

Three-port beam splitter based on a sandwiched grating with an improved aspect ratio

WENHAO SHU, BO WANG^{*}, HONGTAO LI, WENHUA LI, LI CHEN, LIANG LEI, JINYUN ZHOU

School of Physics and Optoelectronic Engineering, Guangdong University of Technology, Guangzhou 510006, China

^{*}Corresponding author: wangb_wsx@yeah.net

In this paper, a fused-silica transmission grating used as a three-port beam splitter is designed by using the rigorous coupled-wave analysis, which is based on the sandwiched grating structure at the wavelength of 800 nm under normal incidence. Firstly, it is feasible to realize such a grating with the prescribed grating duty cycle and grating period. Next, high efficiency can be also achieved for both TE and TM polarizations. Moreover, the aspect ratio of the grating depth to the ridge width can be improved, which is significant for practical applications. At last, the three-port beam splitter is designed with a covering layer on the surface, which can extend its life service.

Keywords: aspect ratio, sandwiched grating, three-port beam splitter.

1. Introduction

The beam splitter is an extremely important optical element, which can couple the incident light into several specified diffraction orders [1–3]. A three-port beam splitter is widely used in interferometers [4] and holography [5]. However, compared with the conventional beam splitter based on multilayer coatings, grating-based beam splitters have advantages, such as a compact shape, low cost, and high efficiency [6–8]. The typical research work related to the three-port beam splitter is based on the surface-relief grating [9], where a 1×3 beam splitter is designed for both TE and TM polarizations. However, from reported results, the aspect ratio of the grating depth to the ridge width is 4.85, which should be improved for easy fabrication.

As far as we know, no one has reported a wideband and highly efficient transmission three-port beam splitter based on the sandwiched grating. In this paper, we describe a transmission three-port beam splitter based on a sandwiched fused-silica grating, where energies are reflected in the 0th and ± 1 st orders. Furthermore, the 1×3 beam splitter is presented for both TE and TM polarizations under normal incidence. Grating parameters are optimized by using the rigorous coupled-wave analysis (RCWA) [10].

Calculations with RCWA show that the high efficiency and the wideband proposed here can be achieved and also the tolerance to the parameters of structure which makes them very easy to be fabricated with current technology. This design has values of effective protection of the grating surface and improved aspect ratio. During fabrication, a surface-relief grating can be etched by the holographic recording and the inductively coupled plasma technology. Due to the improved aspect ratio, it is easy to fabricate such a grating during etching. Then, the covering layer and the surface-relief grating can be bonded together by heavy weight and high temperature.

2. Design optimization of the sandwiched grating for a three-port beam splitter

The schematic of a transmission three-port beam splitter is shown in Fig. 1. Such a novel structure is a sandwiched grating with the period of d . The grating ridge is fused silica with the depth of h and the refractive index $n_2 = 1.45332$ and the grating groove is air. The substrate and the covering layer are both fused silica. The thicknesses of top and bottom fused-silica layers are several millimeters, and has a little effect on the efficiency. A plane wave with the wavelength λ is incident upon the grating. Since it is a three-port beam splitter, energies are reflected in the 0th and the ± 1 st diffracted orders, respectively. However, the efficiencies of the 1st and the -1 st diffractive orders are always the same because of symmetry. So, only the 0th and the 1st diffractive orders need to be considered in this paper.

In order to design a high efficiency beam splitter, the RCWA can be adopted to calculate and optimize this device. Grating parameters such as a duty cycle, grating period, and grating depth are chosen as the optimizing grating parameters by using the RCWA. Figure 2 shows the contour of the efficiency ratio between the 1st and the 0th diffractive orders of the grating *versus* the grating period and groove depth.

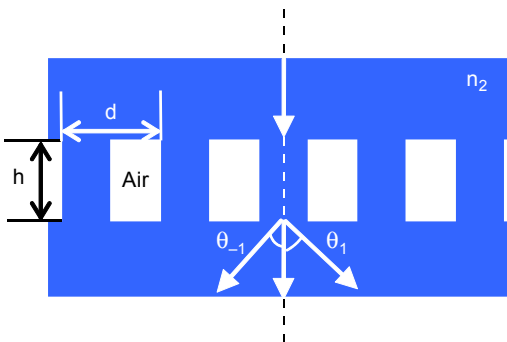


Fig. 1. Schematic of a sandwiched grating for a transmission three-port beam splitter (refractive index n_2 – fused silica, d – period, h – grating depth, θ_{-1} and θ_1 – diffraction angles of the -1 st and the 1 st orders, respectively).

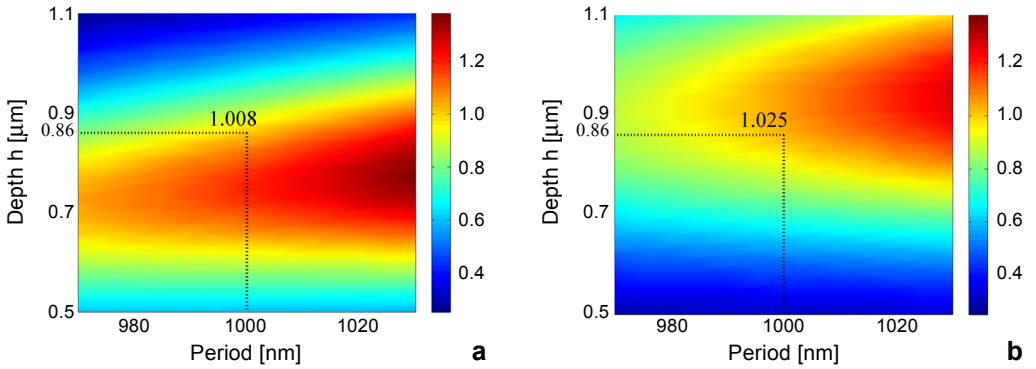


Fig. 2. Contour of the efficiency ratio between the 1st and the 0th reflective orders of the grating *versus* the grating period and groove depth with the duty cycle of 0.5 and the incident wavelength of 800 nm under normal incidence: TE (a) and TM (b) polarization.

With the optimized grating period of 1000 nm and depth of 0.86 μm , the value of the efficiency ratio can reach 1.008 for TE polarization and 1.025 for TM polarization. The three-port beam splitter grating can separate TE polarization with the efficiency of 32.54% in the 1st reflected order and 32.29% in the 0th reflected order. For TM polarization, 33.08% and 32.28% can be separated into the two orders.

Furthermore, the fabrication tolerance of a duty cycle should be taken into account during production. Figure 3 shows the transmission efficiency and efficiency difference of the three-port beam splitter sandwiched grating *versus* the grating duty cycle at the incident wavelength of 800 nm. In Fig. 3, the efficiency difference less than 5% between the 1st and 0th diffractive orders for both TE and TM polarizations can be achieved within the duty cycle range of 0.46–0.55, where the sum of total transmission

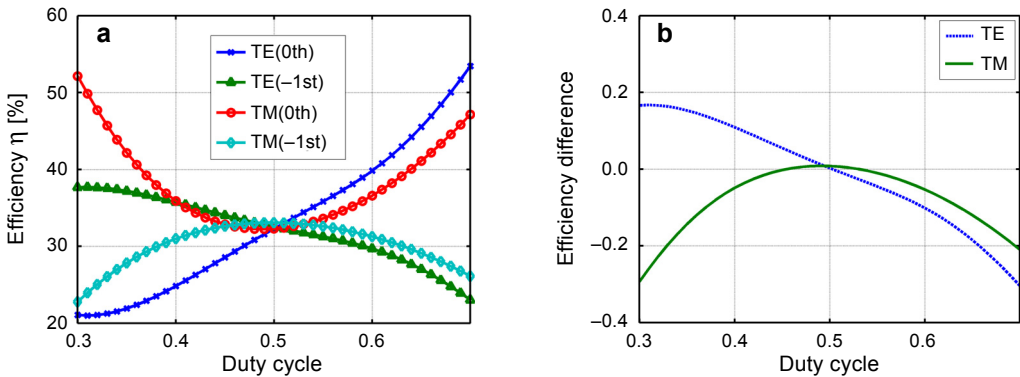


Fig. 3. Transmission efficiency (a) and efficiency difference between the 1st and the 0th diffractive orders (b) of the three-port beam splitter sandwiched grating *versus* the grating duty cycle for both TE and TM polarizations.

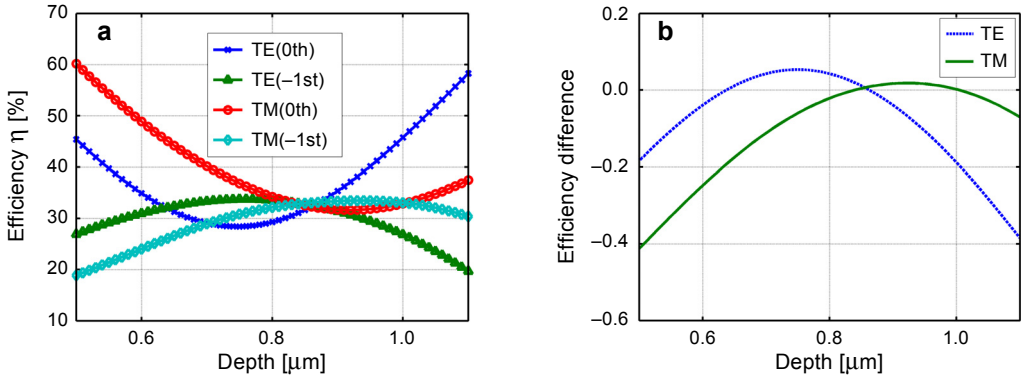


Fig. 4. Transmission efficiency (a) and efficiency difference between the 1st and the 0th diffractive orders (b) of the three-port beam splitter sandwiched grating *versus* the grating depth for both TE and TM polarizations.

efficiencies can be obtained to be more than 96.5%. Figure 4 shows the transmission efficiency and efficiency difference of the three-port beam splitter sandwiched grating *versus* the grating duty cycle at the incident wavelength of 800 nm. It can be seen that the efficiency difference less than 5% can be obtained with the grating etched depth range of 0.78–0.90 μm .

3. Diffraction properties with the optimized grating profile parameters

Optimized results of the transmission three-port beam splitter by a sandwiched structure are designed for the incident wavelength of 800 nm. However, high efficiency can be obtained within a wide range of incident wavelength for both TE and TM polarizations. Figure 5 shows the transmission efficiency with different incident wavelength for optimized grating parameters by using the RCWA. Transmission efficiencies of

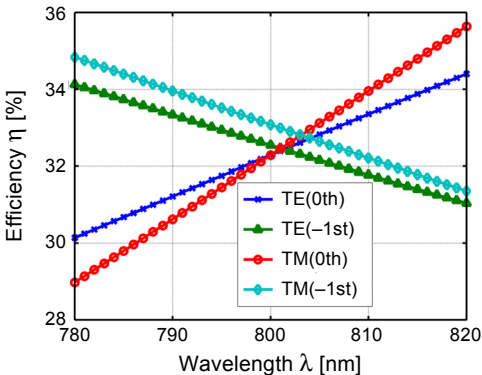


Fig. 5. Efficiencies of the 0th and the 1st diffractive orders of the sandwiched grating three-port beam splitter *versus* the incident wavelength with optimized grating parameters.

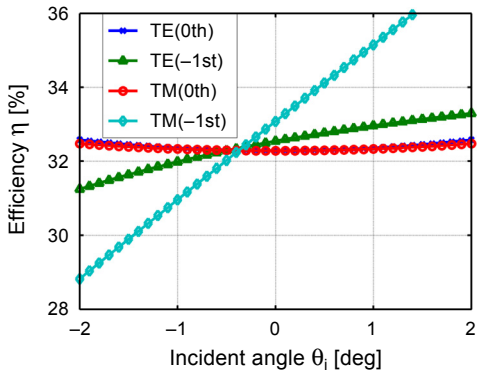


Fig. 6. Transmission efficiency of the three-port beam splitter *versus* the incident angle for a wavelength of 800 nm with optimized grating parameters.

two orders are both above 32% for TE polarization within the range 798–807 nm and for TM polarization within the range 799–812 nm.

Although the transmission three-port beam splitter grating is designed, it will be convenient if the sandwiched grating can have the advantage of wide incident angular bandwidth. Figure 6 shows the angular responses of the three orders at the wavelength of 800 nm. It can be seen from Fig. 6 that the efficiencies around the range of 32% to 34% are for both TE and TM polarizations when the incident angle is limited in the range of -0.5° to 0.4° .

4. Conclusion

In this paper, a novel three-port beam splitter is presented based on the sandwiched grating. The RCWA is applied to analyze and calculate the efficiency. With the optimized duty cycle of 0.5, period of 1000 nm, depth of 0.86 μm , high efficiencies of 32.54% and 32.29% can be obtained in the $\pm 1\text{st}$ and the 0th orders for TE polarization and efficiencies of 33.08% and 32.28% for TM polarization can be achieved for the incident wavelength of 800 nm under normal incidence. Reference [9] describes the grating with the aspect ratio of 4.85, while the sandwiched grating in this letter shows that the aspect ratio of the grating depth to the ridge width is 1.72, which can be etched in fused silica easily and effectively. The physical mechanism can be derived from modes coupling [9]. Therefore, the presented three-port beam splitter based on the sandwiched grating should be useful for numerous practical applications.

Acknowledgements – This work is supported by the National Natural Science Foundation of China (11304044, 61475037), the Excellent Young Teachers Program of Higher Education of Guangdong Province, and the Pearl River Nova Program of Guangzhou (201506010008).

References

- [1] BO WANG, LI CHEN, LIANG LEI, JINYUN ZHOU, *Polarization-selective beam splitter by a sandwiched grating*, *Optica Applicata* **43**(2), 2013, pp. 229–236.

- [2] JUNBO YANG, ZHIPING ZHOU, WEI ZHOU, XUEAO ZHANG, HONGHUI JIA, *High efficient subwavelength binary blazed grating beam splitter via vertical coupling*, IEEE Photonics Technology Letters **23**(13), 2011, pp. 896–898.
- [3] BO WANG, LI CHEN, LIANG LEI, JINYUN ZHOU, *Two-layer dielectric grating as two-port beam splitter*, IEEE Photonics Technology Letters **25**(9), 2013, pp. 863–866.
- [4] SCHNABEL R., BUNKOWSKI A., BURMEISTER O., DANZMANN K., *Three-port beam splitter-combiners for interferometer applications*, Optics Letters **31**(5), 2006, pp. 658–660.
- [5] KLEPP J., TOMITA Y., PRUNER C., KOHLBRECHER J., FALLY M., *Three-port beam splitter for slow neutrons using holographic nanoparticle-polymer composite diffraction grating*, Applied Physics Letters **101**(15), 2012, article 154104.
- [6] JUNBO YANG, ZHIPING ZHOU, *Double-structure, bidirectional and polarization-independent subwavelength grating beam splitter*, Optics Communications **285**(6), 2012, pp. 1494–1500.
- [7] BO WANG, LI CHEN, LIANG LEI, JINYUN ZHOU, *Highly-efficient element and two-port beam splitter of multilayer-based grating*, Journal of Optoelectronics and Advanced Materials **14**(9–10), 2012, pp. 769–773.
- [8] LINGWEI GUO, JIANYONG MA, *Broad band beam splitter based on the double-groove fused silica grating*, Optik – International Journal for Light and Electron Optics **125**(1), 2014, pp. 232–234.
- [9] JIUN FENG, CHANGHE ZHOU, BO WANG, JIANGJUN ZHENG, WEI JIA, HONGCHAO CAO, PENG LV, *Three-port beam splitter of binary fused-silica grating*, Applied Optics **47**(35), 2008, pp. 6638–6643.
- [10] 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.

*Received January 4, 2015
in revised form March 4, 2015*