolerance. However, the efficiency of only 80% can be reached for TM polarization with the optimized region. Moreover, deep-etched transmission gratings were presented for high efficiency at a femtosecond laser wavelength of 800 nm [11]. With a pair of fabricated gratings, the chirped input can be compressed into the nearly Fourier transform-limited pulse. The design is for the TE polarization and approximately 84% efficiency can be obtained for the fabricated gratings. The above proposed transmission gratings have the duty cycle of 0.5. For such a usual duty cycle, high efficiency can be obtained for TE polarization. But for TM polarization, it is hard to diffract the incident wave into the –1st order with high efficiency. Recently, a mixed metal-dielectric reflection grating has been proposed with high efficiency, where a surface-relief dielectric grating is etched on a reflective mirror [14]. For TE and TM polarizations, reflection efficiencies higher than 90% can be exhibited over the 120 nm bandwidth around the incident wavelength of 800 nm.

In this paper, a binary-phase metal-based sandwiched grating is presented with high efficiency for both TE and TM polarizations. The feasibility is investigated based on the modal method by excited effective indices of the grating region. The grating parameters are accurately optimized by numerical calculations using RCWA. The presented grating can have high efficiency for both TE and TM polarizations with a usual duty cycle of 0.5. The diffraction analysis can indicate that wide etched grating depth with high efficiency will be significant for practical fabrication of such a binary-phase metal-based sandwich grating. The flat surface of a metal-based sandwiched grating can have the advantage of easy cleaning.

2. High-efficiency binary-phase metal-based sandwiched grating

Figure 1 shows the schematic of a binary-phase metal-based sandwiched grating with the period of d and the depth of h_g. The incident region is air with the refractive index of $n_1 = 1$ and the grating region is fused silica with the refractive index $n_2 = 1.45$. For a reflection design, there is an Ag slab with the refractive index of n_3 and the thickness of h_m. As a sandwiched grating, a layer with the thickness of h_c is covered on the grating region. The incident wave with the wavelength of λ illuminates the binary-phase metal-based sandwiched grating under Littrow's mounting at a Bragg angle of $\theta_i = \sin^{-1}(\lambda/(2n_1d))$. High efficiency can be obtained in the reflection –1st order for not only TE polarization but also TM polarization. For the new type of a binary-phase metal-based sandwiched grating, there are five parameters to be optimized: duty cycle, period, depth, the thickness of covering layer and metal slab. Although the number of parameters is much bigger than in a conventional binary grating, the optimization process will be effective using the modal method and RCWA.

The incident wave can excite two modes in the grating region for the subwavelength grating based on the modal method, which will help to understand the physical

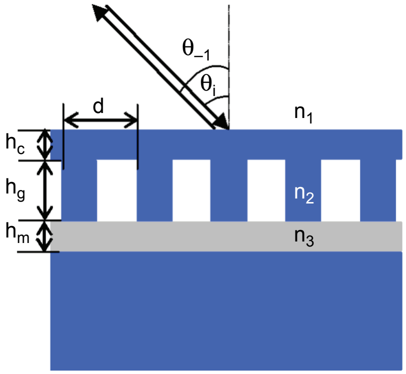

Fig. 1. Schematic of a binary-phase metal-based sandwiched grating (refractive indices: n_1 – air, n_2 – fused silica, n_3 – Ag, d – period, h_g – grating depth, h_c and h_m – thickness of the covering layer and metal slab, respectively, θ_i – incident angle, θ_{-1} – diffraction angle of the –1st order).

mechanism of propagation process clearly. Phase difference can be accumulated between two excited modes due to different effective indices after propagating through the grating region. According to the two-beam interference, high efficiency can be obtained in the –1st order for the phase difference of the odd-numbered multiple of π such as π, 3π, and so on. In the design, TE and TM polarizations will be diffracted into the –1st order with high efficiency. The duty cycle of 0.5 can be chosen for easy fabrication. With the usual duty cycle of 0.5, the ratio of the effective index difference of TE to TM polarization is 3 for the grating period of 1050 nm. Thus, the odd-numbered multiple of π can be obtained for TM and TE polarizations simultaneously, and high efficiency can be diffracted into the –1st order with polarization independence.

The metal slab can be set to 100 nm, where the thickness is enough to obtain the reflection grating with high efficiency. There are only two parameters left to be optimized: the grating depth and the thickness of the covering layer, which can be

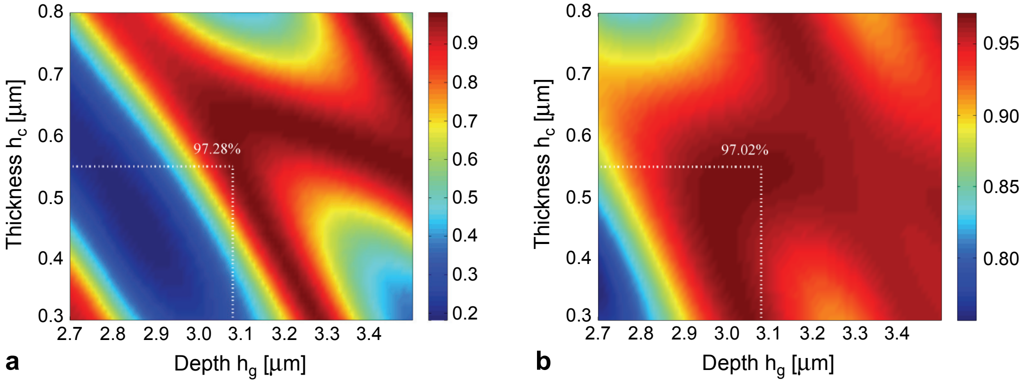

Fig. 2. Diffraction efficiency versus grating depth and thickness of the covering layer with the duty cycle of 0.5 and the period of 1050 nm for the incident wavelength of 1550 nm under Littrow's mounting: TE (**a**) and TM (**b**) polarization.

accurately optimized using RCWA. Figure 2 shows the diffraction efficiency versus the grating depth and thickness of the covering layer with the duty cycle of 0.5 and the period of 1050 nm for the incident wavelength of 1550 nm under Littrow's mounting. As can be seen in Fig. 2, the efficiencies of 97.28% and 97.02% can be obtained in the –1st order with the optimized depth of 3.07 μm and covering layer thickness of 0.56 μm for TE and TM polarizations, respectively. With the period of 1050 nm, the metal slab thickness of 100 nm, the depth of 3.07 μm and the covering layer thickness of 0.56 μm, high efficiency can be diffracted into the –1st order for not only TE but also TM polarizations with the usual duty cycle of 0.5.

3. Wide etched depth and diffraction property

Based on the modal method and RCWA, a binary-phase metal-based sandwiched grating can be optimized for high efficiency with polarization independence. The grating duty cycle and the period are designed by effective indices of the modal method. And the grating depth and the thickness of the covering layer are optimized using RCWA. When the grating parameters deviate from the optimized results, the performance will be affected for TE and TM polarizations. It is necessary to investigate the fabrication tolerance during practical applications. Figure 3 shows the reflection efficiency of the –1st order versus the grating depth under Littrow's mounting with different covering layer thickness for the duty cycle of 0.5, the period of 1050 nm, and the incident wavelength of 1550 nm. The efficiency larger than 90% can be achieved within the grating depth of 3.03 μm < h_g < 3.50 μm and the covering layer thickness of 0.56 μm < h_c < 0.64 μm. Therefore, the wide fabrication tolerance should be desirable and significant during fabrication for a practical use, especially the grating etched depth.

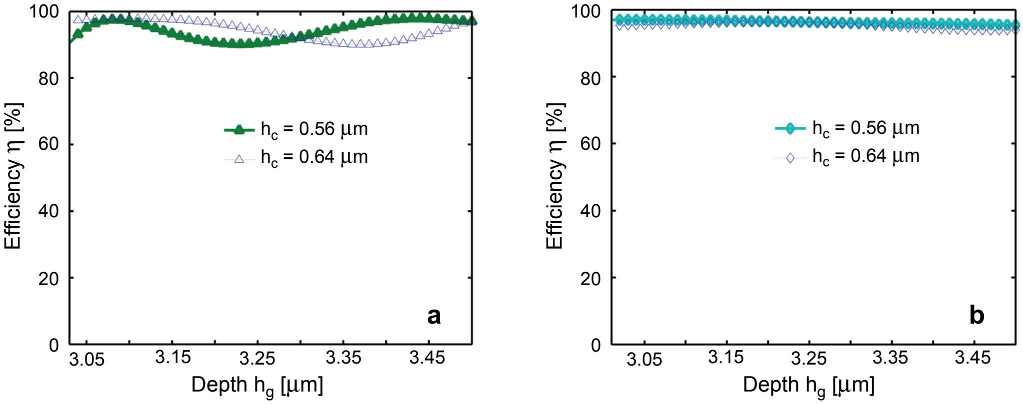

Fig. 3. Reflection efficiency of the –1st order versus grating depth under Littrow's mounting with different covering layer thickness for the duty cycle of 0.5, the period of 1050 nm, and the incident wavelength of 1550 nm: TE (**a**) and TM (**b**) polarization.

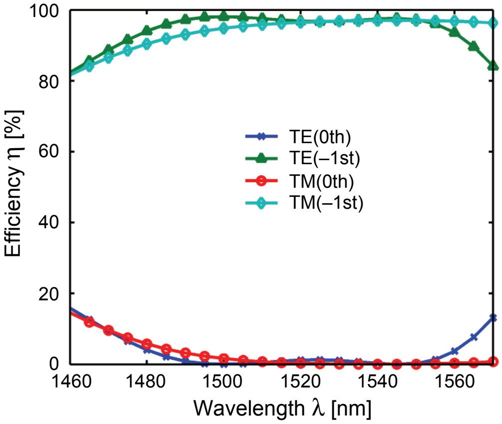

Fig. 4. Reflection efficiency versus incident wavelength under Littrow's mounting with the optimized grating parameters.

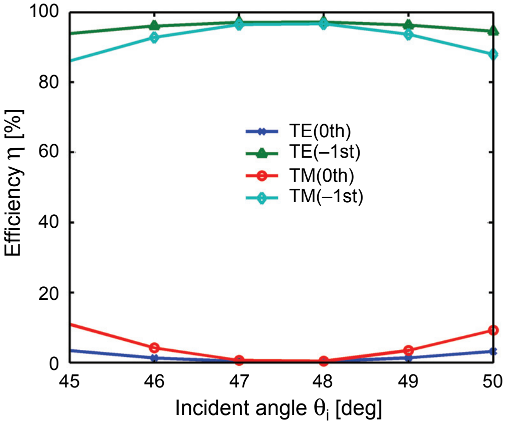

Fig. 5. Reflection efficiency versus incident angle for the incident laser wavelength of 1550 nm with the optimized grating parameters.

With the optimized grating parameters, the binary-phase metal-based sandwiched grating is designed with high efficiency for the incident wavelength of 1550 nm and Bragg's angle. The wideband property for the incident wavelength and angle is important for operation. Figure 4 shows the reflection efficiency versus the incident wavelength under Littrow's mounting with the optimized grating parameters. In Fig. 4, efficiency larger than 90% can be obtained within the wavelength range of 1479–1564 nm. Figure 5 shows the reflection efficiency versus the incident angle for the incident laser wavelength of 1550 nm with the optimized grating parameters. In Fig. 5, when the incident angle is around the Bragg angle, the efficiency larger than 90% for TM polarization and 95% for TE polarization can be obtained within 45.53°–49.69°.

It is attractive that a wide incident wavelength range and angular bandwidth can be operated for the binary-phase metal-based sandwiched grating with high efficiency.

4. Conclusions

In conclusion, a novel high efficiency element is proposed based on a binary-phase metal-based sandwiched grating. Such a grating can be optimized using the modal method and RCWA. The duty cycle of 0.5 and the period of 1050 nm are optimized by effective indices of the modal method from physical mechanism. And the grating etched depth of 3.07 μm and the covering layer thickness of 0.56 μm are accurately optimized using numerical calculations of RCWA. The efficiency larger than 90% can be achieved within the wavelength range of 1479–1564 nm and the angular bandwidth of 45.53°–49.69°. It is not easy to diffract the incident wave into the –1st order for TM polarization with a usual duty cycle for a conventional binary grating. Based on the binary-phase metal-based sandwiched grating, high efficiency can be obtained for both TE and TM polarizations. And the wide fabrication tolerance, especially the grating depth, will be significant for a practical application during fabrication. The metal-based sandwiched grating has a flat surface, which can have the advantage of easy cleaning compared to the surface-relief grating.

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References

[1] YU J., ZHOU C., JIA W., HU A., WANG S., MA J., *Circular Dammann grating under high numerical aperture focusing*, Applied Optics **51**(7), 2012, pp. 994–999.

[2] FOLEY J.M., ITSUNO A.M., DAS T., VELICU S., PHILLIPS J.D., *Broadband long-wavelength infrared Si/SiO2 subwavelength grating reflector*, Optics Letters **37**(9), 2012, pp. 1523–1525.

[3] TONCHEV S., JOURLIN Y., VEILLAS C., REYNAUD S., LYNDIN N., PARRIAUX O., LAUKKANEN J., KUITTINEN M., *Subwavelength cylindrical grating by holistic phase-mask coordinate transform*, Optics Express **20**(7), 2012, pp. 7946–7953.

[4] PENG Z., FATTAL D.A., FARAON A., FIORENTINO M., LI J., BEAUSOLEIL R.G., *Reflective silicon binary diffraction grating for visible wavelengths*, Optics Letters **36**(8), 2011, pp. 1515–1517.

[5] ESTRUCH T., JAECK J., PARDO F., DERELLE S., PRIMOT J., PELOUARD J.-L., HAIDAR R., *Perfect extinction in subwavelength dual metallic transmitting gratings*, Optics Letters **36**(16), 2011, pp. 3160–3162.

[6] CHEN Y., LIU W., *Design and analysis of multilayered structures with metal-dielectric gratings for reflection resonance and color generation*, Optics Letters **37**(1), 2012, pp. 4–6.

[7] BOTTEN I.C., CRAIG M.S., MCPHEDRAN R.C., ADAMS J.L., ANDREWARTHA J.R., *The dielectric lamellar diffraction grating*, Optica Acta **28**(3), 1981, pp. 413–428.

[8] MOHARAM M.G., POMMET D.A., GRANN E.B., GAYLORD T.K., *Stable implementation of the rigorous coupled-wave analysis for surface-relief gratings: enhanced transmittance matrix approach*, Journal of the Optical Society of America A **12**(5), 1995, pp. 1077–1086.

[9] Zhang Y., Zhou C., *High-efficiency reflective diffraction gratings in fused silica as (de)multiplexers at 1.55 μm for dense wavelength division multiplexing application*, Journal of the Optical Society of America A **22**(2), 2005, pp. 331–334.

[10] Wang S., Zhou C., Zhang Y., Ru H., *Deep-etched high-density fused-silica transmission gratings with high efficiency at a wavelength of 1550 nm*, Applied Optics **45**(12), 2006, pp. 2567–2571.

[11] Jia W., Zhou C., Feng J., Dai E., *Miniature pulse compressor of deep-etched gratings*, Applied Optics **47**(32), 2008, pp. 6058–6063.

[12] Wang S., Zhou C., Ru H., Zhang Y., *Optimized condition for etching fused-silica phase gratings with inductively coupled plasma technology*, Applied Optics **44**(21), 2005, pp. 4429–4434.

[13] Brückner F., Kroker S., Friedrich D., Kley E.-B., Tünnermann A., *Widely tunable monolithic narrowband grating filter for near-infrared radiation*, Optics Letters **36**(4), 2011, pp. 436–438.

[14] Hu A., Zhou C., Cao H., Wu J., Yu J., Jia W., *Polarization-independent wideband mixed metal dielectric reflective gratings*, Applied Optics **51**(20), 2012, pp. 4902–4906.

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