Optica Applicata, Vol. XLVI, No. 4, 2016
DOI: 10.5277/oa160413

A polarization selective beam splitter based on a subwavelength multisubpart profile grating structure

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In this study, a polarization selective beam splitter constructed by only a single layer subwavelength multisubpart profile grating is presented. Rigorous coupled-wave analysis is adopted to investigate the properties of the structure. It is shown that for a transverse electric polarized wave, the device demonstrates very high reflectivity (> 97%) from 1.46 to 1.58 μm; and for a transverse magnetic polarized wave, at the wavelength of 1.55 μm, it exhibits about 50/50 beam ratio under normal incidence. To evaluate the response of the polarizing beam splitters under variation in structure parameters, we also investigated the fabrication tolerances of the device.

Keywords: diffraction and gratings, polarizing beam splitter (PBS), leaky-mode resonance (LMR).

1. Introduction

Due to their simple structures and natural partnership with interference, resonant subwavelength grating related devices are key components for numerous optical devices, such as mirrors [1], vertical-cavity surface-emitting lasers (VCSELs) [2] and absorbers [3] in integrated optics. Theoretical analysis shows that the reflection or transmission spectra can present unique characteristics when the diffracted orders of gratings couple with the guided or leaky modes supported by the equivalent waveguide structures [4]. Based on the principle, LEE *et al.* [5, 6] had reported the broadband reflectors realized by single layer subwavelength gratings. SHIQIAN SHAO *et al.* [7] proposed a T-shaped compact polarization-independent output grating coupler with the output coupling efficiencies for both the TE and the TM modes larger than 50% in the wavelength range of 1.48–1.58 μm. On the other hand, owing to the fact that dividing the grating into multisubparts can enable a rich set of Fourier series component distribution with the concomitant emergence of additional spectral features, much attention has been diverted to multisubpart profile grating (MPG) structures. To emphasize the different characteristics introduced by multisubpart profiles, CHE-LUNG HSU *et al.* presented that flattened broadband notch filters can be implemented by using a grating with four-subpart profiles [8]. HUAMING WU *et al.* showed a broadband compact polarizing beam splitter (PBS) constructed by only a single layer subwavelength MPG [9]. By using a multilayered grating structure with a multisubpart profile, HUANG *et al.* reported a high-performance reflector with a 70 nm bandwidth [10]. For TE polarization, we presented a four-part reflector with a ~630 nm bandwidth [11].

However, the most reported subwavelength gratings are single-function devices. If two different functions can be fulfilled with only one grating, this would be useful for practical applications. Based on a subwavelength fused silica grating, JIJUN FENG *et al.* presented a dual-function polarization-selective beam splitter. For TE polarization, the grating can function as a device with high transmissivity at the –1st order, while for a TM-polarized wave, it can be used as a two-port beam splitter [12]. In this study, we proposed another dual-function grating that can be used as a beam splitter for TM polarization and as a device with high reflectivity at zero order for TE polarization.

2. Device design and results

As an example, we propose here a four subpart surface-relief grating polarization selective beam splitter (PSBS), as shown in Fig. 1. The device is defined by its period *T*, thickness t_g and transition points (x_1, x_2, x_3). In this paper, for simplicity, it is assumed

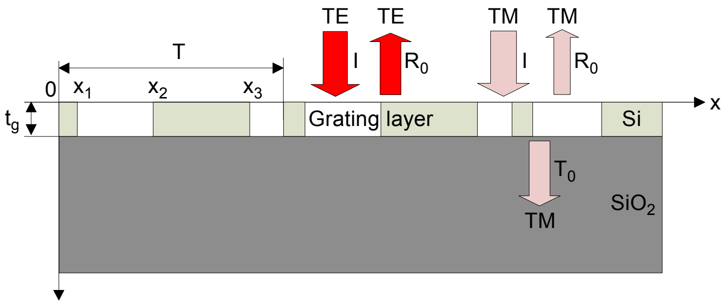

Fig. 1. Schematic of a grating PSBS. We denote T, t_g, x_1, x_2 and x_3 as the grating period, thickness, and transition points, respectively. The incidence medium is air, and the substrate is silica. The refractive indices are: $n_{air} = 1.0$, $n_{Si} = 3.48$, $n_{silica} = 1.47$.

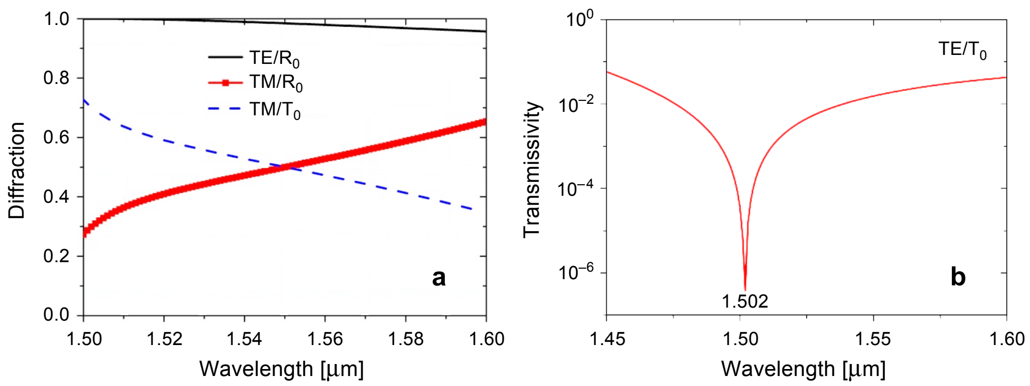

Fig. 2. Spectra of the structure shown in Fig. 1. Reflectivity spectra of the device (**a**). Transmissivity of the grating PSBS at a log scale; the resonance wavelength is 1.502 µm (**b**).

that the structure is transversely infinite and that the dielectric materials are lossless and dispersion free. In this study, rigorous coupled-wave analysis [13] associated with a particle swarm optimization method [14] is adopted to design and optimize the device. As for the PSBS, the parameters to be optimized are grating transition points (x_1, x_2, x_3), thickness t_g and period T. During the optimization, we assumed the structure is illuminated at normal incidence with TE/TM polarized plane waves of a unit amplitude. The refractive indices of Si and SiO_2 are 3.48 and 1.47, respectively. The optimized results are $T = 0.9$ µm, $t_g = 0.39$ µm, $x_1/x_2/x_3 = 0.09/0.39/0.73$ µm.

Figure 2**a** presents reflectance (TE/R_0, TM/R_0) and transmittance (TM/T_0) of the TE and TM polarization components under normal incidence. As can be seen, the proposed device has a flat TE stopband from 1.46 to 1.58 µm with reflectance $R_0 > 97\%$, and in a TM wave it exhibits about 50/50 beam ratio at the wavelength of 1.55 µm. One transmittance dip exists inside the reflection band as depicted on a logarithmic scale in Fig. 2**b**, which corresponds to a leaky-mode resonance (LMR) [15]. Since 100% reflection is associated with LMR, it means that the broadband high reflectivity results from the TE LMR. Physically, the origins of the broadband reflection are resulting from the large refractive index difference among materials and the multisubpart configured top grating layer [16, 17]. Firstly, the high-index-contrast grating layer can expand resonances and eventually fashion the broadband reflectance spectra. Secondly, the leaky-mode degeneracy of the grating PBS can be removed by the MPG layer [18], which opens the possibility of a flat reflection band for a TE wave.

Figure 3 illustrates the angular spectrum response of the grating PSBS at the wavelength of 1.55 µm for both TE- and TM-polarized waves. As presented, for TE polarization, over 97% reflection can be obtained at incident angles ranging from –13.86° to 13.86°. And for TM polarization, the PSBS can achieve a beam ratio (> 45/55) at the range of –3.15° to 3.15°. The angular bandwidth of the zero diffracted order is com-

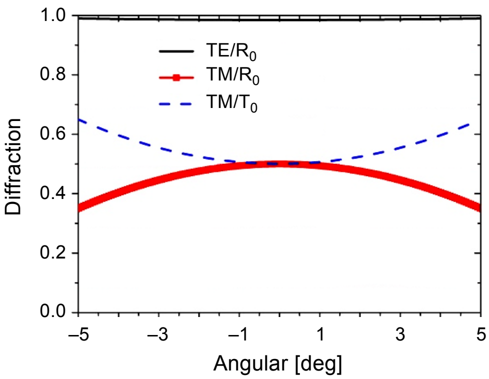

Fig. 3. Angular spectrum of the grating PSBS at the wavelength of 1.55 µm.

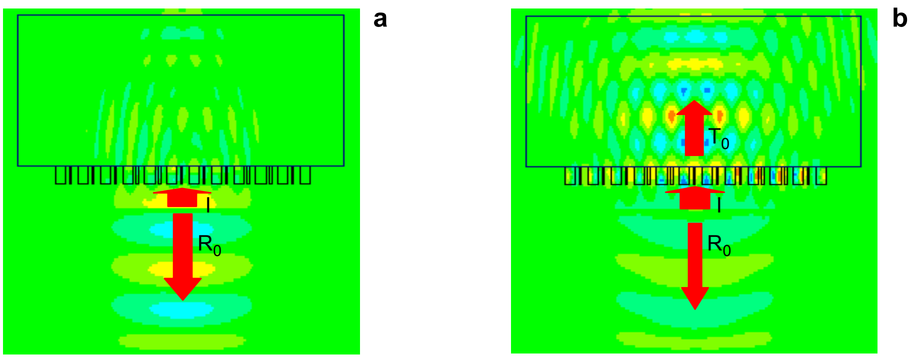

Fig. 4. Field distribution at 1.55 µm. TE (**a**) and TM (**b**) polarized input wave.

paratively wide, which exhibits reasonable angular robustness as necessary for practical applications.

Field distribution of the device is calculated by using the finite-difference time-domain (FDTD) method. The structure is normally illuminated by a plane wave with both TE and TM polarized waves at 1.55 µm. As can be seen in Fig. 4, the TE polarized waves can be efficiently reflected by the grating PSBS, and under TM illumination it exhibits nearly 50/50 beam ratio.

3. Parameter analysis

Varying the device parameters such as grating period, thickness, and profile modulation can change the number and location of resonances, which ultimately tunes the bandwidth. The effect of changing the parameters is described in this section.

Figure 5 presents the effects of variation in grating thickness t_g. As shown in Fig. 5**a**, the changes in thicknesses t_g, result in the flat band shifts to longer wavelength. Since the structure bandwidth is determined by the grating depth, with an increasing of t_g, the bandwidth of the structure gradually increases. And for TM polarization, as

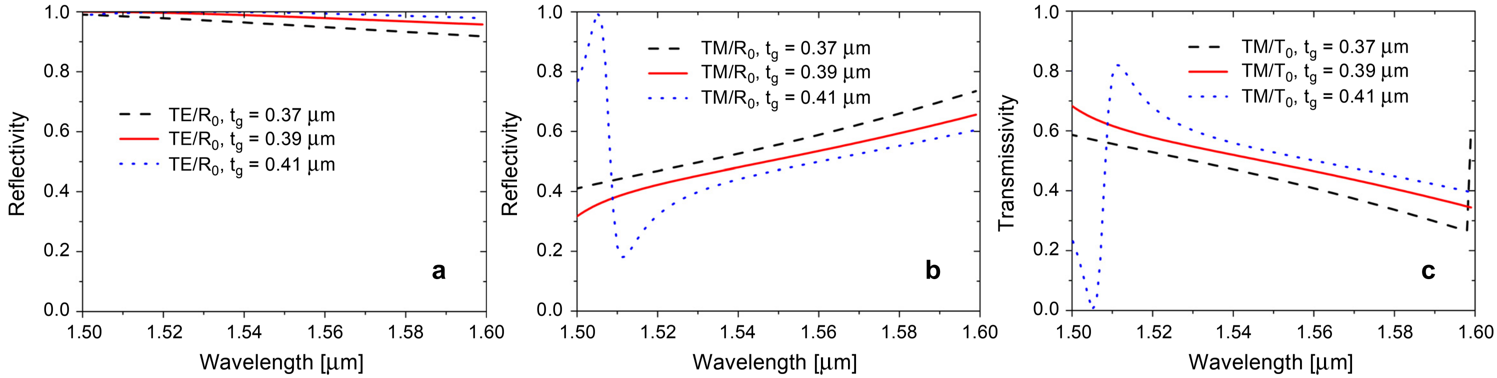

Fig. 5. Spectra of variations in grating thickness t_g. Reflectance (TE/R_0) of the TE polarized input wave (**a**), reflectance (TM/R_0) of the TM polarized input wave (**b**) and transmittance (TM/T_0) of the TM polarized input wave (**c**). Other parameters are the same as in Fig. 1.

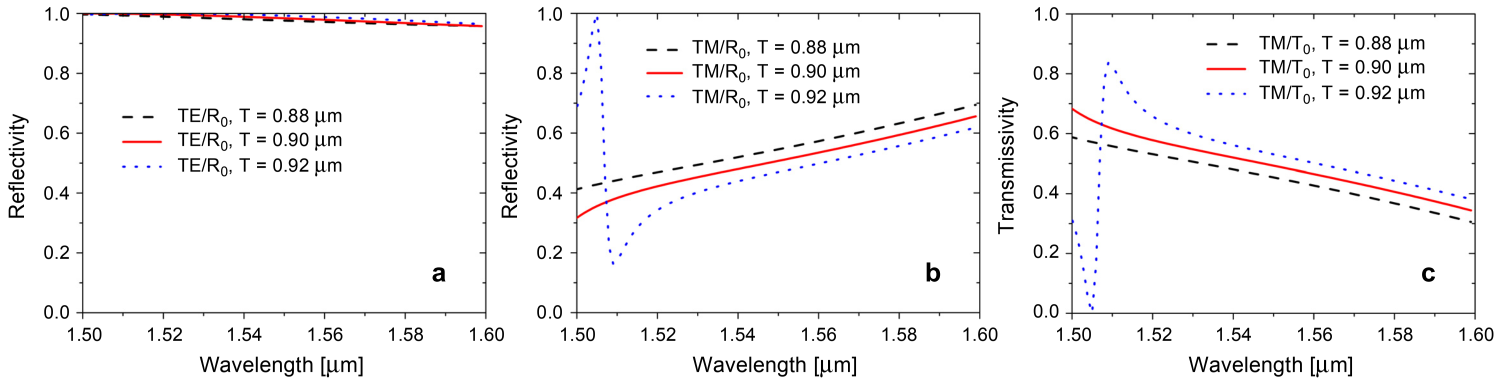

Fig. 6. Effect of variation in period T. Reflectance (TE/R_0) with variation in period for TE polarization (**a**), reflectance (TM/R_0) with variation in period for TM polarization (**b**) and transmittance (TM/T_0) with variation in period for TM polarization (**c**). Other parameters are the same as in Fig. 1.

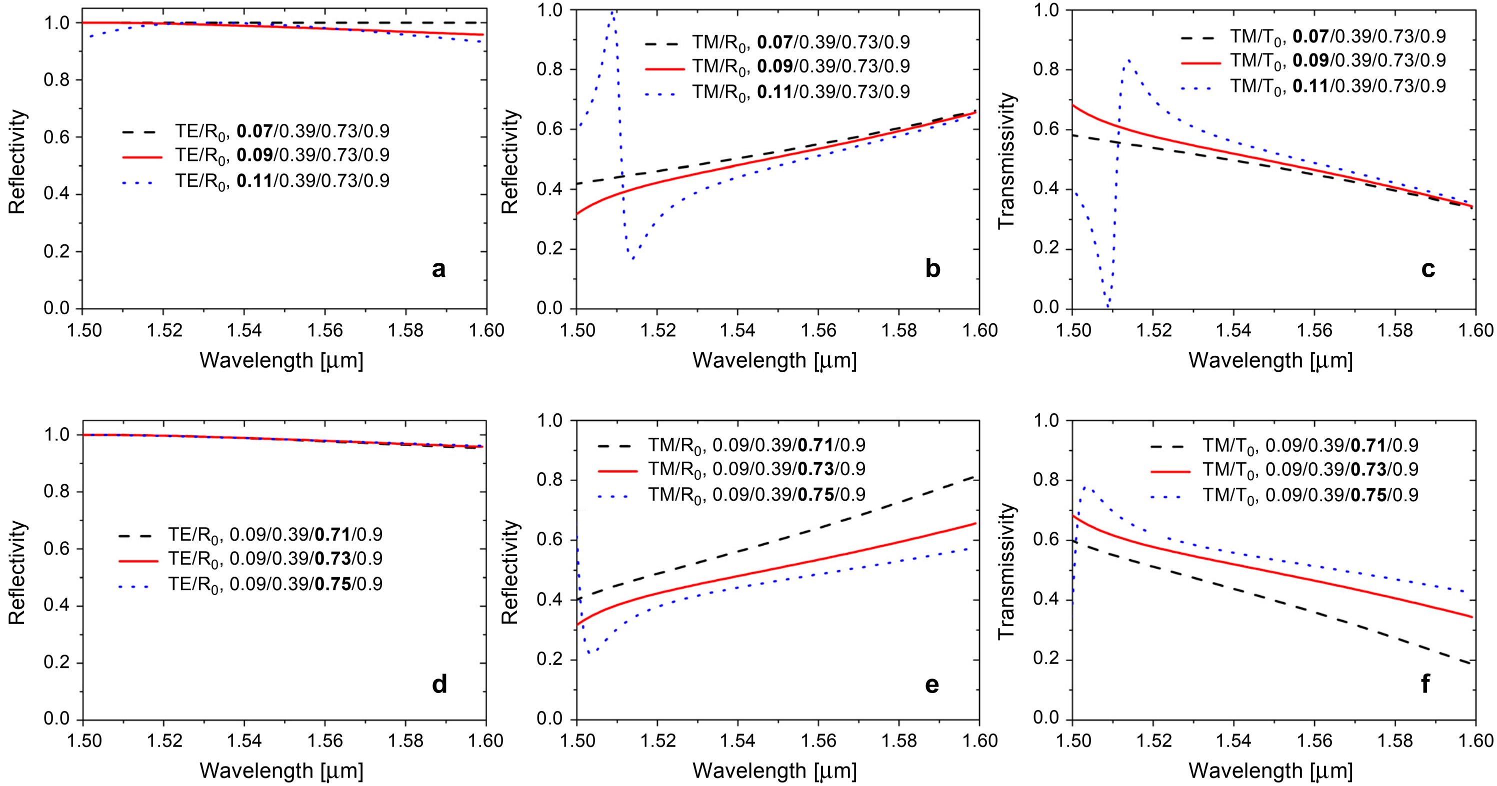

Fig. 7. Spectrum response of the PSBS under the variation of the profile modulation. Reflectance (TE/R_0) with varying the first high-index binary block (x_1) for TE polarization (**a**). Reflectance (TM/R_0) with varying the first high-index binary block (x_1) for TM polarization (**b**). Transmittance (TM/T_0) with varying the first high-index binary block (x_1) for TM polarization (**c**). Reflectance (TE/R_0) with varying the second high-index binary block (x_2) for TE polarization (**d**). Reflectance (TM/R_0) with varying the second high -index binary block (x_2) for TM polarization (**e**). Transmittance (TM/T_0) with varying the second high-index binary block (x_2) for TM polarization (**f**).

presented in Figs. 5**b** and 5**c**, the PSBS exhibits a beam ratio (> 45/55) at the range of 1.543 to 1.55 μm, which is useful in the fabrication of grating PSBSs.

Figure 6 shows the spectra of variations in the grating period *T*. As can be seen in Fig. 6**a**, an increase in the grating period *T* can modify the reflection slightly in the interested wavelength of range (from 1.5 to 1.6 μm). For TM polarization, as displayed in Figs. 6**b** and 6**c**, the structure presents a beam ratio (> 45/55) at the range of 1.545 to 1.551 μm.

In addition, we have demonstrated the spectrum response of the PSBS under the variation of the profile modulation. As illustrated in Figs. 7**a**–7**f**, changes in modulation profile parameters can slightly effect the performance of the structure. Since besides the modulation strength, the modulation profile can also control the diffraction efficiency of the PSBS, the variations in the profile modulation can change the nondegeneracy of the leaky mode resonances and resonance locations, resulting in the performance changes of the PSBS [19].

The tolerance analysis above leads us to conclude that the proposed structure has a reasonably fabrication tolerance, which provides a favorable advantage in the fabrication process.

4. Conclusion

To summarize, we have proposed a grating PSBS that demonstrates very high reflectivity (> 97%) from 1.46 to 1.58 μm for a TE polarized wave, and for a TM polarized wave, at the wavelength of 1.55 μm, it exhibits about 50/50 beam ratio under normal incidence. The combined merits resulted from the high-index contrast and multisubpart profile modulation of the grating. The effects of deviation from the design parameters on the diffractive efficiency are also presented, which shows that the proposed structure has a reasonably fabrication tolerance. The demonstrated PSBS requires only a single layer subwavelength grating to construct, which makes it easy to be integrated with other elements [20]. The grating PSBSs can be potentially used in an optical communication system as routing or switching, and so on.

Acknowledgements – The authors would like to thank the members of Micro/nano Optoelectronic Devices and Materials group in National Engineering Laboratory for Non-destructive Testing and Optoelectronic Sensing Technology and Applications, Nanchang Hangkong University, for their helpful discussions. We also sincerely thank the reviewers for the good comments during the whole review process. This work was supported in part by the National Natural Science Foundation of China under the Grant No. 11264031, Natural Science Foundation of Jiangxi Province Major Program for Youths under the Grant No. 20143ACB21011, Natural Science Foundation of Jiangxi Province under the Grant Nos. 20151BAB207054, 20114BAB201019, and Scientific Research Startup Foundation of Nanchang Hangkong University under the Grant No. EA201008232.

References

[1] HUANG L., LIANG D., ZENG J., XIAO Y., WU H., XIAO W., *SOI-based high performance multi-subpart profile grating mirror*, Optics and Laser Technology **78**(Part B), 2016, pp. 1–4.

[2] TSUNEMI Y., YOKOTA N., MAJIMA S., IKEDA K., KATAYAMA T., KAWAGUCHI H., *1.55-μm VCSEL with polarization-independent HCG mirror on SOI*, Optics Express **21**(23), 2013, pp. 28685–28692.

[3] WENHUA WU, MAGNUSSON R., *Total absorption of TM polarized light in a 100 nm spectral band in a nanopatterned thin a-Si film*, Optics Letters **37**(11), 2012, pp. 2103–2105.

[4] LIU Z.S., TIBULEAC S., SHIN D., YOUNG P.P., MAGNUSSON R., *High-efficiency guided-mode resonance filter*, Optics Letters **23**(19), 1998, pp. 1556–1558.

[5] LEE K.J., MAGNUSSON R., *Single-layer resonant high reflector in TE polarization: theory and experiment*, IEEE Photonics Journal **3**(1), 2011, pp. 123–129.

[6] KHALEQUE T., UDDIN M.J., MAGNUSSON R., *Design and fabrication of broadband guided-mode resonant reflectors in TE polarization*, Optics Express **22**(10), 2014, pp. 12349–12358.

[7] SHIQIAN SHAO, YI WANG, *Highly compact polarization-independent grating coupler*, Optics Letters **35**(11), 2010, pp. 1834–1836.

[8] CHE-LUNG HSU, MOUNT-LEARN WU, YUNG-CHIH LIU, YUN-CHIH LEE, JENQ-YANG CHANG, *Flattened broadband notch filters using guided-mode resonance associated with asymmetric binary gratings*, IEEE Photonics Technology Letters **18**(24), 2006, pp. 2572–2574.

[9] HUAMING WU, WENQIN MO, JIN HOU, DINGSHAN GAO, RAN HAO, RUIMIN GUO, WENHUA WU, ZHIPING ZHOU, *Polarizing beam splitter based on a subwavelength asymmetric profile grating*, Journal of Optics **12**(1), 2010, article 015703.

[10] HUANG L., LIANG D., ZENG J., XIAO Y., WU H., XIAO W., *A silicon-based wideband multisubpart profile grating reflector*, Optics and Laser Technology **78**(Part B), 2016, pp. 79–82.

[11] WU H, HUANG L, XIAO Y, ZHANG C, LI S, LUO N, HE X, GAO Y., *A wideband reflector realized by a subwavelength multi-subpart profile grating structure*, Journal of Optics **15**(3), 2013, article 035703.

[12] JIJUN FENG, CHANGHE ZHOU, JIANGJUN ZHENG, HONGCHAO CAO, PENG LV, *Dual-function beam splitter of a subwavelength fused-silica grating*, Applied Optics **48**(14), 2009, pp. 2697–2701.

[13] MOHARAM M.G., GRANN E.B., POMMET D.A., GAYLORD T.K., *Formulation for stable and efficient implementation of the rigorous coupled-wave analysis of binary gratings*, Journal of the Optical Society of America A **12**(5), 1995, pp. 1068–1076.

[14] SHOKOOH-SAREMI M., MAGNUSSON R., *Particle swarm optimization and its application to the design of diffraction grating filters*, Optics Letters **32**(8), 2007, pp. 894–896.

[15] SHOKOOH-SAREMI M., MAGNUSSON R., *Wideband leaky-mode resonance reflectors: influence of grating profile and sublayers*, Optics Express **16**(22), 2008, pp. 18249–18263.

[16] MATEUS C.F.R., HUANG M.C.Y., YUNFEI DENG, NEUREUTHER A.R., CHANG-HASNAIN C.J., *Ultrabroadband mirror using low-index cladded subwavelength grating*, IEEE Photonics Technology Letters **16**(2), 2004, pp. 518–520.

[17] MATEUS C.F.R., HUANG M.C.Y., LU CHEN, CHANG-HASNAIN C.J., SUZUKI Y., *Broad-band mirror (1.12–1.62 μm) using a subwavelength grating*, IEEE Photonics Technology Letters **16**(7), 2004, pp. 1676–1678.

[18] DING Y., MAGNUSSON R., *Use of nondegenerate resonant leaky modes to fashion diverse optical spectra*, Optics Express **12**(9), 2004, pp. 1885–1891.

[19] MAGNUSSON R., SHOKOOH-SAREMI M., *Physical basis for wideband resonant reflectors*, Optics Express **16**(5), 2008, pp. 3456–3462.

[20] ZHIPING ZHOU, HUAMING WU, JUNBO FENG, JIN HOU, HUAXIANG YI, XINGJUN WANG, *Silicon nanophotonic devices based on resonance enhancement*, Journal of Nanophotonics **4**(1), 2010, article 041001.

Received March 1, 2016
in revised form May 17, 2016