Guided-mode resonant Brewster filter consisting of two homogenous layers and a single grating with an equal refractive index*

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In this paper, a new type of resonant Brewster filter (RBF) consisting of two homogenous layers and a single grating with an equal refractive index is presented. The properties are studied by using the plane waveguide method (PWM) and rigorous coupled-wave analysis (RCWA). It is found that the variation of the grating thickness does not effectively change the position of the resonant wavelength, however it has a remarkable effect on the line width, and the resonant peak can be adjusted back to its original position by slightly tuning the grating period. Moreover, by simultaneously tuning the thicknesses of the homogeneous layers above and beneath the grating structure, multiple channels can also be obtained when the RBF is illuminated at the Brewster angle calculated with the effective medium theory (EMT) of subwavelength grating. The adjacent optical thickness for acquiring the multiple channels is about three-quarters of the resonant wavelength. Furthermore, it is demonstrated that the line width at the operating resonant wavelength can be appreciably narrowed by tuning the thickness of the homogenous layer to its corresponding thickness without fine tuning the grating period or the thickness. Therefore, it is very useful for designing filters with different line widths at the desired wavelength. In addition, it is shown from our calculations that the symmetrical line feather can be obtained if the total optical thickness for the homogeneous layer meets the special condition.

Keywords: guided mode resonance, Brewster effect, plane waveguide method

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1. Introduction

Due to the resonance of externally diffracted waves with the waveguide modes of the resonant grating,[1−4] a sharp reflection peak can emerge in the spectrum or the angular band. We refer to this phenomenon as the guided-mode resonance (GMR) effect of waveguide grating. Narrow-band filters based on the GMR property have been realized in microwave,[5] near infrared,[6] and visible spectrum regions.[7] In addition, this kind of optical element can be easily extended to other areas, such as biology,[8] medicine,[9] and sensors.[8,10]

Based on the GMR and Brewster effects, a new type of narrow-band reflection filter was first designed by Magnusson *et al.*,[11] and its optical properties were analysed. Later, Shin *et al.*[12] verified the filter design experimentally. The GMR grating can be regarded as a thin film stack if the incident wavelength is far away from the resonant region. Therefore, extremely low reflection can be obtained when the GMR Brewster grating is illuminated with transverse magnetic (TM) polarization light at the Brewster angle. If the resonant condition is met, a high reflection peak with a very narrow line width can appear in the corresponding wavelength band. It is an excellent narrow band filter, which can not only increase the reflection of the resonant light but also reduce the side band reflection. In 2006, Wang *et al.*[13] put forward the concept of a multiple-channel GMR Brewster filter and provided a design by using the electromagnetic theory. In order to obtain a multiple-channel filter with shallow grating, we designed a new GMR Brewster filter using the surface relief grating.[14] Through varying the thickness of the waveguide layer beneath the grating layer, the multiple channel phenomena can also be found. In addition, the surface relief grating is the most commonly used grating in actual applications, which can be easily fabricated.

In the present paper, a new type of resonant

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Brewster filter (RBF) consisting of two homogenous layers and a single grating with an equal refractive index is proposed, and the properties are demonstrated by using the plane waveguide method (PWM) and rigorous coupled-wave analysis (RCWA).[15–18] The multiple-channel phenomenon is also presented when we adjust only the thicknesses of the homogenous layers above and beneath the grating layer. Instead of adjusting the grating thickness directly, the above adjustment can be more easily realized with very shallow grating. Moreover, it is found that a symmetrical line feather with an extremely low sideband at the operating wavelength can be obtained if the total optical thickness for the homogeneous layer is approximately odd-number times of the quarter resonant wavelength.

2. Numerical analysis and simulation

A guide-mode resonant grating consisting of two homogenous layers and a single grating with an equal refractive index under TM polarization light at the Brewster angle is depicted in Fig. 1. In this paper, the high and the low refractive indices of the grating are denoted as $n_{\rm h}$ and $n_{\rm l}$, respectively. The refractive indices of the cover, the substrate, and the homogeneous layer are denoted as $n_{\rm c}$, $n_{\rm s}$, and $n_{\rm f}$, respectively. The thicknesses of the grating and the homogeneous layers are $d_{\rm g}$ and $d_{\rm h}$, respectively, and f and T are the filling factor and the period of the grating, respectively.

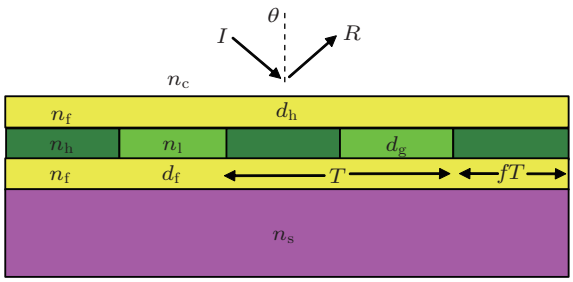


Fig. 1. (colour online) Structure of the RBF under TM illumination at Brewster angle θ.

It should be noted that the refractive indices and the thicknesses of these two homogenous layers are both the same in our calculations. To obtain a highly efficient filter, a subwavelength grating ($T < \lambda$) is chosen to prevent the higher-order diffraction from propagating. According to the waveguide theory, the grating layer can be treated as a thin film whose refractive index is equal to that of the grating. Therefore, the plane waveguide method can be used. The eigenvalue equation of the RBF can be expressed as[19]

$$P_{\rm c}A + P_{\rm c}P_{\rm s}B + C + P_{\rm s}D = 0, \tag{1}$$

where A, B, C, and D are the four components. They are given by

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \prod_{m=1}^{M} \begin{bmatrix} T_{11,m} & T_{12,m} \\ T_{21,m} & T_{22,m} \end{bmatrix}, \tag{2}$$

where

$$\begin{aligned} T_{11,m} &= \cos\gamma_m, \\ T_{12,m} &= (-{\rm j}\sin\gamma_m)/P_m, \\ T_{21,m} &= -{\rm j}P_m\sin\gamma_m, \\ T_{22,m} &= \cos\gamma_m, \end{aligned} \tag{3}$$

$\gamma_m = k_0 d_m P_m$, ${\rm j} = \sqrt{-1}$, $k_0 = 2\pi/\lambda$, M is the total number of layers of the multilayer waveguide structure, $M = 3$ in our case, and d_m is the thickness of the m-th layer. For the TM polarization, P_m, $P_{\rm c}$, and $P_{\rm s}$ can be given as

$$\begin{aligned} P_m &= [n_m^2 - (\beta_m/k_0)^2]^{1/2}/n_m^2, \\ P_{\rm c} &= [n_{\rm c}^2 - (\beta_m/k_0)^2]^{1/2}/n_{\rm c}^2, \\ P_{\rm s} &= [n_{\rm s}^2 - (\beta_m/k_0)^2]^{1/2}/n_{\rm s}^2. \end{aligned} \tag{4}$$

Under the resonant condition, the diffraction grating equation can be written as

$$\beta_m = \beta_{i,\nu}/k_0 = n_m\sin\theta_m - i\lambda/T, \tag{5}$$

where i is the diffracted order ($i = 0, \pm1, \pm2, \ldots$), ν is the waveguide mode order in the m-th layer ($\nu = 0, 1, 2, \ldots$), and θ_m is the refraction angle in the m-th layer. The resonant equation (1) can be calculated when β_m in Eqs. (1)–(4) is replaced with that in the diffraction grating equation. The effective refractive index of the grating layer for the TM polarization is given by the effective medium theory (EMT) of the subwavelength grating, that is

$$n_{\rm eff} = \left\{n_{\rm h}^2 n_{\rm l}^2/\left[f n_{\rm l}^2 + (1-f)\, n_{\rm h}^2\right]\right\}^{1/2}. \tag{6}$$

The multilayer eigenvalue equation is a simple one, which can be used to roughly estimate the resonant position with respect to wavelength, grating thickness, homogeneous layer thickness, and other parameters. The exact resonant location of the waveguide grating can be accurately obtained by using rigorous diffraction algorithms, such as RCWA.

Suppose that $n_{\rm c} = 1$, $n_{\rm f} = 2$, $n_{\rm s} = 1.45$, $d_{\rm h} = 60$ nm, $d_{\rm g} = 86$ nm, and $f = 0.5$, the refractive indices of the ridge and groove can be determined using

formula (6). Since the homogenous layers have the same refractive index as that of the resonant grating, hence, $n_h = 2.25$, and $n_l = 1.8$. Based on the transfer matrix of the thin film theory, the Brewster angle is 57.13°. In order to excite the resonance at the wavelength of 800 nm at the Brewster angle, the grating period should be tuned to 333 nm.

Figure 2 shows the angular response of the RBF illuminated with TM polarization light at the wavelength of 800 nm. It is apparent that a very sharp peak appears when the incident angle is about 57.13°, which is very close to the value calculated with the transfer matrix of the thin film. Based on the most popular method for analysing the diffraction problem, RCWA, the spectrum response of the RBF at the Brewster angle is illustrated in Fig. 3. It is obvious that a very sharp peak emerges at the operating wavelength 800 nm. Since the structure can be treated as a thin film stack when the wavelength is far from the resonant peak, the side band reflection is extremely low due to the Brewster effect of the thin film.

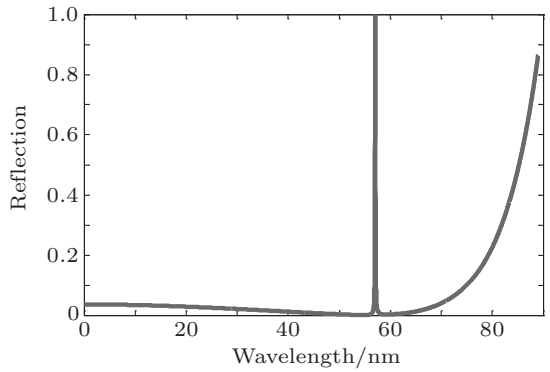


Fig. 2. Angular response of the RBF for TM polarization light at Brewster angle 57.13° and incident wavelength 800 nm. Other parameters are $n_c = 1$, $n_h = 2.25$, $n_l = 1.8$, $n_s = 1.453$, $d_g = 86$ nm, $d_h = 60$ nm, $f = 0.5$, and $T = 333$ nm.

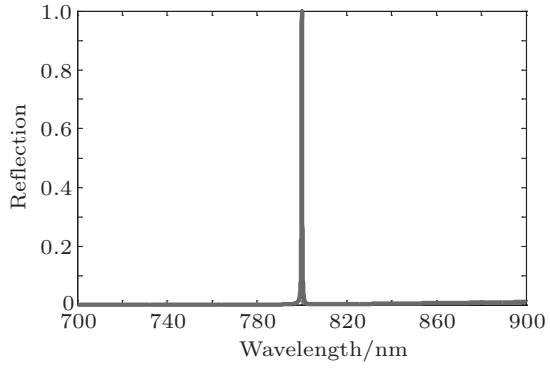


Fig. 3. Spectral response of the RBF shown in Fig. 1 for TM polarization light at the Brewster angle. Parameters are the same as those in Fig. 2.

Figure 4 shows the spectrum responses of the RBF when the grating thickness is positively and negatively changed from its design value. It can be seen from the figure that the resonant wavelength can be red- or blue-shifted if we tune the grating thickness, and the filtering properties, such as the narrow line width and the extremely low side band, can be maintained. The resonant wavelength can be adjusted back to its original position when we slightly tune the grating period, and the excellent filter characteristics, such as the symmetrical line width and the low sideband can be maintained, as shown in Fig. 5.

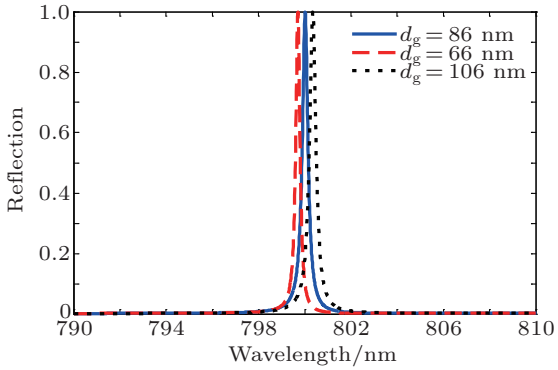


Fig. 4. (colour online) Spectral response of RBF shown in Fig. 1 for TM polarization light at the Brewster angle. Parameters are the same as those in Fig. 2 except d_g.

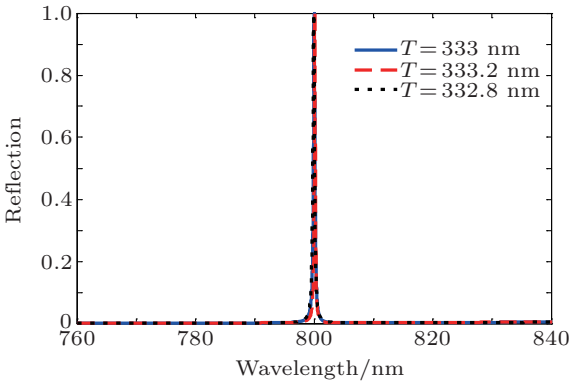


Fig. 5. (colour online) Spectral response of the RBF for TM polarization light at the Brewster angle. Most parameters are the same as those in Fig. 2 except that $d_g = 86$ nm and $T = 333$ nm for solid curve, $d_g = 66$ nm and $T = 333.2$ nm for dash curve, and $d_g = 106$ nm and $T = 332.8$ nm for dot curve.

According to the multilayer waveguide equation, we present the dispersion curves for different thicknesses of homogenous layer. It can be seen from Fig. 6 that a series of resonant locations for the different waveguide modes can be found when the thickness of the homogenous layer is increased. If the thickness is fixed at 60 nm, only the fundamental mode

(TM0) at the wavelength of 800 nm can be supported by the structure. When the thickness is changed to 221 nm, TM0 and TM1 waveguide modes can be excited with the resonant wavelengths at 800 nm and 900 nm, respectively. If the thickness is further increased to 381 nm, the resonant peaks for TM0, TM1, and TM2 can appear at the wavelenghs of 800 nm, 870 nm, and 925 nm, respectively. Figure 7 demonstrates the spectra in the corresponding thicknesses. It is shown that filters with single, double, and triple channels can be obtained when the thickness of the homogenous layer is tuned to the corresponding ones. The multiple channels correspond to the second stop bands of TM0, TM1, and TM2. In addition, it is found from our calculation that the thickness corresponding to the adjacent waveguide mode is three quarters of the resonant wavelength. Furthermore, it is obvious that the multiple-channel filter with an extremely low side band and a very high reflection can be obtained with a very shallow grating at the Brewster angle. Contrary to the Brewster filter with the multiple channels in Ref. [13], it is very easy to obtain the multiple-channel properties without increasing the thickness of the grating. Because it is very difficult to fabricate a deep grating with a good profile, multiple channels obtained with a very shallow grating is beneficial. In our case, the grating thickness is only 86 nm, which will further simplify the fabrication process of such filters.

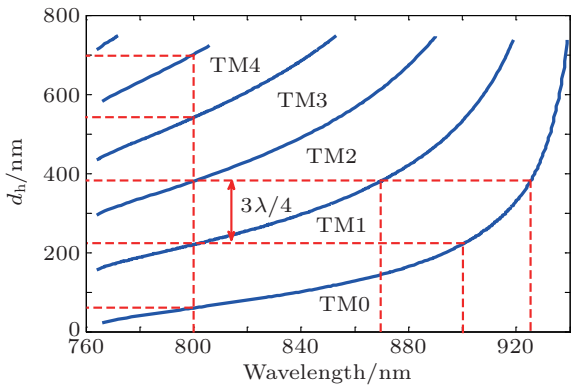


Fig. 6. (colour online) Thickness of a single homogenous layer versus wavelength for different waveguide modes. Parameters are the same as those in Fig. 2.

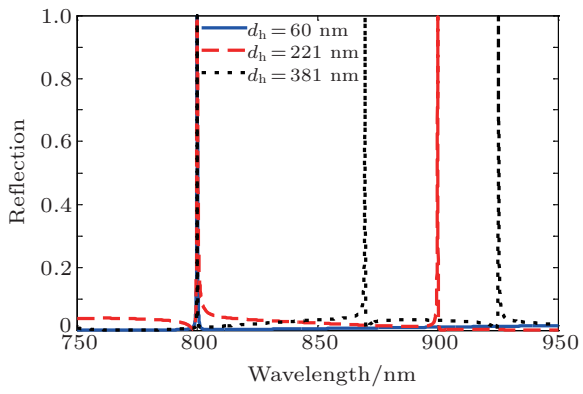


Fig. 7. (colour online) Spectral responses of filters with different thickness d_h. Other parameters are the same as those in Fig. 2.

Figure 8 shows the spectrum responses under different thicknesses of the homogenous layer. Different symmetrical line widths (solid curve is for 1 nm case, dash curve for 0.4 nm case, and dot curve for 0.2 nm case) are obtained at the central wavelength of 800 nm when the thickness is varied from 60 nm (solid curve) to 381 nm (dash curve) and 701 nm (dot curve). Note that the optical thickness for the single homogenous layer meets the following formula:

$$2n_f d_h \cos(\theta) = |(2m+1)\lambda/4|, \quad m = 0, -2, -4, \quad (7)$$

where θ is the refractive angle in the homogenous layer. Therefore, if the total optical thickness of the homogenous layer meets the above condition, a symmetrical line width can be obtained at the operating wavelength. Contrary to the surface relief resonant grating, there is no need to slightly tune the grating period for fixing the resonant wavelength at 800 nm. Generally speaking, the line width of the RBF can be varied with the position of the resonant wavelength changed when the thickness of the homogenous layer is varied.

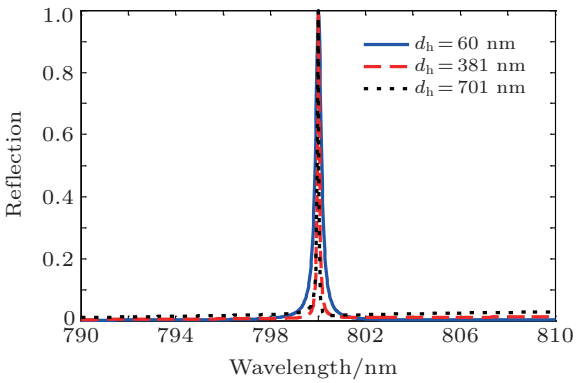


Fig. 8. (colour online) Spectral responses of filters with different thickness d_h at operating wavelength 800 nm. The other parameters are the same as those in Fig. 2.

3. Conclusion

In conclusion, a new type of RBF composed of two homogenous layers and a single grating with an equal refractive index is proposed. By simultaneously tuning the thicknesses of the homogeneous layers above

and beneath the grating structure, multiple channels can also be obtained at the Brewster angle. Furthermore, it is demonstrated that the line width at the operating resonant wavelength can be appreciably narrowed by adjusting the thickness of the homogenous layer to its corresponding thickness.

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