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Investigation of defect modes with Al_2O_3 and TiO_2 in one-dimensional photonic crystals

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ABSTRACT

One-dimensional photonic crystal (1D PC) filters with one defect layer are investigated at visible frequencies both theoretically and experimentally. 1D PC filters containing one Al_2O_3 or TiO_2 defect layer are fabricated by pulsed laser deposition. The optical properties of the filters, including the transmittance and the resonance wavelength, are numerically calculated by using the transfer matrix method. Our results show that the defect layer with the lower refractive index is more suitable for the filters. Both blue- and red- shifts of the filter resonance are observed, depending on the thickness of the defect layer. We also find that the resonance may disappear as the number of periods in the filter increases (with the optical thickness of the defect layer fixed at 3/2 λ.

1. Introduction

Photonic crystals (PCs) are periodic optical structures that possess photonic band gaps within which the propagation of light is forbidden [1–3]. Due to their easy fabrication processes and optical properties similar to three-dimensional (3D) PCs under certain conditions, one-dimensional (1D) PCs have attracted considerable attention [4–9]. Interference filters, as one of the most important devices in optics, have been realized with either 1D discrete multilayer or gradient-index materials. By introducing defects into 1D PCs, single and multiple narrow-band-pass (multichannel) filters have been extensively investigated [10–14].

One of the most interesting aspects of 1D PC filters is the tunability of their resonances. Generally, the transmission of light through photonic crystals is affected by both the geometric and compositional parameters. Thus the resonance tuning may be achieved by manipulating, e.g., the optical thickness of the defect layer, the number of periods, and the permittivity or permeability of the constituent materials [15]. In addition to the resonance tunability, the channel multiplicity of the filters is also very useful in wavelength division multiplexing technology [16].

So far, various conventional film deposition techniques, such as the sol–gel method [4], electron beam evaporation [6] and glance angle deposition [17], have been employed to construct 1D PCs with a wide range of materials, e.g., TiO_2/SiO_2 [5] and GaAs/AlAs [18] for near IR and Na_3AlF_6/Ge for visible light [19]. However, to the best of our knowledge, the fabrication of 1D PC filters at visible frequencies with TiO_2/Al_2O_3 has been rarely reported.

In this paper we study the transmission spectra and the resonance tunability of 1D PC filters with a single defect layer of different materials and thicknesses. Our theoretical analysis is based on the transfer matrix method (TMM), and our experimental samples are fabricated by pulsed laser deposition (PLD). The experimental data agree well with the theoretical results.

2. Theoretical formulation

A typical ideal 1D PC (i.e., without defects) consists of periodically arranged units, each containing two quarter-wavelength dielectric layers of different refractive indices. For convenience, we denote the (finite) 1D PC as $(LH)^n$, where n is the number of units in the structure and L and H respectively represent the lower and higher refractive index layers in a unit. To construct a wavelength filter, we insert one defect layer (I) in the middle of the 1D PC to break the periodicity. Effectively, the original 1D PC $[(LH)^n]$ is divided into two identical Bragg mirrors $(LH)^{n/2}$ separated by the

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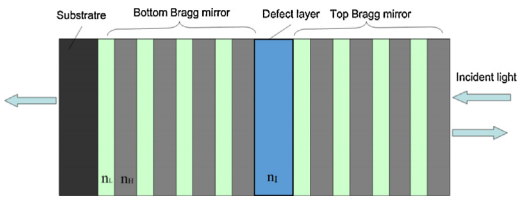

Fig. 1. Schematic of a 1D PC filter with a dielectric defect layer.

defect layer I. The optical properties of the resulting 1D PC filter can be controlled by the thickness of the insert layer.

A schematic of the 1D PC filter $(LH)^{n/2}I(LH)^{n/2}$ is depicted in Fig. 1. In this paper, we use d_i and n_i (i = L, H, I) to denote the thickness and refractive index of the layers, respectively, and the dielectric material for the defect layer is chosen to be either Al_2O_3 or TiO_2 layer.

The incoming light is assumed to be at normal incidence, i.e., with an incident angle $\theta \equiv 0°$. The transfer matrix [10,16,20] for the kth layer of the filter is given by

$$M_K = \begin{pmatrix} \cos\,\delta_k & i/\eta_k \sin\,\delta_k \\ i\eta_k \sin\,\delta_k & \cos\,\delta_k \end{pmatrix}, \tag{1}$$

with

$$\delta_k = \left(\frac{2\pi}{\lambda}\right) n_k d_k. \tag{2}$$

Here n_k and d_k are respectively the refractive index and the thickness of the kth layer, $\eta_k = n_k/\cos\theta_k$ for the TM polarization and $\eta_k = n_k/\cos\theta_k$ for the TE polarization. The total transfer matrix for the filter is obtained by multiplying the single-layer transfer matrices in proper order.

$$M = \prod_{k=1}^{n+1} M_K = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix}, \tag{3}$$

which in turn gives the reflectivity (r) and transmissivity (t), as well as the corresponding reflectance (R) and transmittance (T), of the filter

$$r = \frac{(M_{11} + M_{12}\eta_{n+2})\eta_o - (M_{21} + M_{22}\eta_{n+2})}{(M_{11} + M_{12}\eta_{n+2})\eta_o + (M_{21} + M_{22}\eta_{n+2})}, \tag{4}$$

$$t = \frac{2\eta_o}{(M_{11} + M_{12}\eta_{n+2})\eta_o + M_{21} + M_{22}\eta_{n+2}}. \tag{5}$$

$$T = |t|^2, \tag{6}$$

$$R = |r|^2. \tag{7}$$

Note that the first and the last layers are respectively the air and the glass substrate, and η_0 and η_{n+2} are the effective admittance of the corresponding media.

Based on the above equations, we numerically study the optical properties of the 1D PC filters $(LH)^{n/2}I(LH)^{n/2}$. In our simulations, we take the parameters (in accordance with our experimental data of monolayer oxide films) to be d_L = 83 nm, d_H = 50 nm, n = 8, and n_L = 1.44, n_H = 2.36 (at λ = 480 nm), and neglect the losses in the dielectric materials. The filter transmission spectra for two different defect layer materials (of identical optical thickness) are given in Fig. 2. One can see clearly that both filters have a photonic band-gap (PBG) within the same wavelength range from 400 nm to 600 nm. However, the resonant transmittance of the filters is different: with Al_2O_3 as the defect layer, the peak value of the resonance is 97.7%, while with TiO_2 it drops to 67.5%. This suggests that the lower refractive index material (Al_2O_3) is more suitable to be the defect layer of the filter.

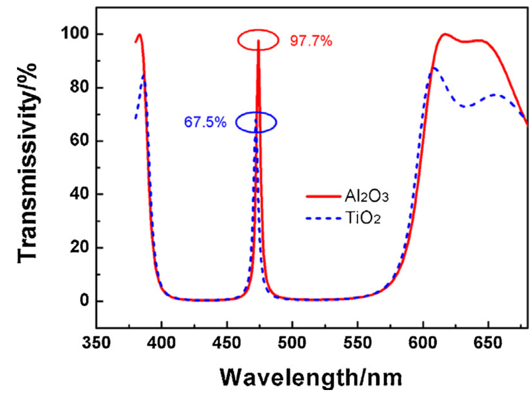

Fig. 2. Simulated transmission spectra of the filters $(LH)^4I(LH)^4$ with different defect layers I, where I is Al_2O_3 (red solid) or TiO_2 (blue dash).

The width of the resonance is an important performance factor of the filter, which can be improved by increasing the number (n) of periods in the 1D PC. Fig. 3 shows the transmission spectra of 1D PC filters with Al_2O_3 as the defect layer. Here the optical thickness of the defect layer is fixed at 1/4 λ while the number of periods varies between 6 and 10. Form the figure it is evident that as n increases, the filter resonance becomes narrower. This result allows us to choose the appropriate number of periods for the filter.

Next we analyze the effects of the thickness of the defect layer on the optical properties of the filter. In Fig. 4 we present the filter transmission spectra for various defect-layer optical thickness and two different numbers of periods (n = 8 and n = 10), with other parameters being the same as in Fig. 3. In Fig. 4(a), the number of periods is n = 8. With the optical thickness ($n_I d_I$) of the defect layer

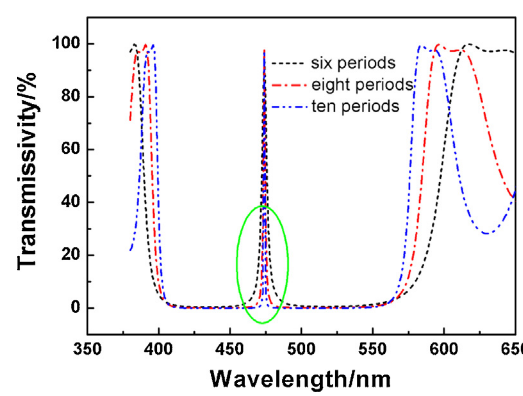

Fig. 3. Simulated transmission spectra of the filters $(LH)^{n/2}I(LH)^{n/2}$ with Al_2O_3 as the defect layer I, for period number n = 6, 8, 10.

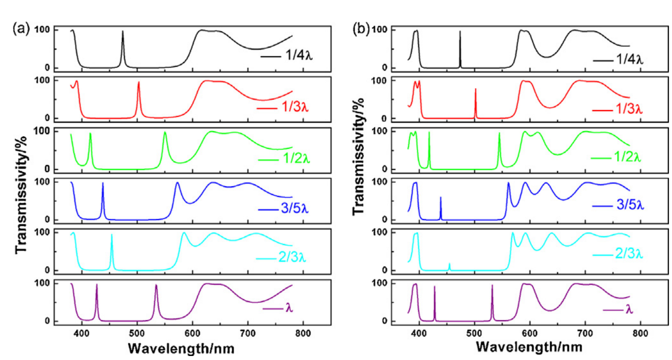

Fig. 4. Simulated transmission spectra of the filters $(LH)^{n/2}I(LH)^{n/2}$ with an Al_2O_3 defect layer of various optical thickness. The period number n is 8 in (a) and 12 in (b).

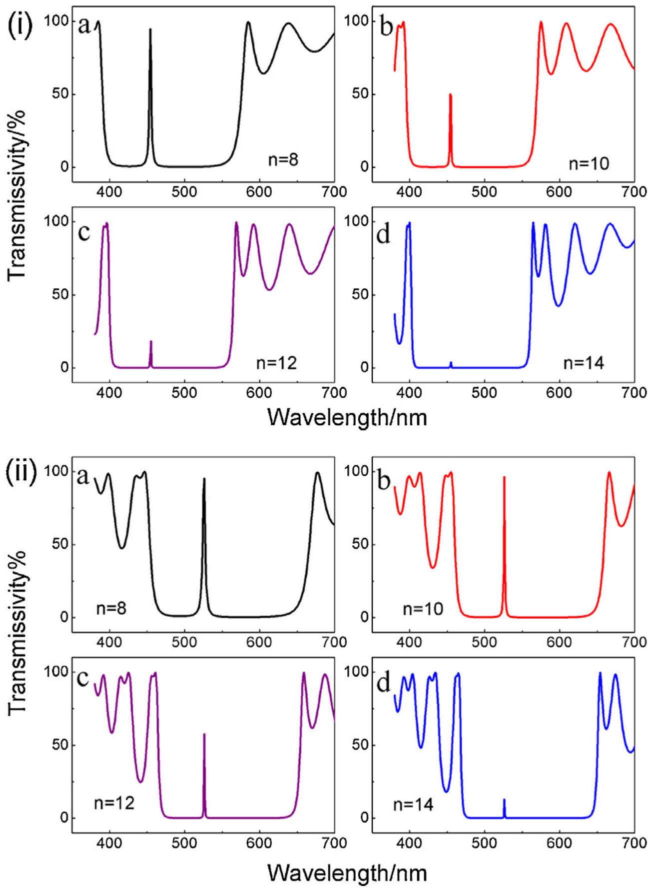

Fig. 5. Measured transmission spectra of the filters $(LH)^{n/2}I(LH)^{n/2}$ with an Al_2O_3 defect layer of 3/2 λ optical thickness, for various period number *n*. The reference wavelength λ is 480 nm in (i) and 550 nm in (ii).

increasing from λ/4 to λ/2, the filter resonance is red-shifted to the right. For $n_I d_I = \lambda/2 (d_I = 166\,nm)$, a second resonance emerges from the left band edge, leading to what we call a double-filter. As $n_I d_I$ further increases beyond λ/2, both resonances move to the right – the first one eventually disappears into the right band edge while the second one continues moving until, for $n_I d_I = \lambda (d_I = 332\,nm)$, another resonance emerges from the left band edge again. For $n = 12$ in Fig. 4(b) we find similar transmission resonance behaviors. Thus the resonant characteristics of the filter can be controlled by adjusting the optical thickness of the defect layer.

We note that in Fig. 4(b), for $n_I d_I = 2/3\ \lambda (d_I = 222\,nm)$, the resonance becomes very weak (almost vanishing). To further study the conditions for this "resonance disappearance" phenomenon, we numerically calculate the transmission spectra for filters with the period number *n* varying from 8 to 14, and present the results in Fig. 5. The optical thickness of the defect layer is fixed at 3/2 λ, and the reference wavelengths are 480 nm in (i) and 550 nm in (ii). It can be seen that the defect mode (resonance) within the forbidden gap is gradually weakened as *n* increases. The critical period number (at which the resonance vanishes) for the reference wavelength of 480 nm is larger than that for 550 nm. Therefore, we can control the transmittances of the filters by adding or removing dielectric layers on both sides.

3. Experiments and results

In our experiments, the samples were fabricated by pulsed laser deposition (PLD). The light source was a KrF excimer laser (Lambda Co., Germany), and the parameters for the light pulse were as follows: central wavelength = 248 nm, temporal width = 20 ns, repetition rate = 5 Hz, and single-pulse energy = 130 mJ. The vacuum equipment (with a vacuum degree up to 10^{-8}) was provided by the Instrument Company of the Shenyang Division of the Chinese Academy of Science. The transmission spectra of the samples were measured with a UV-VIS spectrophotometer (Hitachi Co., Japan, with slit width = 2 nm and rectangular beam spot at normal incidence). Two 1D PC samples with different defect materials, $(LH)^4L(LH)^4$ and $(LH)^4H(LH)^4$, were fabricated, where H and L are TiO_2 and Al_2O_3 layers (both of λ/4 optical thickness), respectively. The parameters of the layers are the same as those for the numerical simulations in the previous section: $d_L = 83\,nm$, $d_H = 50\,nm$, $n = 8$, $n_L = 1.44$ and $n_H = 2.36$ (at $\lambda = 480\,nm$).

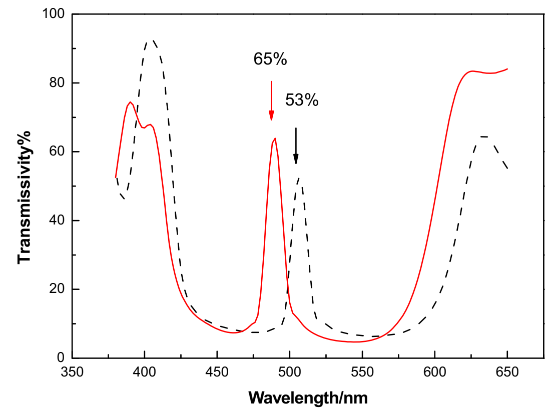

Fig. 6. Measured transmission spectra of the 1D PC structures of $(LH)^4I(LH)^4$ with different defect layers Al_2O_3 (red line) and TiO_2 (black dotted line).

Fig. 6 shows the measured transmission spectra of the above two 1D PC filters, with Al_2O_3 (lower refractive index) and TiO_2 (higher refractive index) as the defect layers, respectively. With Al_2O_3 as the defect layer, the center wavelength and the peak transmissivity of the filter resonance are 483 nm and 65%, while with TiO_2 these values are 500 nm and 53%. Thus the lower-refractive-index defect layer Al_2O_3 leads to better filter performance, i.e., higher resonance transmittance. We note that the discrepancy between the measured (Fig. 5) and the calculated (Fig. 4) results is due to the absorption of the glass substrate and the drawback of the dielectric layers.

4. Conclusion

We have fabricated 1D PC filters with one Al_2O_3 or TiO_2 defect layer and studied their optical properties both theoretically and experimentally. Our numerical simulations show that the lower refractive index defect layer Al_2O_3 leads to a stronger transmission resonance, and thus is more suitable for the filter. This result was verified by our experiment. We also analyzed other resonant features of the filter by adjusting the number of periods, the thickness of the defect layer and the reference wavelength. The filter resonance is gradually shifted toward longer wavelength as the thickness of the defect layer increases. Keeping the optical thickness of the defect layer at 3/2 λ, we found that, as the number of periods increases, the filter resonance becomes weaker and eventually vanishes. The critical period number (at which the resonance vanishes) is larger for longer reference wavelength.

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