Rugate filters prepared by rapidly alternating deposition*

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A methodology for the fabrication of composite $(Nb_2O_5)_{1-x}(SiO_2)_x$ thin-film rugate filters by using pulsed direct current magnetron sputtering is presented. The two materials are mixed using rapidly alternating deposition technology. The optical properties of the composite films varying with the composition of the material are studied in detail. Refractive indices between 1.50 and 2.14 can be realized in our coating system. Two designed rugate filters with a reflection band at the wavelength of 532 nm are fabricated using an automatic deposition process. The microstructure of the rugate filter is investigated by using scanning electron microscopy. The calculated and the measured transmittance spectra are in good agreement with each other. The causes of the slight differences between them are also analysed.

Keywords: rapidly alternating deposition, rugate filter, magnetron sputtering, mixed oxides

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1. Introduction

The rugate filter, as a special kind of graded-refractive-index film, has continuously periodical modulation in the refractive index profile along the stack axis. Compared with a traditional filter, such a filter exhibits many advantages, such as a higher laser-induced damage threshold,[1] smaller sensitivity to angle variation of incident light,[2] suppression of higher frequency harmonics,[3,4] smaller residual stress[5] and higher temperature stability.[6] However, preparation of the rugate filter is relatively difficult because of the requirement for accuracy in realizing the continuous refractive index profile. The filter can be fabricated by mixing two or more materials with high and low refractive indices,[7−9] or by varying the content of the reactive gas with a single source.[10−12] The electrochemical etching of silicon[13] and the glancing angle deposition[14,15] are also used to make porous rugate filters.

In the present paper, we use pulsed direct current (dc) magnetron sputtering to fabricate Nb_2O_5–SiO_2 composite films with Nb and Si targets. The constantly altering deposition method is applied to the fabrication process. It is shown that any value of the refractive index in the range from 1.50 to 2.14 can be achieved in our experiment. A 11-period rugate filter, which has a sinusoidal variation in the refractive index, is fabricated. In addition, the apodization technique and the index-matching layers are used to suppress the sidelobes in the transmittance region.

2. Experiment

Composite $(Nb_2O_5)_{1-x}(SiO_2)_x$ thin films were deposited by using a pulsed dc magnetron sputtering system. A diagram of the deposition chamber is shown in Fig. 1. The mixing of two materials was realized by the rapid rotation of the substrate, which was controlled by a computer. The BK7 glass (φ 30 mm×3 mm) substrates were ultrasonically cleaned in acetone and ethanol before being introduced into the vacuum system. All the thin films were deposited at ambient temperature. Nb (purity 99.95%) and Si (purity 99.999%) targets, $3.5'' \times 8'' \times 0.25''$ in size, were used in the experiment. The background pressure was less than 1.0×10^{-3} Pa and the sputtering pressure was 0.5 Pa. During the deposition process, the flow

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rates of oxygen and argon were both held constantly at 20 sccm. A removable shutter was placed between the substrate and the target holder, which was used during the presputtering process for 10 min and then removed. The energy of the two sputtering sources was provided by an Advanced Energy Pinnacle^{TM} Plus+ 5×5 kW power supply. The sputtering process was carried out with a pulse frequency of 300 kHz and a pulse reverse time of 1 μs. In the experiment, the power of Nb (P_{Nb}) and Si (P_{Si}) targets satisfied

$$P_{Nb} + 2.5 \times P_{Si} = 1050 \text{ W}, \quad (1)$$

where P_{Nb} was set in the range from 50 W to 800 W, and the corresponding P_{Si} changed from 400 W to 100 W. Their continuous variation could be achieved by using a computer. The cross-sectional microstructure was observed by using field emission scanning electron microscopy (SEM) with a Zeiss Auriga microscope. The transmittance spectra of the rugate filters were measured by a Lambda 1050 spectrophotometer.

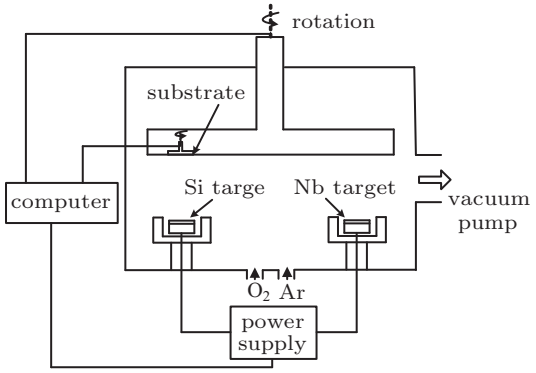


Fig. 1. Schematic diagram of the magnetron sputtering deposition system.

3. Results and discussion

3.1. Optical properties of Nb_2O_5–SiO_2 composite films

The transmittance spectra of the $(Nb_2O_5)_{1-x}(SiO_2)_x$ composite thin films deposited under different power conditions are shown in Fig. 2. Based on the transmission spectra, the effective refractive indices of the samples are calculated according to Cauchy's dispersion equation,[16–18]

$$n(\lambda) = A_1 + \frac{A_2}{\lambda^2} + \frac{A_3}{\lambda^4}, \quad (2)$$

where A_1, A_2, and A_3 are all fitting parameters. The physical thickness of the film is given by

$$d = \frac{\lambda_1 \lambda_2}{2(\lambda_1 n_2 - \lambda_2 n_1)}, \quad (3)$$

where n_1 and n_2 are the refractive indices at two adjacent minimum wavelengths λ_1 and λ_2. The simulated dispersion curves of the refractive indices are shown in Fig. 3. It is found that the refractive index of the composite thin film decreases with the decrease of P_{Nb} (the increase of P_{Si}).

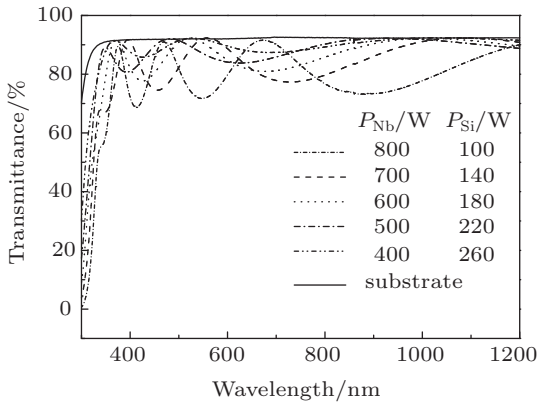


Fig. 2. Transmittance spectra of composite films with different P_{Nb}:P_{Si} ratios.

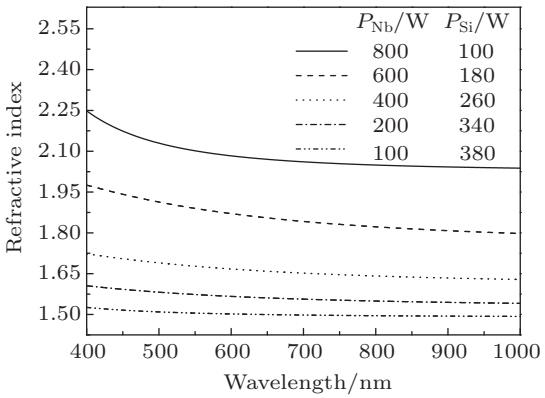


Fig. 3. Disperse refractive index for $(Nb_2O_5)_{1-x}(SiO_2)_x$ films with different power ratios.

Figure 4(a) illustrates the effective refractive indices (at $\lambda = 532$ nm) under different values of P_{Nb} (P_{Si}). As shown in the figure, any value of the refractive index between 1.50 and 2.14 can be realized. The fitted polynomial expression reads

$$n(P_{Nb}) = 1.49102 + 0.33066P_{Nb} + 0.76274P_{Nb}^2 - 0.19762P_{Nb}^3. \quad (4)$$

The physical thicknesses of the composite films, which are deposited in equal intervals of time, versus P_{Nb} are shown in Fig. 4(b). As can be seen, the thickness initially decreases with the increase of P_{Nb}, then becomes larger and larger once the power of the Nb target goes to above 0.55 kW. The fitting result is given by

$$d(P_{Nb}) = 397.959 - 234.891P_{Nb} + 106.295P_{Nb}^2 + 131.482P_{Nb}^3. \quad (5)$$

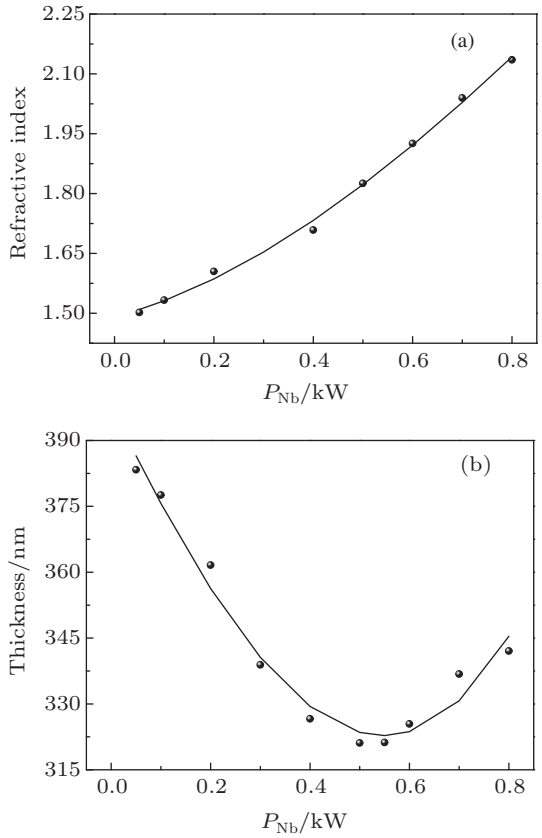


Fig. 4. Fitted refractive index at $\lambda = 532$ nm (a) and physical thickness (b) of Nb_2O_5–SiO_2 composite films versus power of the Nb target.

3.2. Rugate filters

A simple rugate filter possesses a sinusoidal periodic-modulated refractive index profile in the form[19]

$$n(x) = n_{\rm a} + \frac{1}{2} n_{\rm p} \sin\Big(\frac{4\pi x}{\lambda_0} + \phi_0\Big), \qquad (6)$$

where $n_{\rm a}$ is the average index, $n_{\rm p}$ is the peak-to-peak refractive index modulation, λ_0 is the wavelength at the stop band position and ϕ_0 is the initial phase. Figure 5 shows a 11-cycle refractive index profile with $n_{\rm a} = 1.82$, $n_{\rm p} = 0.64$, and $\phi_0 = 0$ at a central wavelength of 532 nm. The resulting transmittance spectrum of the designed filter is given in Fig. 6 in comparison with the measured one. It can be found that the experimental measurement values fit the theoretical calculated results. Figure 7 shows the SEM cross-sectional pattern of the sample. The image reveals a periodic change of the contrast that corresponds to the different mixing proportion layers. The dark (white) region corresponds to the layer with a higher (lower) percentage of SiO_2. Unlike the traditional multilayer film, our sample has a very smooth interface.

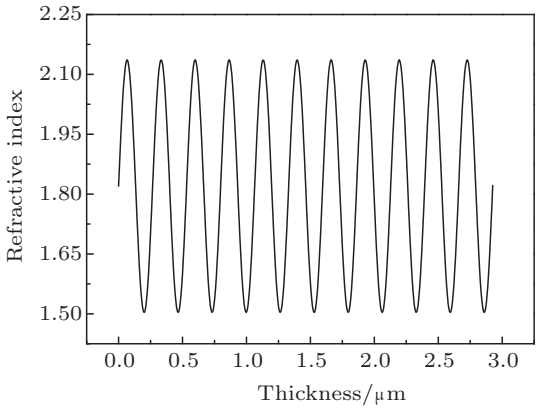


Fig. 5. Refractive index distribution of the 11-cycle rugate filter.

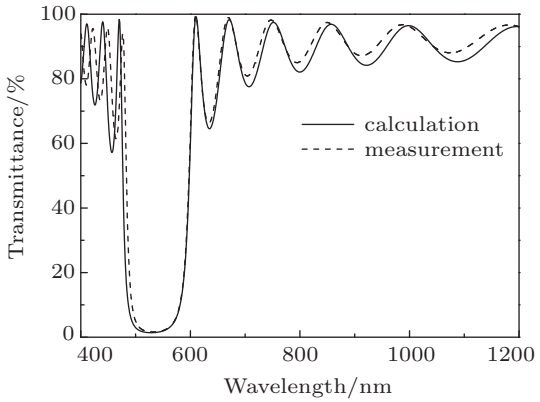


Fig. 6. Calculated and measured transmittance spectra of the filter.

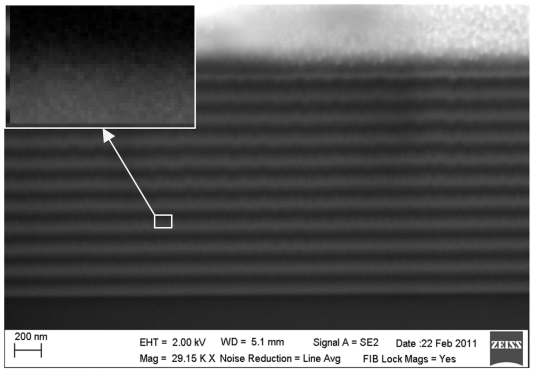


Fig. 7. Cross-sectional SEM micrograph of the sample.

The ripples on both sides of the stop band (Fig. 6) might be caused by two factors. One is the refractive index contrast at the two boundaries of the filter and the other is the index mismatch between the rugate structure and the mediums.[3,13] In order to suppress the sidelobes, we add the matching equation (Eq. (9)) and the apodizing function (Eq. (8)) to the refractive index profile (Eq. (7)), as shown in Fig. 8. The total optical thickness of the filter is 9.98 μm. The quintic matching layers at the substrate and the ambient

medium sides are both 1 μm thick, and the refractive index varies from 1.52 to 1.82.

$$n(x) = n_{\rm a} + \frac{1}{2} n_{\rm p} f(x) \sin\Big(\frac{4\pi x}{\lambda_0}\Big), \tag{7}$$

$$f(x) = 10x^3 - 15x^4 + 6x^5, \tag{8}$$

$$n(x) = n_{\rm s} + (n_{\rm a} - n_{\rm s})(10x^3 - 15x^4 + 6x^5), \tag{9}$$

where $n_{\rm s}$ is the refractive index of the substrate.

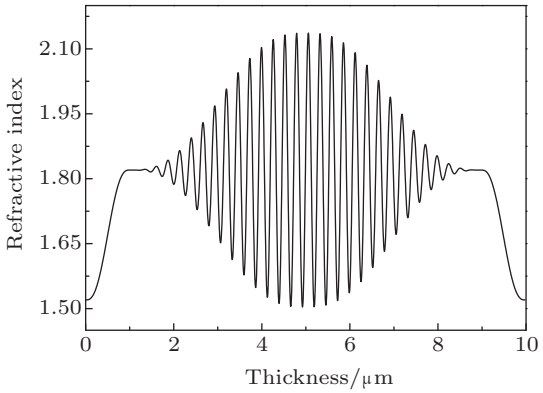


Fig. 8. Refractive index distribution of the rugate filter with quintic apodization and quintic matching on each side.

As shown in Fig. 9, the measured transmittance curve coincides well with the design. The differences between the measured and the calculated values in the shortwave range might result from the absorption of the composite thin film at these wavelengths. It can be resolved by increasing the oxidation of the composite material. The slight shift of the stop-band centre might be due to inaccuracy in the thickness control. Further measurement should be conducted to improve the deposition rate stability.

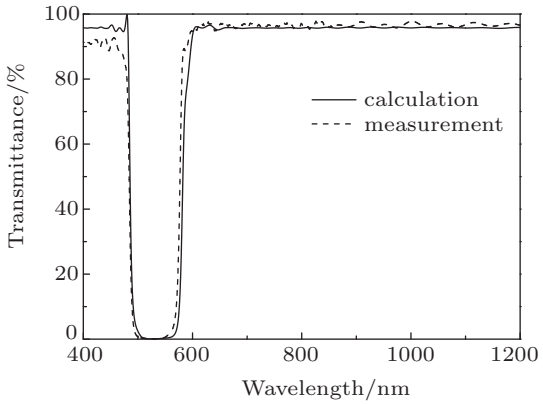


Fig. 9. Calculated and experimentally measured transmittance spectra of the rugate filter.

4. Conclusion

Nb_2O_5–SiO_2 composite thin films are prepared by using pulsed dc magnetron sputtering with alternating deposition technology. The refractive index increases with the increase of Nb_2O_5 content in the composite film. The thickness of the composite film deposited in the same amount of time reduces at first and then increases as the power of the Nb target increases. It is possible to obtain any value of refractive index between 1.50 and 2.14 (at $\lambda = 532$ nm). Two rugate filters are designed and deposited by using automated computer control. We add quintic apodization and quintic matching layers to reduce the sidelobes. The samples have rather smooth interfaces, as confirmed by SEM observation. The measured transmittance spectra are in excellent agreement with the theoretical calculations. The results show that rapidly alternating deposition technology is an effective method to fabricate rugate filters.

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