Design of internal Brewster guided-mode resonance filter

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An internal Brewster guided-mode resonance (GMR) filter is designed. For this kind of GMR filter, the Brewster reflection occurs at the interface of grating/waveguide layers rather than at the interface of air/grating layers. At Brewster angle of 60°, the GMR filter owns almost 100% reflection at the resonance wavelength of 800 nm with the full-width at half-maximum (FWHM) of 0.2 nm. Its angle response changing with the fabrication deviation is also discussed.

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Guided-mode resonance (GMR) effect is a type of grating anomaly effect which is observed in thin film structures containing diffractive grating layers and homogenous waveguide layers[1−4]. When the evanescent diffractive order waves diffracted by the grating layer couple into the waveguide mode which can be propagated by the waveguide layer, a GMR effect will occur within a narrow range of parameters (just like wavelength, incident angle, etc.)[5]. This will result in an efficient energy exchange between reflection wave and transmission wave. This characteristic makes GMR filter be interesting in many fields just like laser cavity reflectors, filters, optical switching devices, etc.[1,6−8] Traditionally, the wave reflection is eliminated at Brewster angle for TM wave. Brewster GMR filter is a type of filter which owns high reflection at Brewster angle for TM wave, and also owns narrow wavelength range and angle response. This kind of Brewster GMR filter was firstly predicted by Magnusson *et al.*[9,10] Wang *et al.* reported double-layer multichannel Brewster GMR filters. To our knowledge, for all the reported Brewster GMR filters[1,9−13], the Brewster reflection occurs at the interface between the cover layer (air) and the film structure (the grating layer). In this letter, a new kind of Brewster GMR filter is reported, in which the Brewster reflection occurs in the film structure and at the interface between the grating layer and the homogenous waveguide layer rather than at the interface between the cover layer and the film structure. Its angle response and wavelength response are also discussed.

A GMR structure contains grating structure and waveguide layer. For the grating structure, according to effective index theory, the effective index of the grating layer can be expressed by[5−14]

$$n_{\mathrm{g}} = [(1-f)n_{\mathrm{gL}}^2 + f n_{\mathrm{gH}}^2]^{1/2}, \qquad (1)$$

where n_{g} is the effective index of the grating layer, f is the grating filling factor, n_{gL} and n_{gH} are the low and high refractive indices of the two materials forming the grating structure, respectively.

To satisfy the Brewster reflection condition at the interface between the grating layer and the waveguide layer, the effective refractive index of the grating structure n_{g} and the refractive index of the waveguide layer n_{w} need to satisfy[15]

$$\frac{n_{\mathrm{g}}}{\cos\,\theta_{\mathrm{g}}} = \frac{n_{\mathrm{w}}}{\cos\,\theta_{\mathrm{w}}}, \qquad (2)$$

where θ_{g}, and θ_{w} are the refractive angles in the grating layer and the waveguide layer, respectively.

According to Snell's law, the refraction angles and the films' refractive indices satisfy

$$n_0 \sin\,\theta_0 = n_{\mathrm{g}} \sin\,\theta_{\mathrm{g}} = n_{\mathrm{w}} \sin\,\theta_{\mathrm{w}}, \qquad (3)$$

where the subscript 0 denotes the incidence material (air). Substituting Eq. (3) to Eq. (2) yields

$$\frac{1}{(\sin\,\theta_0)^2} = \frac{n_0^2}{n_{\mathrm{g}}^2} + \frac{n_0^2}{n_{\mathrm{w}}^2}. \qquad (4)$$

To design the internal Brewster GMR filter, the refractive effective index of the grating structure n_{g} and the refractive index of the waveguide layer n_{w} which satisfy Eq. (4) should be chosen firstly. The relationship between n_{g} and n_{w} with different incident angles θ_0 is shown in Fig. 1. Any point in Fig. 1 represents two material indices n_{g} and n_{w}, the points below the curve of the 90° incident angle have a corresponding incident angle which satisfies Eq. (4), and the two refractive indices can be used to design the internal Brewster GMR filter.

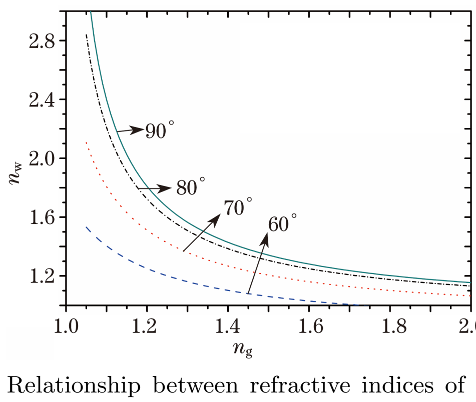

Fig. 1. Relationship between refractive indices of the grating layer and the homogenous waveguide layer. Points below the curve of 90° incidence can be used to design the internal Brewster GMR filter.

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Figuer 2 shows the structure of our Brewster guided-mode filter which consists of a grating layer and a homogeneous waveguide layer for TM mode wave. In our design, the incident angle, effective refractive index of the grating layer, refractive index of the waveguide layer, and refractive index of the substrate were chosen as θ_0=60°, $n_{gL} = n_0 = 1.0$, $n_{gH} = n_w = 1.65$, and $n_s = 1.45$, respectively. The filling factor f of the grating structure can be calculated from Eqs. (1) and (4) to be 0.204. The designed resonance wavelength of 800 nm was achieved by setting the grating period Λ to 333 nm and the waveguide layer thickness d_w to 448.7 nm, and the thickness of the grating structure d_g was chosen as 100 nm.

Rigorous coupled-wave analysis (RCWA) method, which is an exact electromagnetic grating diffraction model providing purely numerical solutions, was used to calculate the Brewster GMR filter's angular and wavelength spectra. Figure 3 illustrates the numerically calculated angular response of the internal Brewster GMR filter. The inset of Fig. 3 gives a magnified view of the resonance response, which peaks at 60.03°. The reflection at the Brewster angle is almost 100% and the full-width at half-maximum (FWHM) of the resonance angle is about 0.7°. Figure 4 illustrates the reflection with the incident angle and also with the wavelength for the same internal Brewster GMR filter. It can be found that for different incident angles, the resonance wave will be located at different wavelengths, and the resonance wavelength increases with the decrease of the incident angle. For the internal Brewster angle of 60°, the TM mode's reflection is almost zero for a wide wavelength range except 800 nm, and the residual reflection for the Brewster angle is caused by the reflection between the air/grating interface and the waveguide layer/substrate interface. This kind of internal Brewster filter also owns a very narrow wavelength width. For the resonance wavelength of 800 nm, the wavelength FWHM is only about 0.2 nm.

This kind of internal Brewster GMR filters are very sensitive to the variations of the device parameters just like grating thickness and waveguide layer thickness. Figure 5 illustrates the angle responses with different grating layer thicknesses while the other parameters keep unchanged. It is found that the deviation of the grating thickness results mainly in the change of the linewidth and also results in slight change of the angle location, which is similar to Wang's result[1]. The line width increases with the increase of grating thickness. The grating thickness primarily affects the coupling strength between the input light and the waveguide modes, thus one can get desired linewidth by varying the grating thickness[1]. The angle FWHMs for the grating thicknesses of 80, 100, and 120 nm are 0.05°, 0.07°, and 0.09°, respectively.

Figure 6 shows the angle responses with different waveguide layer thicknesses while the other parameters keep unchanged. It is found that the deviation of the waveguide layer thickness result mainly in the resonance angle shift. The resonance angle decreases with the increase of waveguide layer thickness. The resonance angles for the waveguide thicknesses of 428.7, 448.7, and 468.7 nm are 60.79°, 60.03° and 59.34°, respectively.

In conclusion, a new kind of internal Brewster GMR filter is designed. For this kind of filter, the Brewster reflection occurs at the interface of grating/waveguide

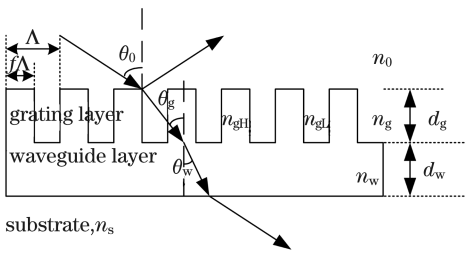

Fig. 2. Structure of the internal Brewster GMR filter consisting of a grating layer and a homogeneous waveguide layer for TM mode wave.

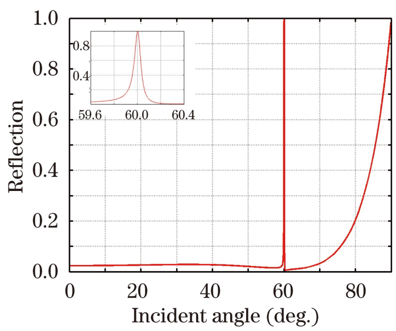

Fig. 3. Angle response of an internal Brewster GMR filter consisting of a grating layer and a homogeneous waveguide layer for TM mode wave. The resonance wavelength is 800 nm, $\theta_0 = 60°$, $n_{gL} = n_0 = 1.0$, $n_{gH} = n_w = 1.65$, $n_s = 1.45$, $\Lambda = 333$ nm, $f = 0.204$, $d_w = 448.7$ nm, and $d_g = 100$ nm. Inset shows a magnified view of the resonance response.

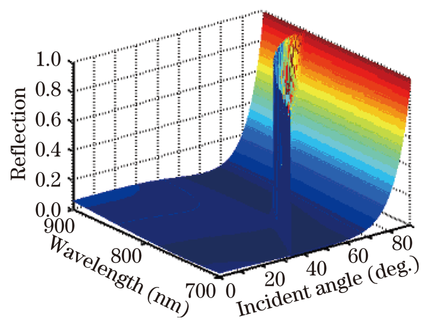

Fig. 4. Reflection changing with the incident angle and the wavelength of the internal Brewster GMR filter. The parameters are the same as those in Fig. 3.

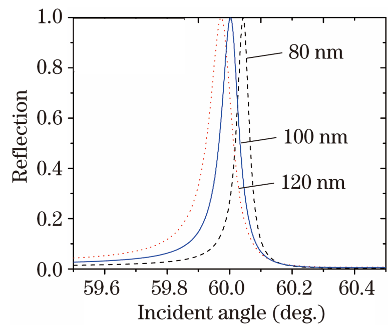

Fig. 5. GMR filter angle responses with different grating thicknesses of 80, 100, and 120 nm. The rest parameters are the same as those in Fig. 3.

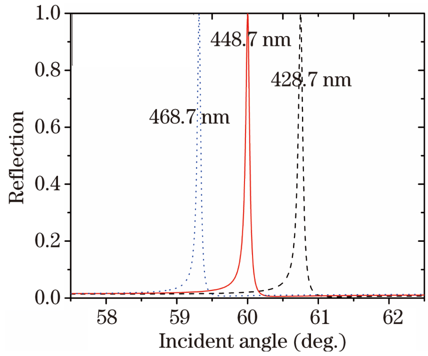

Fig. 6. GMR filter angle responses with different waveguide layer thicknesses of 428.7, 448.7, and 468.7 nm. The rest parameters are the same as those in Fig. 3.

layer rather than at the interface of air/grating layer. To design this kind of internal Brewster angle filter, the incident angle should be decided firstly, the refractive indices of the grating layer and the waveguide layer can be selected according to the incident angle, and the filling factor of the grating structure can be calculated by the incident angle and the film refractive indices. This kind of GMR filter owns narrow wavelength linewidth and low reflection sidebands. The angle response with the fabrication deviation is also discussed. The deviation of the grating layer will result in different resonance angle widths, and the deviation of the waveguide layer will result in different resonance angle locations.

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