Intensity-tunable guided mode resonance reflectance filter with dual channels

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An intensity-tunable reflectance filter with an unetched grating that is based on guided mode resonance is proposed. The unetched grating is designed for simplifying the fabrication proceeds and avoiding the errors of etching. The dual resonant wavelength channels are calculated by rigorous coupled-wave analysis to be at 747.3 and 786.5 nm. Theoretical and experimental data indicate that the intensity of the spectral reflectance at the peak wavelength of 747.3 nm increases monotonically with variation of the azimuthal angle from 0° to 90°. Conversely, the intensity of the spectral reflectance decreases monotonically under the same conditions at the resonant wavelength of 786.5 nm. It is found experimentally that the intensity can be tuned via the azimuthal angles, and this agrees well with the results of the theoretical analysis. In addition, the influence of the structural parameters on the value of the wavelength separation between the dual resonance channels is analysed, and the electric field distributions at the resonant wavelengths are presented.

1. Introduction: Filters based on the guided-mode resonance (GMR) effect have been widely proposed because of advantages that include their design structure flexibility and filtering sensitivity [1–3]. GMR-based filters have proved to be a feasible and effective way to present characteristics such as narrow-band and high-efficiency filtering and tunable optical effects [4–6]. The tuning characteristics of these filters have attracted widespread interest. The application of the tunable optical effects was first proposed by Gale *et al.* [7]. Authentication labels using GMR filters were reported by Wu, and variable diffraction efficiency was obtained by varying the angle of incidence [8]. Dobbs fabricated a GMR filter with spectral reflectance features that varied linearly as a function of waveguide thickness [9]. Niederer *et al.* [10] designed a tunable oblique-incidence resonant grating filter based on variation of the angle of incidence that could adjust the resonance wavelength in the range from 1526 to 1573 nm. Qian *et al.* [11] presented a bandwidth-tunable filter based on a polarisation-tailored dichroic resonator.

GMR filters with multiple channels have also attracted considerable research attention [12, 13]. Ma *et al.* [14] designed a type of GMR filter with an antireflective surface that could provide multiple channels when the depth of the antireflective surface was increased. However, less attention has been paid to the spectral reflectance intensity of GMR filters, especially for tuning of the reflectance intensity over the multiple channels of these filters. The phenomenon of tunable intensity at the resonant wavelengths can be obtained by varying the azimuthal angle [15–17]. In this paper, we present a triple-layer GMR filter and investigate its spectral reflectance characteristics. By theoretical and experimental analysis, it is shown that intensity-based tuning of the reflectance spectrum can be realised by adjustment of the azimuthal angle.

2. Device design and fabrication: The design principle of a GMR filter is based on coupling of the incident wave to a leaky waveguide mode by phase-matching using a second-order grating. Waveguiding can only occur when the effective index of the guided mode is higher than that of the surrounding medium but less than the refractive index of the core itself. A triple-layer guided-mode resonant filter was designed in this work. The grating layer of the filter was fabricated by the method of laser interference lithography (LIL).

Fig. 1 shows the structure of the GMR device. From top to bottom, the GMR filter includes a cover layer (air), a photoresist (PR) grating layer, a waveguide layer (composed of PR and ZnO) and a substrate layer (K9). The grating groove depth is denoted by d_g. For simplifying the fabrication proceeds and avoiding the errors caused by etching, the designed grating is unetched, so that there exists a PR layer that is present throughout the fabrication process. The remaining PR and ZnO layers constitute the waveguide layer and their thicknesses are expressed as d_l and d_w, respectively. In addition, the grating period is Λ, and its duty cycle is f. The incident light is linearly polarised, but its polarisation orientation may not be appropriate. To solve this problem, a polariser is used to adjust the azimuthal angle.

To verify the phenomenon of intensity tuning of the reflectance spectrum at the resonance wavelength based on variation of the azimuthal angle, a reflectance filter was fabricated using the structure shown in Fig. 1. The GMR filter fabrication process was as follows. First, a 135-nm-thick ZnO film was deposited by magnetron sputtering. Then, a 130-nm-thick PR film was spin-coated on the ZnO layer. The film thicknesses were measured using an ellipsometer (Uvisel, Horiba). Finally, by the LIL method, a one-dimensional grating was formed. The groove depth and period of the grating were measured by atomic force microscopy (AFM, XE-100, PSIA), and the results are presented in Fig. 2*a*. The AFM measurement results show that the grating groove depth (d_g) is 95 nm, the grating period (Λ) is 484 nm, and the duty cycle (f) is approximately 0.5. A photograph of the fabricated filter is shown in Fig. 2*b*.

3. Simulation and experiment: The theoretical spectral responses are calculated by the rigorous coupled-wave analysis (RCWA) method [18, 19], and the experimental reflectance spectra are detected using an optical spectrum analyser (USB4000, Ocean Optics) with a wide-band light source (tungsten halogen lamp, LS-01, Ocean Optics).

The theoretical and experimental results for the GMR filter reflection spectra are shown in Fig. 3. The theoretical results are shown as dashed lines, and the experimental results are shown as

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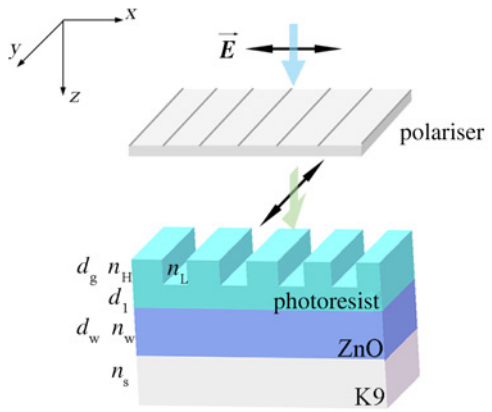


Fig. 1 *Structure of designed unetched triple-layer GMR filter*

solid lines. The angle of incidence of the linearly polarised light is 0°. When the azimuthal angle is 0°, a single resonance peak located at 786.5 nm with 99.9% intensity is found in the calculations, while

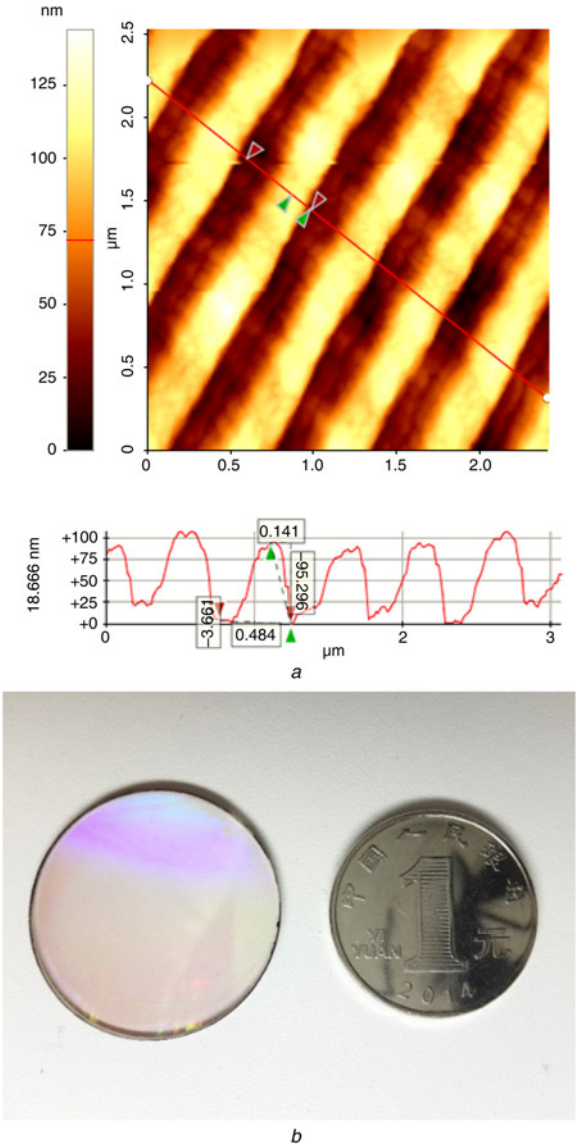


Fig. 2 *AFM measurement and picture of the fabricated GMR filter*

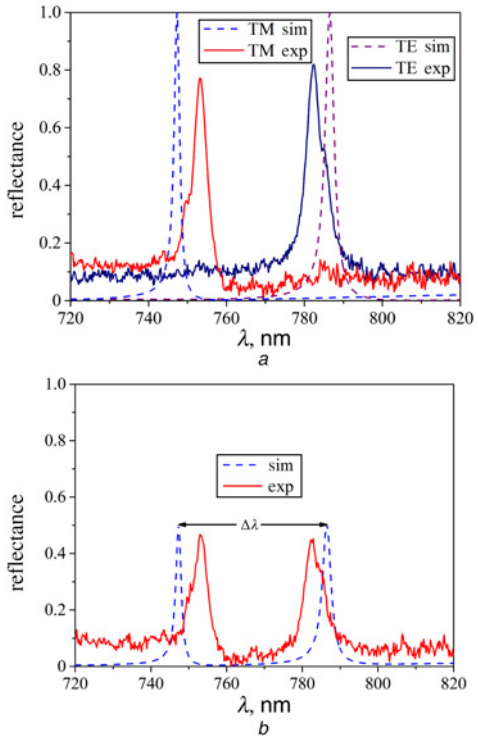


Fig. 3 *Theoretical and experimental distributions of the reflectance response for different azimuthal angles under vertical input incidence*
a Shows the result for the azimuthal angle $\phi = 0°$(TE) and $\phi = 90°$(TM)
b Shows the result for the azimuthal angle $\phi = 45°$

a resonance peak at 782.5 nm with an intensity of 81.9% is obtained experimentally. The resonance peak wavelength shows a blue shift of ~30 nm after the azimuthal angle is changed to 90°. The theoretical efficiency at 747.3 nm is 99.9%, and the experimental efficiency obtained at 752.9 nm is 77.3%. In addition, at an azimuthal angle of 45°, resonance peaks appeared at 786.5 and 747.3 nm with efficiency of 50% in the theoretical results, while two resonance peaks were obtained with efficiencies of 46% in the experimental results. It also can be noted that the linewidth of experimental reflectance spectrums is wider than the theoretical results, which is probably because of the incompletely vertical angles of PR gratings.

The numerical spectral responses demonstrate that tuning of the reflectance intensity with dual channels could be realised by adjustment of the azimuthal angles, and this is verified experimentally. Fig. 4 illustrates the relationship between the intensity of the spectral reflectance and the azimuthal angle based on an analysis of the

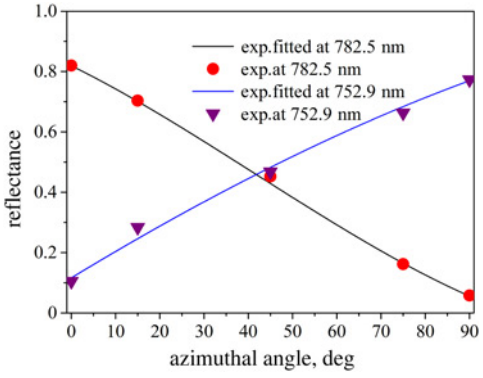


Fig. 4 *Experimental relationship between azimuthal angle and reflectance at resonant wavelength*

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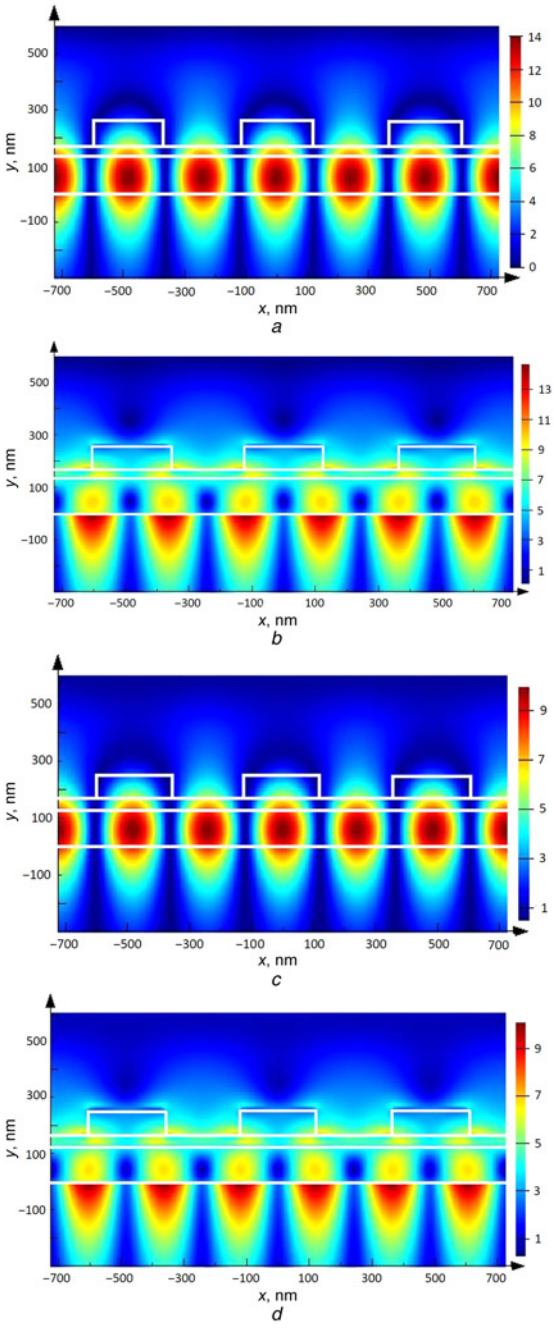


Fig. 5 *Electric field distributions of the cross-sections at the resonant wavelength. Structural parameters: $\Lambda = 484$ nm, $f = 0.5$, $d_w = 135$ nm, $d_1 = 35$ nm, $d_g = 95$ nm*
a Shows the azimuthal angle $\phi = 0°$ at 786.5 nm
b Shows $\phi = 90°$ at 747.3 nm
c and *d* show the results for $\phi = 45°$ at 786.5 nm and 747.3 nm, respectively

experimental results. The figure shows that the intensity of the peak wavelength at 752.9 nm increases monotonically with variation of the azimuthal angle from 0° to 90°. Meanwhile, the intensity decreases monotonically under the same conditions at the resonant wavelength of 782.5 nm.

The guided mode resonance effect will generate sharp variations in the intensities of the observable electromagnetic fields over a small parameter range. This mechanism will lead to an exchange of efficiency between the reflected wave and the transmitted wave. RCWA is a relatively straightforward technique that can be used to obtain exact solutions of Maxwell's equations for electromagnetic diffraction by grating structures. In this case, k_{xi} is the

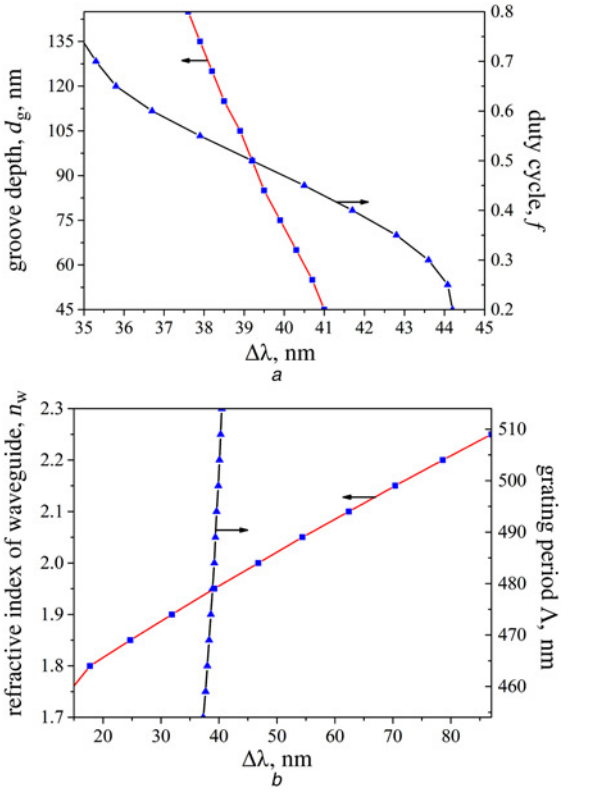


Fig. 6 *Numerical results of relationships between the structural parameters and Δλ (spectral distance between two peaks)*
a Shows the results for the duty cycle (f) and the groove depth (d_g)
b Shows the results for the waveguide refractive index (n_w) and the period (Λ)

vector component of the ith diffracted wave in the x-axis direction, which is determined using the Floquet condition, and is given by

$$k_{xi} = k_o[n_I \sin\theta - i(\lambda_o/\Lambda) \tag{1}$$

where $k_o = 2\pi/\lambda_o$. $k_{I,zi}$ is the vector component of the ith reflected wave in the z-axis direction, and is defined as

$$k_{I,zi} = \left[k_o^2 - k_{xi}^2\right]^{1/2} \tag{2}$$

then, at normal incidence, the reflected diffraction efficiency is expressed as

$$\mathrm{DE}_{Ri} = |R_{si}|^2 \mathrm{Re}(k_{I,zi}/k_o) + |R_{pi}|^2 \mathrm{Re}(k_{I,zi}/k_o) \tag{3}$$

where R_{si} and R_{pi} are the electric and magnetic field vector components normal to the diffraction plane, respectively. The detailed derivations can be seen in [19, 20].

4. Analysis: As part of an in-depth investigation, the electric field distributions at the resonant wavelengths are shown in Fig. 5. The white lines indicate the filter structure. An energy accumulation effect is seen to exist in the inner waveguide. When Figs. 5*a* and *b* are compared with Figs. 5*c* and *d*, the enhancement of the inner energy with $\phi = 90°$ and $\phi = 0°$ is seen to be much stronger in the former cases than in the case where $\phi = 45°$, which causes intensity tuning of the reflectance for the dual channels. The reflectance intensity is determined by the strength constraint of the tangential component of the electric vector.

Note that the calculated wavelength separation between the two peaks ($\Delta\lambda$) is wider than that of the experimental results shown in Fig. 3. To investigate the influence of the structure on the

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wavelength separation thoroughly, we numerically investigated $\Delta\lambda$ by changing the structural parameters. Fig. 6 indicates that $\Delta\lambda$ varies linearly with respect to the grating parameters. $\Delta\lambda$ varies in direct proportion to the refractive index of waveguide layer but inversely proportional to grating depth and the duty cycle. Furthermore, the grating period has just a little impact on the wavelength separation.

5. Conclusion: In conclusion, a GMR filter has been presented where the resonant intensity of the spectral reflectance can be tuned by varying the azimuthal angle. To verify the results of the theoretical study, a GMR filter was fabricated using LIL and magnetron sputtering technologies, meanwhile, the grating is designed to be unetched in order to simplify the proceeds prevent the etching error. From analysis of the reflection using the detected parameters, the intensity of the peak at the resonant wavelength of 747.3 nm is observed to increase monotonically when the azimuthal angle is varied from 0° to 90°. In contrast, the intensity decreases monotonically at the resonant wavelength of 786.5 nm. The variation trend when the intensity is tuned based on the azimuthal angles agrees well with the theoretical results. The electric field distribution is also presented for analysis of the intensity tuning mechanism. The corresponding influence of the structure on the wavelength separation of the two peaks is then analysed. The results show that wavelength separation varies in direct proportion to the refractive index of waveguide layer but inversely proportional to thickness of grating depth and the duty cycle. This type of intensity-tunable reflectance-based multi-wavelength filter has broad application prospects in areas such as detection of bioactive fluorescent protein dyes, displays, optical communications, and spectroscopic measurements.

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