

## Integration and Evaluation of Multichannel Photonic Crystal Wavelength Filters Consisting of Autocloned Ta<sub>2</sub>O<sub>5</sub>/SiO<sub>2</sub> Multilayer Thin Films

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We report on the fabrication of multichannel photonic crystal (PC) wavelength filters and their evaluation at wavelength division multiplexing (WDM) wavelengths. The devices utilize three-dimensional (3D) PCs consisting of Ta<sub>2</sub>O<sub>5</sub>/SiO<sub>2</sub> multilayer thin films fabricated by the autocloning method. The 3D PCs serve as Bragg mirrors in the devices and finite-difference time-domain (FDTD) simulations of these mirrors revealed that their Bragg wavelength shifted by +19.8 nm as the in-plane lattice constant of the crystal increased from 400 nm to 800 nm. We fabricated these filters with a Ta<sub>2</sub>O<sub>5</sub> cavity and obtained a wavelength shift of +24.0 nm. [DOI: 10.1143/JJAP.42.L1219]

KEYWORDS: photonic crystal, wavelength filter, WDM, Ta<sub>2</sub>O<sub>5</sub>/SiO<sub>2</sub>, autocloning, Bragg mirror, multichannel, Ta<sub>2</sub>O<sub>5</sub> cavity

Many kinds of wavelength filtering elements have been developed for the present and future WDM systems. These elements whose transmission wavelength varies according to the incident point of light are indispensable in some kinds of wavelength-selective filters, such as those using the change in refractive index or film thickness.

However, most of the elements reported so far have an almost linear and continuous wavelength shift with respect to the incident position,<sup>1)</sup> which limits their scope of application. In developing tunable filters with a wide-range wavelength from 1.31 μm to 1.55 μm, a large refractive index change or extended film thickness is necessary to tune the wavelength. This paper describes the fabrication and evaluation of multichannel wavelength filters that have multilayer thin films in multiple regions with different transmission characteristics on a substrate. The transmission wavelength can be altered without making a large change in refractive index or film thickness. The multichannel wavelength filters utilize 3D PCs as Bragg mirrors, and are fabricated by an autocloning method.<sup>2)</sup>

In our previous work,<sup>3)</sup> a Si/SiO<sub>2</sub> material system for PC filters was utilized and its fundamental band-pass function, in which the transmitted wavelength of the filters shifted by 30 nm as the in-plane lattice constant of the PC increased from 300 nm to 500 nm, was demonstrated. Although Si/SiO<sub>2</sub> is an attractive combination at near-infrared wavelengths by virtue of its large refractive index contrast, in the present work, we chose Ta<sub>2</sub>O<sub>5</sub> as the high refractive index layer for practical reasons. This is because Ta<sub>2</sub>O<sub>5</sub> is believed to be more stable than Si for long-term use when applied to actual WDM systems.

Figures 1(a) and 1(b) show the schematic diagram of the surface lattice geometry of the substrate and the schematic diagram of our PC wavelength filter, respectively. The device has a Fabry-Perot structure in which the autocloned PC serves as a Bragg mirror. The Bragg wavelength of the mirror depends not only on the film thickness of each layer but also on the in-plane periodicity which is a function of  $x$  and  $y$  (Fig. 1(a)). Therefore, by preparing multiple regions with different in-plane periodicities on a substrate, as shown in Fig. 1(a), and by stacking PCs onto it, multiple filter regions with different transmission wavelengths can be fabricated in a single deposition process. For optical measurement, light from an super luminescent diode (SLD) was directed

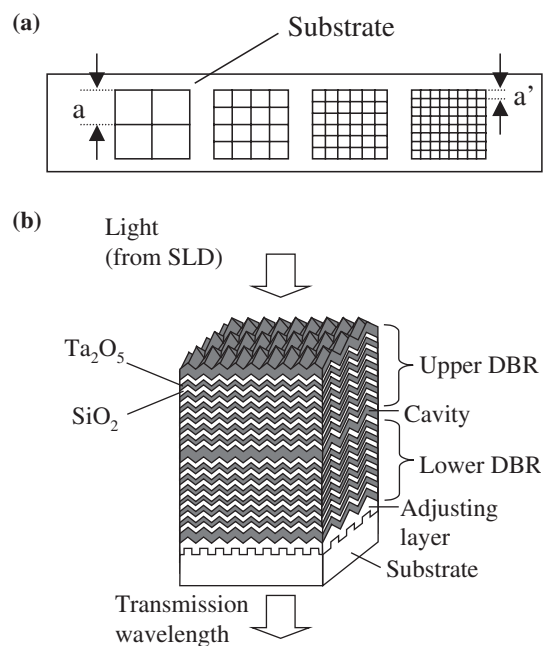


Fig. 1. Schematic diagram of (a) Lattice geometry on substrate and (b) PC wavelength filter. Corrugated multilayer is formed by bias sputtering process (autocloning method).

perpendicularly into the sample, as shown in Fig. 1(b).

First, we designed the stopband wavelength ranges of the Ta<sub>2</sub>O<sub>5</sub>/SiO<sub>2</sub> PC mirrors by calculating the photonic dispersion relation of an infinite PC using the three-dimensional FDTD method.<sup>4)</sup> Figure 2(a) shows the unit cell of a typical autocloned 3D PC with various in-plane lattice constants ( $a$ ). The thicknesses of SiO<sub>2</sub> and Ta<sub>2</sub>O<sub>5</sub> were fixed at 260 nm and 186 nm so that their Bragg wavelength was approximately 1560 nm. We assumed that the slope of the layer was constant (40 degrees) irrespective of  $a$ , which resulted from the inherent nature of the autocloning method used.<sup>5)</sup> Figure 2(b) shows the photonic band structures of a 3D PC with various in-plane lattice constants ( $a$ ) calculated by the FDTD method. The first photonic bandgap in the  $\Gamma$ -Z direction becomes narrower as  $a$  increases from 200 nm to 800 nm. Figure 2(c) shows the relation between in-plane lattice constant and wavelength, where the center and edge wavelengths of the first photonic bandgap are functions of  $a$ . The

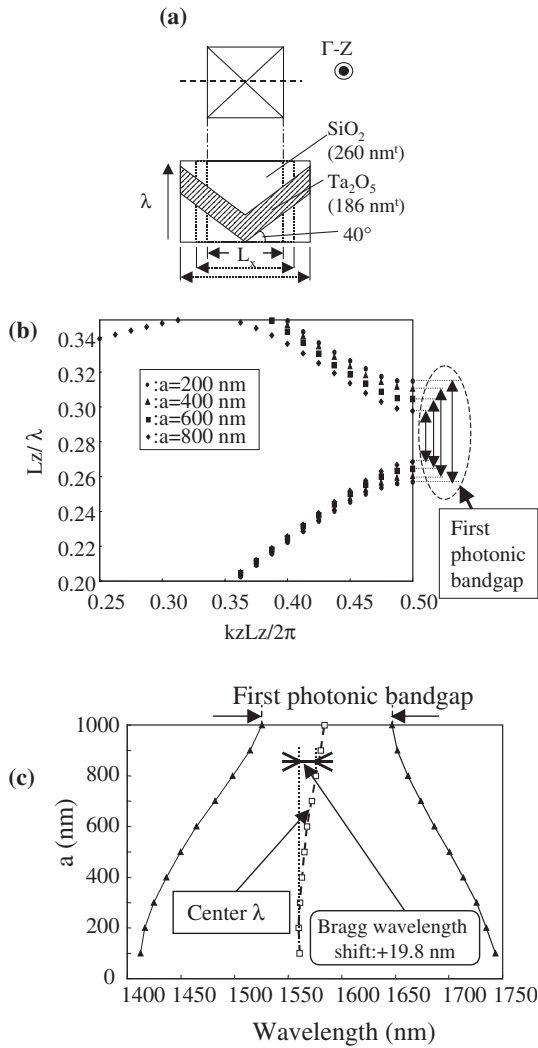


Fig. 2. Characteristics of Bragg mirrors consisting of 3D autocloned PCs. (a) Structure of unit cell of autocloned PC (3D simple cubic lattice). Upper: top view, lower: cross section. (b) Photonic band structures of 3D PC with various in-plane lattice constants ( $a$ ) calculated by the FDTD method. (c) Relation between in-plane lattice constant and Bragg wavelength. Broken line denotes estimated operating wavelength of fabricated filter.

center wavelength increases by +19.8 nm as  $a$  increases from 200 nm to 800 nm.

We fabricated the Ta<sub>2</sub>O<sub>5</sub>/SiO<sub>2</sub> type PC filters according to this design. We first formed arrays of holes in a square-lattice configuration on a fused silica substrate by electron-beam lithography and dry etching. The lattice constants were 400, 600, and 800 nm. We then deposited Ta<sub>2</sub>O<sub>5</sub>/SiO<sub>2</sub> multilayer thin films on the patterned substrate by bias sputtering with an appropriate balance of sputter deposition and sputter etching, i.e., the autocloning method.

Figure 3 shows the cross-sectional scanning electron microscope (SEM) image of the fabricated sample. The bright layers correspond to Ta<sub>2</sub>O<sub>5</sub> and the dark layers to SiO<sub>2</sub>. A  $\lambda/4$ -shifted Ta<sub>2</sub>O<sub>5</sub> cavity layer is sandwiched by 6.5 pairs of Ta<sub>2</sub>O<sub>5</sub>/SiO<sub>2</sub> PC Bragg mirrors. A SiO<sub>2</sub> adjusting layer of 500 nm in thickness has been inserted between the substrate and the first Ta<sub>2</sub>O<sub>5</sub> layer to smoothly connect the square-like surface corrugation of the substrate to the triangular pattern of the autocloning layer.<sup>6)</sup> The boundary between the adjusting layer and the substrate has no effect on

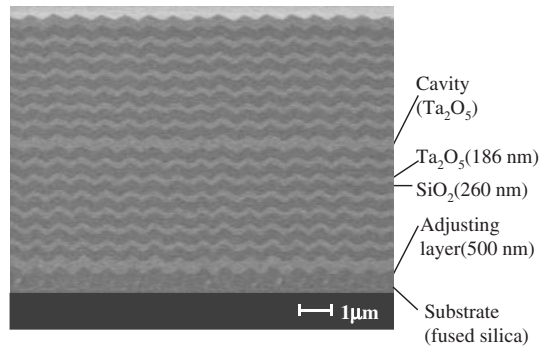


Fig. 3. Cross-sectional SEM image of Ta<sub>2</sub>O<sub>5</sub>/SiO<sub>2</sub> PC wavelength filter. In-plane lattice constant:  $a = 600$  nm.

the light because their refractive indices are equal. As can be seen, the stable corrugation is perfectly preserved from the bottom to the top of the multilayer. The in-plane lattice constant ( $a$ ) of these sections is 600 nm. Although the range of sputtering parameters for fabricating autocloned 3D PC is not very wide, we found a fabrication condition for obtaining autocloned PCs that had a good shape.

Figure 4(a) shows the results of the optical measurement of filters with a Ta<sub>2</sub>O<sub>5</sub> cavity. As can be seen, we achieved an insertion loss of less than 1.0 dB at each transmission wavelength. Many small ripples are caused by the multiple reflections of light between the top and bottom surface of the substrate. The total wavelength shift is +24.0 nm, which is larger than that calculated by FDTD simulation (+19.8 nm). This difference is due to the thickness of the Ta<sub>2</sub>O<sub>5</sub> cavity in the fabricated sample being slightly shorter than  $\lambda_B/2n$ , where  $n$  is the refractive index of the Ta<sub>2</sub>O<sub>5</sub> and  $\lambda_B$  is the

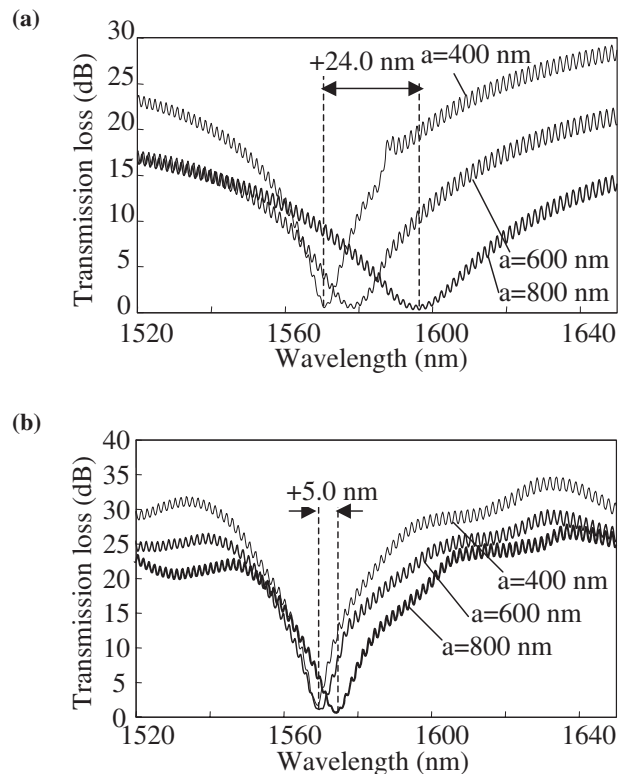


Fig. 4. Measured transmission spectra of PC filters. (a) Ta<sub>2</sub>O<sub>5</sub> cavity type and (b) SiO<sub>2</sub> cavity type.

Bragg wavelength of the mirror. The operating wavelength (broken line in Fig. 2(c)) of the fabricated sample has therefore shifted to the shorter side from the Bragg wavelength of the PC mirror. As a result, the wavelength shift we observed was larger than the design value.

To evaluate the effect of the cavity's refractive index, we also fabricated similar PC filters with a SiO<sub>2</sub> cavity. The lattice constants and the periods of the mirrors were the same as those of the previous Ta<sub>2</sub>O<sub>5</sub> cavity. Figure 4(b) shows the measured transmission spectra. The total wavelength shift is +5.0 nm, which is significantly smaller than that for the Ta<sub>2</sub>O<sub>5</sub> cavity type. This suggests that the use of a material with a higher refractive index for the cavity is advantageous for this type of filter to obtain a large wavelength shift. The reason for these wavelength shifts is as follows. It can be recognized from Fig. 2(c) that the first photonic bandgap becomes narrower and both the edge wavelength of the bandgap shifts somewhat to longer wavelength, as the in-plane lattice constant of the PC filter increases. Moreover, the broken line of the center wavelength in Fig. 2(c), which is converted from the average frequency of the edge wavelengths, leans somewhat to longer wavelength, accompanied with the increase of in-plane lattice constant. This results in the increase in transmission wavelength as the in-plane lattice constant increase.

In summary, we fabricated Ta<sub>2</sub>O<sub>5</sub>/SiO<sub>2</sub> photonic crystal multichannel wavelength filters and verified their operation. A net wavelength shift of +24.0 nm was achieved.

These filters we reported had a Fabry-Perot structure, so that they basically had the same characteristics as conventional multilayer thin film wavelength filters. As the total number of thin film layers or the number of cavity layers is increased, the quality factor of the filter becomes larger or the spectrum of the filter becomes boxlike. The tailoring of transmission spectra, as we mentioned above, and the deposition of anti-reflection coatings will be carried out in a future study.

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