Single-material guided-mode resonance filter for TE waves under normal incidence

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A guided-mode resonance (GMR) filter with the same material (Ta_2O_5) for both the grating layer and the waveguide layer is designed and fabricated. This simple structure is easy to fabricate and can avoid the defects at the grating/waveguide interface using different materials. The spectral response measured with a Lambda 900 spectrophotometer under normal incidence for TE waves exhibits a peak reflectance exceeding 80% at the wavelength of 1040 nm with a full-width half-maximum (FWHM) linewidth of 23 nm. We evaluate the deviations of the fabricated structure from the designed parameters.

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Guided-mode resonance (GMR) filters are integrated optical structures consisting of a waveguide in the presence of a periodic perturbation of the structure's geometric and material properties[1,2]. When a diffracted wave from the grating couples to a leaky mode supported by the waveguide layer, it excites a GMR in small parameter ranges (just like wavelength, incidence angle, refractive index, etc.)[3]. Thus applying the GMR effect, a variety of passive optical elements can be realized. Theoretical analysis shows that GMR filters can be designed to exhibit narrow linewidth and low sideband reflection over an extended wavelength region[1−3], which is promising in the applications of laser cavity reflectors, polarizers, switching devices, light modulators, band-pass filters, etc. Wang *et al.* designed single-layer GMR filters with single film material and multi-layer GMR filters with different materials for film and grating layers[4,5]. Multichannel GMR Brewster filters with different materials for grating layers and waveguide layers were also reported[6]. Fu *et al.* designed a single-material GMR filter (i.e., with the same material for both the grating layer and the waveguide layer)[7]. Although theoretical analysis and designs in this filed are rich[1−10], few experimental results of the GMR filters have been reported[11−13].

The objective of this research is to develop reflection filters with high efficiency and low extended sidebands by use of simple structures and fabrication methods. The GMR filter structure under study is shown schematically in Fig. 1. A GMR filter with the same material (Ta_2O_5) for the grating layer and the waveguide layer is designed and fabricated. This kind of GMR filter can avoid the material change at the grating/waveguide interface and owns fewer defects during the fabricating process, which results in a higher laser damage threshold and can be potentially applied in high-power laser system[14,15].

Using the method mentioned in Ref. [8], we design a GMR reflection filter for TE waves under normal incidence working at 1053 nm with the full-width half-maximum (FWHM) linewidth being 15 nm. The structure is specified as follows: $\Lambda = 640$ nm, $h_g = 122$ nm, $h_w = 155$ nm, $f = 0.5$, $n = 2.1$, $n_s = 1.47$. The device was fabricated by deposition of a 277-nm-thick Ta_2O_5 layer on a square BK7 glass substrate (50×50 (mm)) by magnetron sputtering system and subsequent etching of a holographic grating in the Ta_2O_5 layer. In order to characterize the deposited Ta_2O_5 film, we measured the transmission spectra using Lambda 900 spectrophotometer within the wavelength range of 400–1200 nm before etching the grating. With an envelop method, we extract that the film thickness is 277.83 nm and the optical constants at some critical wavelengths are listed in Table 1. The refractive index deviates from the desired value 2.1 because the film is not too tight, which results in the big extinction coefficients. These non-zero extinction coefficients will decrease the reflection efficiency, which we will analyze later.

A grating with a period $\Lambda = 640$ nm and a thickness of $d_g = 155$ nm was recorded with a He-Cd laser ($\lambda = 441.6$ nm) in a Lloyd mirror interference setup, followed by Ar ion beam rotation etching. The experiments show that if the direction of the ion beam onto the oblique substrate is kept stable, the side of the grating line is steep at the cost of more redeposition of Ta_2O_5. Ion beam rotation etching technique can reduce the redeposition, but the big tilt angle of the substrate will lower the side obliquity of the grating line. So the tilt angle of the substrate must be chosen carefully. In this

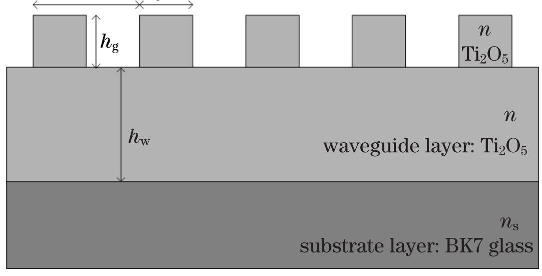

Fig. 1. Schematic representation of a single-material GMR reflection filter.

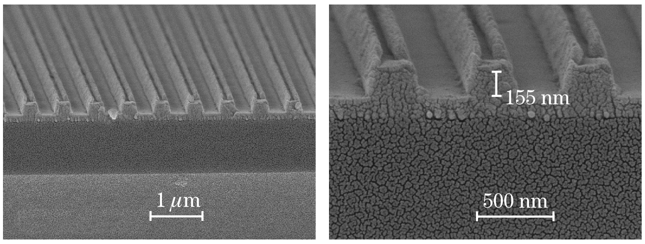

Fig. 2. SEM morphologic images of the fabricated structure. The morphology is observed by SEM in a JSM 6360LA microscope.

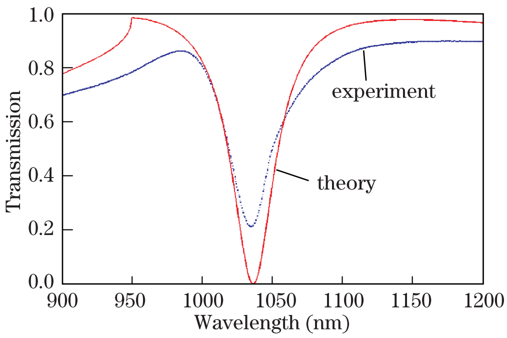

Fig. 3. Theoretical and experimental spectral response of a single-material GMR reflection filter with the structure illustrated in Fig. 1. The parameters used in the theoretical modeling are Λ = 652 nm, h_g = 173 nm, h_w =104 nm, f = 0.54, n = 2.05, n_s = 1.47.

Table 1. Refractive Index and Extinction Coefficients of the Deposited Ta_2O_5 Film

λ (nm)	470.04	578.46	756.74	1125.77
n	2.1232	2.0874	2.0547	2.0143
k	0.0003338	0.0004398	0.0004316	0.0008847

experiment, we adopted the ion beam rotation etching with the tilt angle of the substrate being 60°. An example of a fabricated structure is illustrated by the scanning electron micrograph (SEM) shown in Fig. 2. The grating is regular and even in general. The useful etched dimensions are about 39×40 (mm). The ditches on the ridges of the grating are the main imperfections, which are caused by the redeposition in etching process. The higher the ridge is, the more serious the redeposition is. These ditches will influence the reflection efficiency evidently.

Figure 3 illustrates the experimentally measured spectral response of the GMR filter for a TE-polarized probe beam that is normally incident upon the device, which was measured using Lambda 900 spectrophotometer in increments of 0.2 nm. The spectra of the GMR filter are plotted by normalization of the power transmitted from the device with the power of the incident beam. The GMR filter exhibits a peak reflectance exceeding 80% at the wavelength of 1040 nm with a FWHM linewidth of 23 nm. In order to evaluate the deviations of the fabricated structure from the designed parameters, we deduce the parameters of the structure from the measured transmission spectral using a global optimization algorithm, simulated annealing method. The deduced parameters are Λ = 652 nm, h_g = 173 nm, h_w =104 nm, f = 0.54, n = 2.05, n_s = 1.47. We add the spectral response with the deduced parameters to Fig. 3 by solid line which is calculated using rigorous coupled wave analysis (RCWA). As analyzed in Ref. [8], the period of the grating is decisive to the resonant wavelength. A bigger period (Λ = 652 nm) leads the resonance wavelength to 1040 nm. The high transmission at 950 nm results from the propagation of the first diffracted wave in the substrate. The lower efficiency at the resonant wavelength comes probably from the high extinction coefficients and the roughness of the grating surface.

In conclusion, a GMR filter with the same material for both the grating layer and the waveguide layer is designed and fabricated. The device is fabricated by deposition of a layer of Ta_2O_5 on a BK7 glass substrate by magnetron sputtering system and subsequent etching of a holographic grating in the Ta_2O_5 layer. The measured spectral response with a Lambda 900 spectrophotometer at normal incidence for TE waves exhibits a peak reflectance exceeding 80% at 1040 nm with a FWHM linewidth of 23 nm. The factor that results in the deviation from the designed values is analyzed. This structure is valuable because it is easy to fabricate and does not bring the defects at the grating/waveguide interface. This single-material GMR filters may permit development of a variety of active and passive devices for lightwave communication systems and laser technology.

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