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Surface relief resonant Brewster filters with multiple channels*

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In this paper, a new type of resonant Brewster filters (RBF) with surface relief structure for the multiple channels is first presented by using the rigorous coupled-wave analysis and the *S*-matrix method. By tuning the depth of homogeneous layer which is under the surface relief structure, the multiple channels phenomenon is obtained. Long range, extremely low sidebands and multiple channels are found when the RBF with surface relief structure is illuminated with Transverse Magnetic incident polarization light near the Brewster angle calculated with the effective media theory of sub wavelength grating. Moreover, the wavelengths of RBF with surface relief structure can be easily shifted by changing the depth of homogeneous layer while its optical properties such as low sideband reflection and narrow band are not spoiled when the depth is changed. Furthermore, the variation of the grating thickness does not effectively change the resonant wavelength of RBF, but have a remarkable effect on its line width, which is very useful for designing such filters with different line widths at desired wavelength.

Keywords: resonant Brewster filters, rigorous coupled-wave analysis, *S*-matrix method, effective media theory

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1. Introduction

Guided-mode resonance (GMR) of grating refers to the rapid variation of reflection or transmission, which is due to the resonance of externally diffracted waves with the waveguide modes inside the waveguide grating.[1−4] Filters based on the GMR property can be used as narrow-band filters in microwave,[5] near infrared[6] and visible spectrum region experimentally.[7] Moreover, it is reported recently that the GMR can be easily extended to the areas such as biology,[8] medicine[9] and sensors.[10]

In 1998, Magnusson *et al* put forward a new type of narrow-band reflection filter based on the GMR and Brewster effect.[11] The extremely low sidebands and narrow-band reflection filter can be obtained when the GMR Brewster grating is illuminated with TM polarization at the Brewster angle calculated with effective media theory (EMT)[12] of sub-wavelength grating. It is a type of excellent narrow band filter which can not only increase the reflection of resonant light but also reduce the side band reflection when the TM polarization light transmit with very high transmission at the Brewster angle. Later, the GMR Brewster filter is verified experimentally by Shin *et al*.[13] In 2006, Wang *et al* put forward the concept of GMR Brewster filter with multiple channels and give the designed method by using electromagnetic theory.[14]

In this paper, a new type of multiple channel filter called surface relief resonant Brewster filter (SRRBF) is given and the properties of SRRBF are demonstrated by using the rigorous coupled-wave analysis (RCWA)[15] and the *S*-matrix method.[16] In order to gain the multiple channels phenomenon, we add a homogeneous layer under the surface relief structure, which is contrary to the method proposed by Wang *et al* and more easily realized with very shallow grating. Moreover, it is amazing to know that the position of multiple resonant wavelengths can be linearly tuned by adjusting the thickness of the layer, which will be very useful for designing narrow band filter in dense wavelength-division multiplexing (DWDM) system. Furthermore, the line width of SRRBF can be easily tuned at any given resonant wavelength without

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losing the low side band feature.

2. Theoretical design

A guide-mode resonant grating with surface relief structure under Brewster angle of TM polarization light is depicted in Fig.1. The high and low refractive indices of surface relief structure are labelled as $n_{\rm h}$ and $n_{\rm l}$ respectively. The refractive indices of cover, substrate and homogeneous layer are denoted to be $n_{\rm c}$, $n_{\rm s}$ and n_2 respectively. The depths of surface relief structure and homogeneous layer are d_1 and d_2 respectively. To obtain the highly efficient filter, a sub wavelength grating ($T < \lambda$) is chosen to prevent the higher diffraction orders from propagation. Suppose that $n_{\rm c} = n_1 = 1$, $n_{\rm h} = n_2 = 1.78$, $n_{\rm s} = 1.45$, $d_1 = 50\,{\rm nm}$, $d_2 = 269.3\,{\rm nm}$, $T = 361.5\,{\rm nm}$, $f = 0.57$ and the incident wavelength is 850 nm. The Brewster angle is 55.47° calculated with the transfer matrix of the thin film theory. The effective refractive index of the grating layer is given by *EMT* of the sub wavelength grating. That is:

$$n_{\rm eff} = \left\{ n_{\rm h}^2 n_{\rm l}^2 / \left[f n_{\rm l}^2 + (1-f)\, n_{\rm h}^2 \right] \right\}^{1/2}. \qquad (1)$$

Where f is the filling factor of the grating.

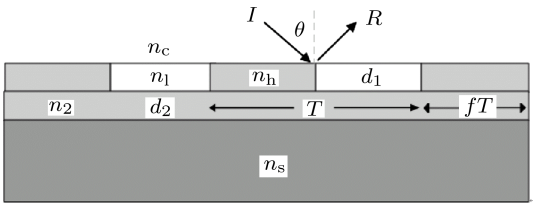


Fig.1. Structure of SRRBF under TM illumination at Brewster angle. The high and low refractive indices of surface relief structure are labelled as $n_{\rm h}$ and $n_{\rm l}$ respectively. The refractive indices of cover, substrate and homogeneous layer are denoted to be $n_{\rm c}$, $n_{\rm s}$ and n_2 respectively. The depths of surface relief structure and homogeneous layer are d_1 and d_2 respectively.

Figure 2 shows the angular response of SRRBF illuminated with TM polarization light at the wavelength of 850 nm. It is apparent that a very sharp peak appears when the incident angle is tuned to 55.48° which is very close to the value calculated with transfer matrix of the thin film. The TM polarization light transmits the SRRBF with very high transmission at off resonant spectrum region while the light at the operation wavelength reflects greatly due to the efficiently coupling of waveguide modes supported by the

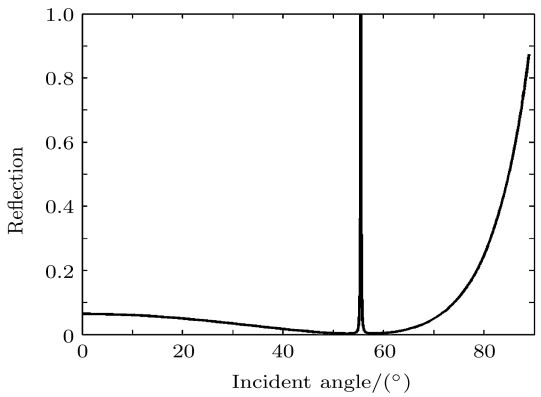


Fig.2. Response of RBF with surface relief structure for TM polarization light at Brewster angle 55.48° and incident wavelength 850 nm. Other parameters are $n_{\rm c} = n_{\rm l} = 1$, $n_{\rm h} = 1.78$, $n_{\rm s} = 1.453$, $d_1 = 50\,{\rm nm}$, $d_2 = 269.3\,{\rm nm}$, $f = 0.57$, $T = 361.5\,{\rm nm}$.

homogeneous layer to the diffracted orders when the structure is illuminated at the Brewster angle, which is illustrated in the Fig.3. It is very clear that a very sharp peak turns out at the designed wavelength 850 nm (solid curve) with extremely low sideband in appreciable spectrum region, which is an excellent narrow band reflection filter. Besides, if the depth of the homogeneous layer under the surface relief structure is adjusted from 243 nm (dot curve) to 297 nm (dash curve), which is a deviation from the designed value of 269.3 nm for 10% negatively and positively relative value, the central wavelength of SRRBF can linearly be shifted while keeping good filtering characteristics. If we increase/decrease the depth of the layer under the surface relief structure, the central wavelength is moved to longer/shorter one respectively. Meanwhile, the optical properties of reflection filter such as high

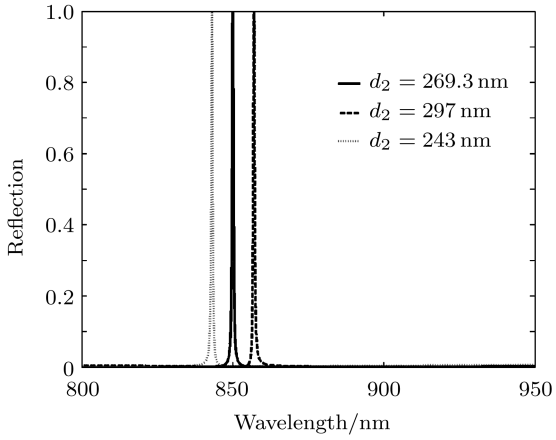


Fig.3. Spectral response of SRRBF depicted in the Fig.1 for TM polarization light at Brewster angle (55.48°) and incident wavelength of 850 nm. Parameters are the same as in Fig.2, except that (solid curve) $d_2 = 269.3\,{\rm nm}$, (dash curve) $d_2 = 297\,{\rm nm}$, and (dot curve) $d_2 = 243\,{\rm nm}$.

diffraction (about 100%) in the resonant wavelength and low side band are not spoiled when we shift the depth of the layer, which is a very easy way to tune the resonant wavelength without the need to change the period of the grating.[17]

Figure 4 shows the reflection under the different depth of the grating. Different line widths (solid for 0.4 nm, dash for 1.0 nm and dot for 1.8 nm) are obtained at the central wavelength 850 nm when the grating depth is varied from 50 nm (solid curve), 80 nm (dash curve) to 120 nm (dot curve). The period of the grating is tuned slightly around the designed value 361.5 nm (solid) for fixing the resonant wavelength in 850 nm. Generally speaking, the line width of the SRRBF can be altered while the position of the resonant wavelength is nearly not changed when the thickness of the surface relief structure is varied. The resonant wavelength can be adjusted back to the designed value without losing low side band property if we slightly adjust the period of grating from its designed value.

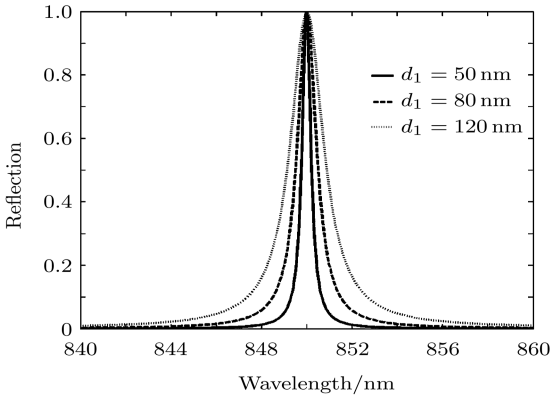


Fig.4. Spectral response of SRRBF depicted in the Fig.1 for TM polarization light at Brewster angle (55.48°) and incident wavelength of 850 nm. Parameters are the same as in Fig.2, except that (solid curve) $d_1 = 50$ nm, $T = 361.5$ nm, (dash curve) $d_2 = 80$ nm, $T = 360.2$ nm and (dot curve) $d_2 = 120$ nm, $T = 359.0$ nm.

Contrary to the Brewster filter with multiple channels referred in the Ref.[14], it is very easy to get the multiple channel properties without the need to increase the depth of the grating because it is a very hard work to fabricate the deep grating with good profile. Moreover, the multiple channels can be obtained with very shallow grating, which will further simplify the fabrication process of such filters. Figure 5 shows the reflection under the variation of the depth of homogeneous layer, as we can see from the Fig.5 that three resonant peaks appear in the range of the depth 0–1.5 μm, which corresponds to the second stop bands of TM0, TM1 and TM2 respectively.[18] When we tune the depth of the homogeneous layer to 269.3 nm, 734.3 nm and 1199.3 nm, the single, double and triple channels are obtained in the Brewster filter respectively. Figure 6 demonstrates the spectrum response of the filter with single (a), double (b) and triple channels(c) when the filter depicted in the Fig.1 is illuminated at the Brewster angle. It is obviously that the multiple channels filter with extremely low side band and very high reflection in the designed wavelength 850 nm can be gained with the very shallow grating at the Brewster angle.

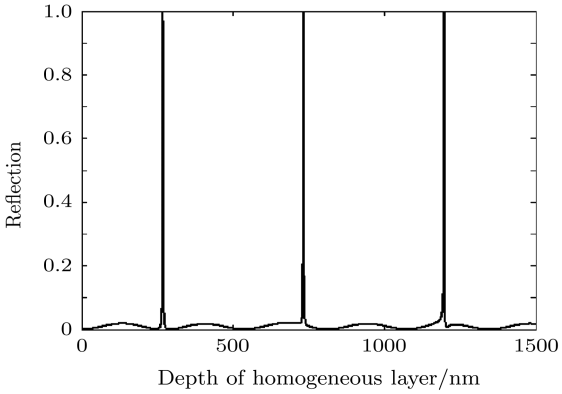
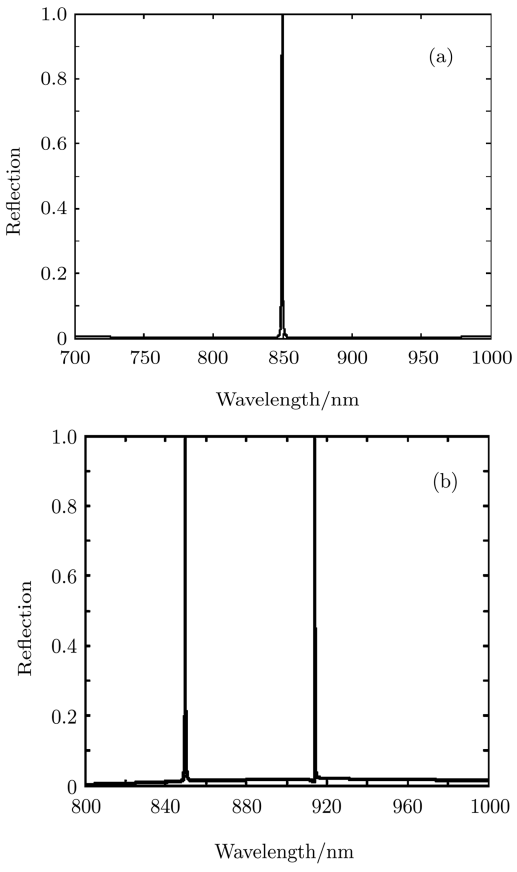


Fig.5. Reflectance vs the homogeneous layer thickness at the Brewster angle 55.48°, other parameters are the same as in Fig.2.



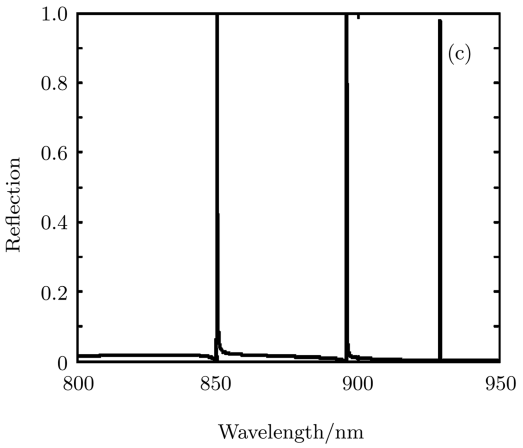


Fig.6. Spectral response of the filter in Fig. 2 for a TM polarized wave incident at the Brewster angle 55.48°. (a) Single channel, $d_1 = 50\,\text{nm}$ and $d_2 = 269.3\,\text{nm}$. (b) Double channels, $d_1 = 50\,\text{nm}$ and $d_2 = 734.3\,\text{nm}$. (c) Triple channels, $d_1 = 50\,\text{nm}$ and $d_2 = 1199.3\,\text{nm}$.

3. Conclusion

In conclusion, a new type of RBF with surface relief structure for the multiple channels is first presented by using the RCWA and the S-matrix method. The multiple channels phenomenon is obtained when we tune the depth of the homogeneous layer under the surface relief structure at the Brewster angle. Contrary to the method proposed by Wang *et al*, the multiple channel filters can be easily acquired with very shallow surface relief grating, which may greatly ease the complexity of fabrication process. Meanwhile, the wavelengths of SRRBF can be easily shifted by changing the depth of homogeneous layer while the main optical properties are kept in an appreciably wide spectrum region. Furthermore, we can design such filters with different line width at given wavelength just through slightly changing the depth of grating at the Brewster angle.

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