50%-50% splitting ratio element by covering-layer grating

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A 50%-50% splitting ratio element is presented by the covering-layer grating. The novel grating introduces a covering layer on the surface-relief grating, which can not only protect the grating surface but also improve the performance of a beam splitter compared with the surface-relief grating. The beam splitter based on fused silica is optimized for the femtosecond laser with high damage threshold. For different incident wavelengths and angles, the 50%-50% splitting ratio element exhibits wideband properties, which are useful compared with most beam splitters operated for certain incident wavelength or angle.

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1. Introduction

A beam splitter element can divide the incident beam into two beams with good uniformity [1-5], which is widely used in high-precision laser interferometers, holographic optical tweezers, and lithography fabrication. Most commercial splitters based on multilayer coatings have disadvantages of thermal deformations and rapid damage near coating defects. Such unwanted thermal effects limit the performance of a beam splitter. To avoid this problem, beam splitters are reported based on high-density deep-etched gratings [6-8]. Especially, fused silica is an excellent optical material, which has stable performance, high damage threshold, and wide transmitting spectrum ranging from deep ultraviolet to far infrared. Generally speaking, the beam splitter grating made of fused silica can have better performance.

A surface-relief grating has been reported as beam splitter at the incident wavelength of 1550 nm [9]. The grating depths are optimized by using the rigorous coupled-wave analysis (RCWA) [10]. For the usual duty cycle of 0.5, efficiencies of 48.39%/48.35% and 49.09%/49.13% are diffracted into the –1st and the 0th orders for TE and TM polarizations, respectively. In experiments, the validity is confirmed by holographic recording and inductively coupled plasma etching. For most beam splitters based on multilayer coatings or high-density gratings, the good uniformity can be obtained for the given incident angle. Although the beam splitter grating etched in fused silica can have high damage threshold compared with the beam splitter based on multilayer coatings, it is necessary to improve the incident angle range for practical applications.

In this paper, a 50%-50% splitting ratio element is presented by the covering-layer grating. Such a novel grating can be obtained by covering the fused-silica layer on the surface-relief grating. The covering layer thickness and the grating depth are optimized to obtain good uniformity for TE and TM polarizations. Such a beam splitter can have wide incident angular bandwidth. And it is easy to clean and protect the grating surface compared with the surface-relief grating.

2. 50%-50% splitting ratio element

Fig. 1 shows schematic of 50%-50% splitting ratio element by covering-layer grating, which is made of fused silica. The incident beam illuminates the beam splitter grating under Littrow mounting at the Bragg angle of $\theta_i=\sin^{-1}(\lambda/(2n_1d)$ from air with the refractive index of $n_1=1$, where λ is the wavelength and d is the grating period. After propagating through the covering layer with thickness of h_c, the incident wave is diffracted by the grating with depth of h_g and refractive index of $n_2=1.45$.

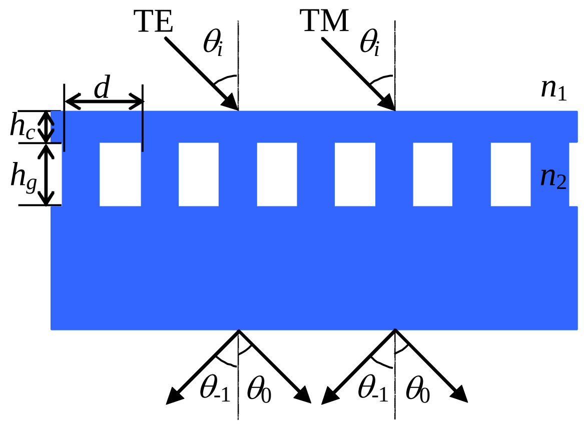
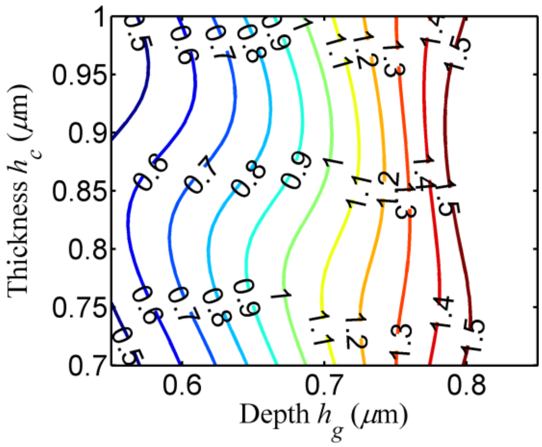
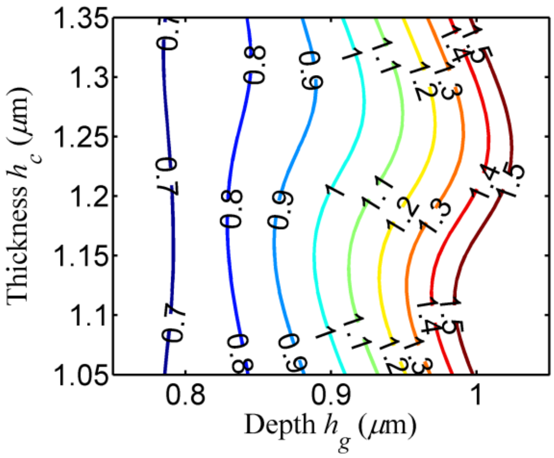


Fig. 1. Schematic of 50%-50% splitting ratio element by covering-layer grating

The covering layer can be divided into a large number of grating slabs, where the electromagnetic fields are determined by the coupled-wave approach. And the electromagnetic boundary conditions can be applied in sequence at the interfaces of slabs. Therefore, the covering layer can not only protect the grating surface but also affect the efficiency of the grating to improve the performance. The diffraction efficiency can be simulated by using RCWA for various grating parameters. For simple fabrication, the grating duty cycle is 0.5. Fig. 2 shows efficiency's ratio between the –1st and the 0th orders versus covering layer thickness and grating depth for the femtosecond laser wavelength of 800 nm with the grating period of 790 nm. For TE polarization, 50%-50% splitting ratio can be obtained with the optimized covering layer thickness of h_c=0.86 μm and grating depth of h_g=0.70 μm. For TM polarization, good uniformity can be achieved with the optimized grating parameters of h_c=1.21 μm and h_g=0.90 μm. The performance can also be calculated with the optimized results. Efficiencies 48.52%/48.63% and 49.23%/49.49% can be split into the –1st and the 0th orders for TE and TM polarizations, respectively.



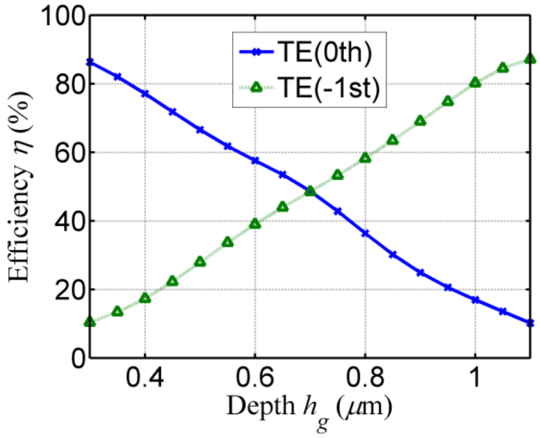
(a)



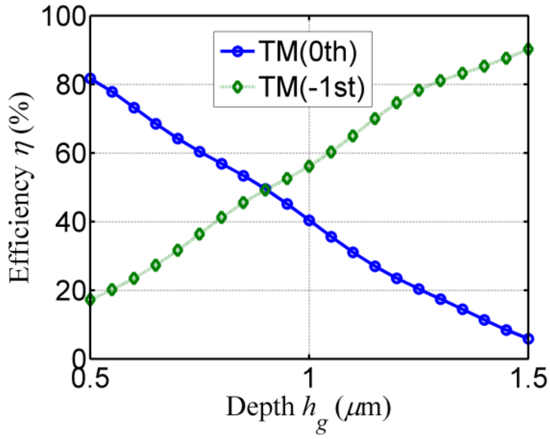
(b)

Fig. 2. Efficiency's ratio between the –1st and the 0th orders versus covering layer thickness and grating depth for the femtosecond laser wavelength of 800 nm: (a) TE polarization, (b) TM polarization

For deep-etched grating, the grating depth can modulate the efficiency of each order. By choosing the proper grating depth, the good uniformity can be exhibited between two diffracted orders. Fig. 3 shows efficiency versus grating depth for the optimized grating covering layer thickness. The efficiency can change with the grating depth sinusoidally for high-density gratings and different splitting ratios can be diffracted. For the optimized gratin depth h_g=0.70 μm and h_g=0.90 μm, good uniformity of nearly 50%-50% splitting ratio can be achieved for TE and TM polarizations, respectively.



(a)

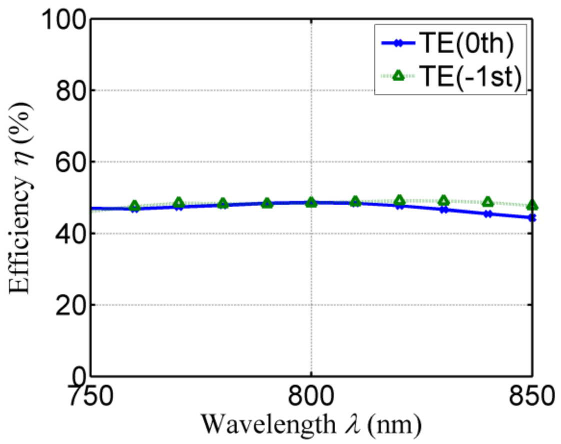


(b)

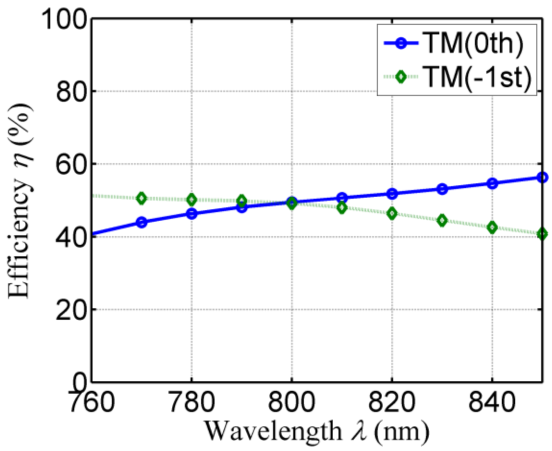
Fig. 3. (Color online) Efficiency versus grating depth for the optimized grating covering layer thickness: (a) TE polarization with h_c=0.86 μm, (b) TM polarization with h_c=1.21 μm

3. Splitting ratio near femtosecond laser wavelength

The covering-layer grating can exhibit good uniformity at the femtosecond laser wavelength of 800 nm. The material of fused silica has high damage threshold compared with multilayer coatings. For the femtosecond laser system, the wavelength can vary around the central value of 800 nm. It is necessary to study the performance with the deviation of the incident wavelength. Fig. 4 shows efficiency versus incident wavelength for TE polarization with h_c=0.86 μm and h_g=0.70 μm and TM polarization with h_c=1.21 μm and h_g=0.90 μm. In Fig. 4 (a), efficiencies more than 45% can be diffracted into the –1st and the 0th orders for TE polarization within the incident wavelength range of 750-843 nm. In Fig. 4 (b), efficiencies more than 45% can be achieved in two orders for TM polarization within the wavelength range of 775-827 nm. It can be seen that the incident wavelength range for TE polarization is much wider than TM polarization.



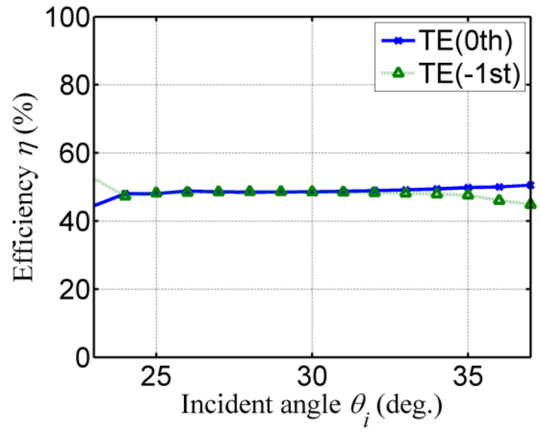
(a)



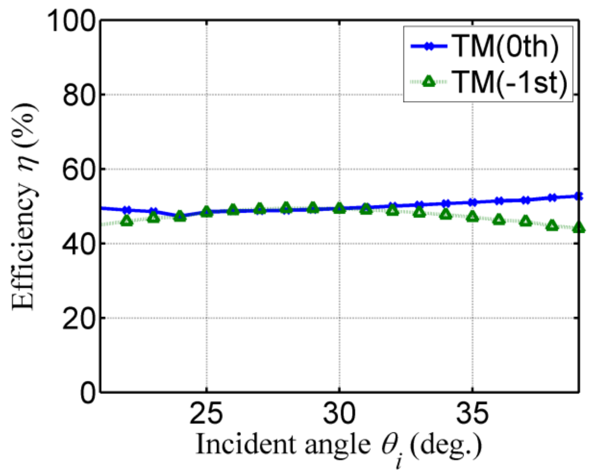
(b)

Fig. 4. (Color online) Efficiency versus incident wavelength for the optimized grating parameters: (a) TE polarization with h_c=0.86 μm and h_g=0.70 μm, (b) TM polarization with h_c=1.21 μm and h_g=0.90 μm

The beam splitters based on multilayer coatings are sensitive to the incident angle. Most beam splitters including some grating-based beam splitters can only be used at the certain incident angle. It is desirable to improve the incident angular bandwidth for applications. Fig. 5 shows efficiency versus incident angle for TE polarization with h_c=0.86 μm and h_g=0.70 μm and TM polarization with h_c=1.21 μm and h_g=0.90 μm. In Fig. 5 (a), efficiencies more than 45% can be obtained in the –1st and the 0th orders for TE polarization within the incident angle range of 23.7-36.8° around the Bragg angle. In Fig. 5 (b), the covering-layer grating can diffract efficiencies more than 45% into two orders for TM polarization within the incident angle range of 21.1-37.1°. One can see that the 50%-50% splitting ratio element can have wide angular bandwidth for both polarizations. And the incident angle range is much wider for TM polarization than TE polarization.



(a)



(b)

Fig. 5. (Color online) Efficiency versus incident angle for the optimized grating parameters: (a) TE polarization with h_c=0.86 μm and h_g=0.70 μm, (b) TM polarization with h_c=1.21 μm and h_g=0.90 μm

4. Conclusions

It should be noted that the 50%-50% splitting ratio element by the covering-layer grating is very different from the metal-based sandwiched dual-function beam splitter grating. To begin with, the two gratings have different functions. The covering layer grating in this paper can separate TE or TM polarization with the 50%-50% splitting ratio. The dual-function beam splitter grating in Ref. [11] can diffract TE polarization into the -1st order with efficiency more than 96% and divide TM polarization with the 50%-50% splitting ratio. Furthermore, the beam splitter in this paper is based on transmission with the covering layer to improve the efficiency. The dual-function beam splitter in Ref. [11] is a reflective grating with a metal slab. Last but not least, the 50%-50% splitting ratio grating in this paper has different optimized grating parameters for TE and TM polarizations. However, the dual-function beam splitter grating in Ref. [11] has the same grating parameters for TE and TM polarizations. In this paper, for TE and TM polarizations, different optimization designs should be provided, which could not be easily obtained from the report work.

In conclusion, a 50%-50% splitting ratio element is proposed by the covering-layer grating. The novel beam splitter introduces a covering layer on the conventional surface-relief grating. Such a covering-layer grating can diffract TE polarization with efficiencies 48.52%/48.63% and TM polarization with efficiencies of 49.23%/49.49% into the –1st and the 0th orders. When the beam splitter is used for the femtosecond laser, efficiencies more than 45% can be exhibited within the incident wavelength range of 750-843 nm for TE polarization and 775-827 nm for TM polarization. For different incident angles, the beam splitter can diffract efficiencies more than 45% within the incident angle range of 23.7-36.8° for TE polarization and 21.1-37.1° for TM polarization. The bandwidth of a 50%-50% splitting ratio element can be enhanced by the covering-layer grating.

Acknowledgements

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References

[1] K. Yamaguchi, Y. Ikuma, M. Nakajima, K. Suzuki, M. Itoh, T. Hashimoto, IEEE Photon. J. **8**, 0600809 (2016).
[2] P. Li, Y. Han, W. Wang, Y. Liu, P. Jin, J. Leng, Sci. Rep. **7**, 44333 (2017).
[3] Q.-K. Li, Q.-D. Chen, L.-G Niu, Y.-H. Yu, L. Wang, Y.-L. Sun, H.-B. Sun, IEEE Photon. J. **8**, 2500208 (2016).
[4] C. Pan, B. M. A. Rahman, IEEE Photon. J. **8**, 7101014 (2016).
[5] F. Zhang, K. Song, Y. Fan, Sci. Rep. **7**, 41726 (2017).
[6] H. Li, B. Wang, Sci. Rep. **7**, 1309 (2017).
[7] J. Wang, C. Zhou, J. Ma, Y. Zong, W. Jia, Chin. Opt. Lett. **15**, 040902 (2017).
[8] Y. Liu, H.-J. Fuchs, Z. Liu, H. Chen, S. He, S. Fu, E.-B. Kley, A. Tünnermann, Appl. Opt. **49**, 4450 (2010).
[9] B. Wang, C. Zhou, J. Feng, H. Ru, J. Zheng, Appl. Opt. **47**, 4004 (2008).
[10] M. G. Moharam, D. A. Pommet, E. B. Grann, J. Opt. Soc. Am. A **12**, 1077 (1995).
[11] B. Wang, L. Chen, L. Lei, J. Zhou, Opt. Laser Technol. **49**, 81 (2013).

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