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Multichannel Photonic Crystal Wavelength Filter Array for Near-Infrared Wavelengths

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***Abstract*—Multichannel wavelength filters consisting of 2-D photonic crystal (PhC) for the near-infrared wavelength region ($\sim$800 nm) are demonstrated. The filter is a thin-film wavy multilayer structure and is fabricated by the autocloning method, which is based on a radio frequency bias sputtering process. Twelve long-pass-type filter regions are integrated on a common silica substrate. Sharp cutoff characteristics and almost equal channel spacing are experimentally verified. To precisely control the effective lattice constant of PhC, a modulated lattice structure on the substrate is utilized.**

***Index Terms*—Autocloning, lattice modulation, photonic band gap (PBG), photonic crystal (PhC), wavelength filter.**

I. Introduction

MULTISPECTRAL imaging is a class of spectroscopic methods that visualize the 2-D distribution of a space-mixed state of target objects with different optical absorption/radiation spectra. Information about the content of constituent media is extracted by the data processing of the wavelength-resolved image acquired by photographing them through multiple optical filters. With the advancement of image sensors, such imaging technologies, especially those in near-infrared (IR) wavelengths, have become important in various fields of research and industry such as medical engineering (mapping of hemoglobin and melanin density on human skin [1], endoscopic tissue observation [2]), plasma science (visualization of the dynamic behavior of the plasma [3]), and remote sensing (land cover classification by reflection spectra [4]).

Multichannel optical filters and image sensors are the basic building blocks of such an imaging system. To detect slight differences in the reflection or radiation spectrum of the object, or to measure the exact feature of the spectra, several wavelength-selective filters with different characteristics are sometimes needed. For some applications, the transmission spectra of individual wavelength channels need to be contiguous within the wavelength band of interest [4].

The ability to integrate such multiple filters on a common substrate by a single manufacturing process has much merit from an industrial viewpoint as such a structure is easily assembled with image sensors and other optical elements and, thus, helps downsize the whole system.

One way to create such a multichanneled optical filter array is to make use of the photonic crystal (PhC) structure fabricated by the autocloning method [5].

Autocloning is a method for fabricating a multilayered-type PhC and is based on lithography and sputtering [6]. First, a 1-D or 2-D array of corrugations is prepared on a substrate by lithography and dry etching. Next, by stacking multiple dielectric films on it by RF bias sputtering, a structure having refractive index modulation in both horizontal and vertical directions is obtained. According to this method, by changing the period of corrugation (in-plane lattice constant) on the initial substrate from position to position, it is possible to fabricate multiple PhC regions with different horizontal lattice structures and common vertical index profiles by a single sputtering process.

We have so far demonstrated several surface-normal-type optical components, including wavelength filters for fiber-optic communication systems by making use of this method [7], [8]. The basic characteristics of autocloning-type PhC wavelength filters are mainly determined by the thickness and refractive index of the multilayer. In addition, transmission or reflection spectra are slightly shifted from those of an ordinary flat multilayer due to the in-plane corrugation. Therefore, by utilizing the above property, parallel integration of various filter regions with different transmission spectra on one substrate is possible.

The multichannel filters we have so far proposed were for the 1550-nm wavelength region [5]. They were Fabry–Pérot-type bandpass filters utilizing the first photonic band gap (PBG) of light propagating in the thickness direction.

The aim of this paper is to demonstrate autocloning-type PhC filters for shorter wavelength range, especially for near IR ($\sim$800 nm). Another purpose of this paper is to propose a structure whose spectrum is more sensitive to the horizontal shape of PhC.

The key points of this paper are as follows.

1) Nb_2O_5 and SiO_2 are chosen as film material. (In our previous work, we used Ta_2O_5/SiO_2 [5].)
2) We use the upper band edge of the second photonic band. The waves on the band are more sensitive to the in-plane layer shape as it is a coupled state of the vertically and horizontally propagating waves.
3) Long-pass filter characteristics are designed.
4) The in-plane lattice constant of the final PhC with resolution smaller than that of electron beam (EB) lithography is controlled by the modulated lattice technique.
5) Twelve channel filters are integrated on one substrate.

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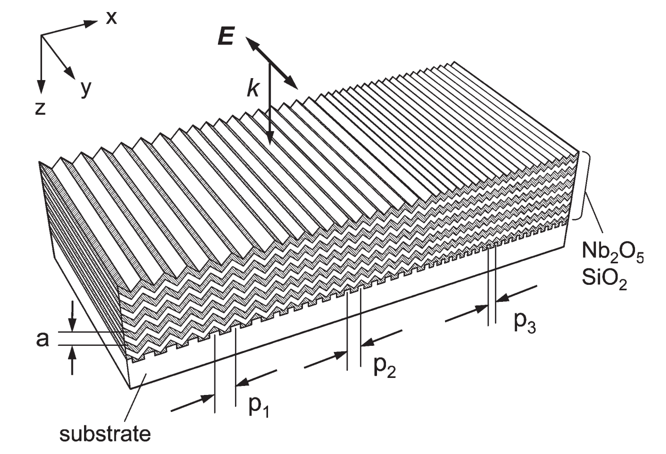

Fig. 1. Schematic view of an array of wavelength filters consisting of 2-D autocloning-type PhC. The refractive index is modulated in the x- and z-directions.

II. Principle of Operation

Fig. 1 shows a schematic view of the PhC filter. It consists of a wavy multilayer on a substrate with a periodic array of grooves and has 2-D modulation of the refractive index in the $x-z$ plane. Light is incident along the z-axis. The global feature of the transmission spectrum is governed by the index profile along the z-axis, while its detail is influenced by the in-plane lattice constant (p).

Polarization-independent operation is possible by making the initial lattice geometry square or triangular. However, in this paper, we employ a polarization-sensitive structure, as shown in the figure, as such 2-D PhCs have a wider PBG and larger spectral shift with respect to p than 3-D structures of square or triangular in-plane geometry. In practice, an additional polarizer has to be used to eliminate the unwanted polarization component for the filter.

Fig. 2(a) shows the dispersion relation of light in the infinitely lying periodic structure. The horizontal axis denotes the length of the z component (normal to the layer) of the Bloch wave vector. In this paper, we used the frequency range around the upper edge of the second band, as indicated by "A" in the figure. Fig. 2(b) shows the dispersion relation of a similar spatial lattice with zero index difference (vacant lattice). The band "B" has a wave vector expressed as

$$\boldsymbol{k} = \boldsymbol{G}_x \hat{\boldsymbol{x}} + k_z \hat{\boldsymbol{z}} \tag{1}$$

where $\boldsymbol{G}_x = 2\pi/p$ is the norm of the reciprocal lattice vector along the x-axis, k_z is the z component of the wave vector, and $\hat{\boldsymbol{x}}$ and $\hat{\boldsymbol{z}}$ are the unit vectors along each direction. The amplitude of the mode "B" oscillates along the x-axis with the same period as the space lattice. The C_1 and C_2 portions in Fig. 2(a), which inherit the nature of B, are also vibrating along the x-axis and therefore exhibit large frequency shift with respect to the lattice constant along the x-axis.

On the other hand, modes D and E in Fig. 2(b) denote the waves simply propagating in the z-direction. The electromagnetic fields of these modes are constant along the x-axis. Therefore, the field modulations of modes F and G in Fig. 2(a), which arise from D and E, are relatively small. This leads to the small dependence of their frequency upon the in-plane lattice constant.

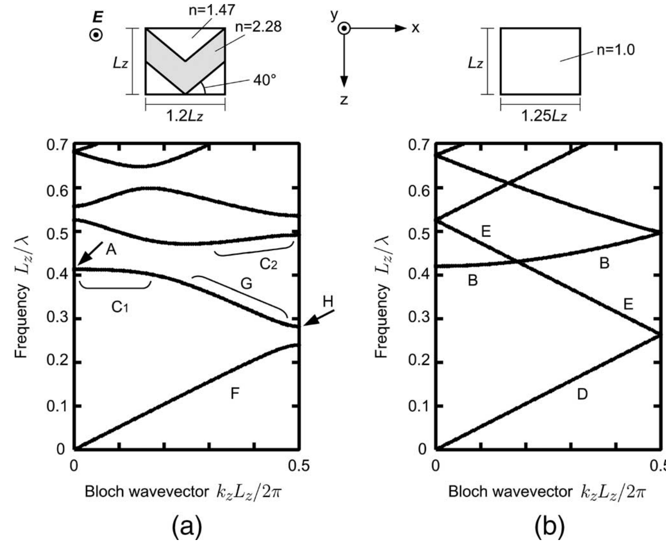

Fig. 2. Calculated dispersion relation of light. (a) TE waves (electric field parallel to the grooves) in a 2-D autocloning-type PhC. Only even symmetric modes are shown. (b) Waves in a vacant lattice (vanishing index difference). A: Operating point. Upper edge of the second photonic band. B: Laterally propagating mode. C_1, C_2: Modes with laterally vibrating fields. D and E: Modes propagating in the z-direction. F and G: Almost vertically propagating mode. H: Lower edge of the second band.

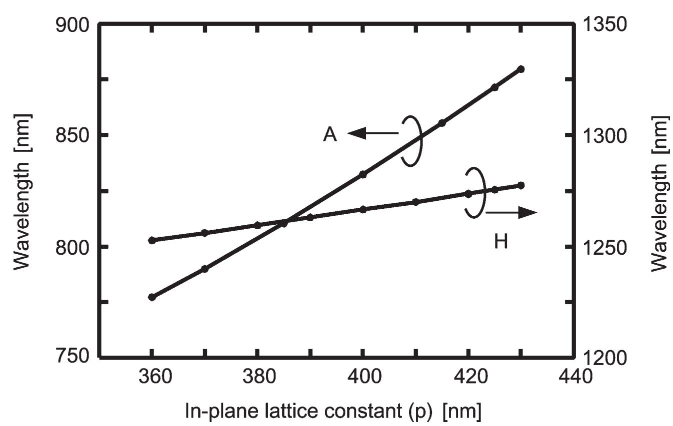

Fig. 3. Calculated relation between wavelength and in-plane lattice constant of the lower (H) and upper (A) edge of the second photonic band for the typical autocloning-type PhC structure. Layer profile is Nb_2O_5 ($n = 2.28$, $d = 180$ nm) / SiO_2 ($n = 1.47$, $d = 180$ nm).

Fig. 3 shows a calculated relation between p and the wavelength of the upper and lower edge of the second band (indicated by H and A in Fig. 2, respectively) for a typical autocloning structure. As can be seen, the band edge "A" (present design) is about four times more sensitive to p than the band edge "H" (previous study [5]).

Fig. 4 shows an example of the calculation of the dispersion relation around the upper edge of the second band for PhCs with common layer thickness and different in-plane lattice constant. The horizontal and vertical axes denote the wavelength and wavenumber, respectively. The thickness of Nb_2O_5 and SiO_2 films are both 180 nm, and the slope of the wavy film interfaces is 45°. According to this lattice design, multichannel

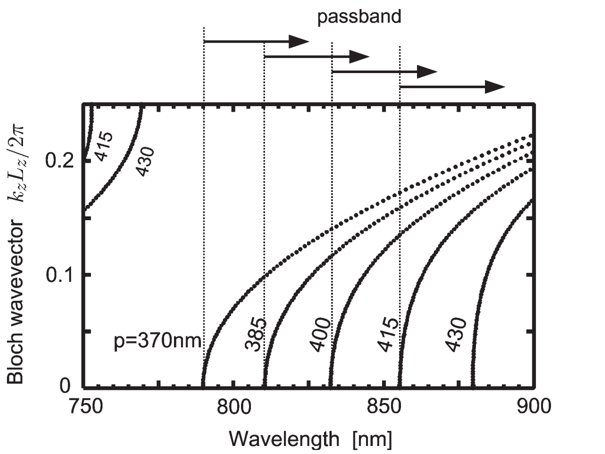

Fig. 4. Calculated relation between the z component of the Bloch wave vector and wavelength for various in-plane lattice constants. Layer profile is the same as the calculation in Fig. 3.

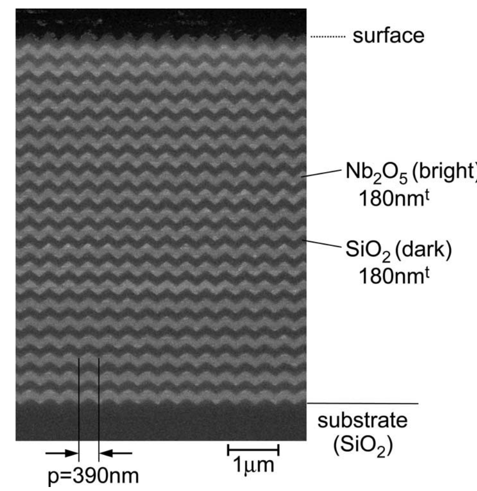

Fig. 6. Cross-sectional picture of a filter with $p = 370$ nm. Dark and bright layers correspond to SiO_2 and Nb_2O_5, respectively.

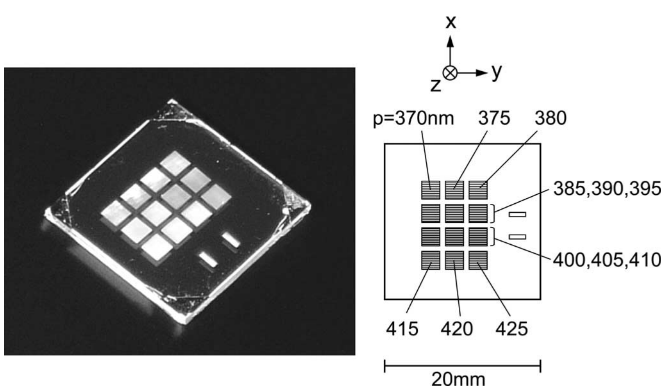

Fig. 5. Picture of the 12-channel PhC wavelength filter.

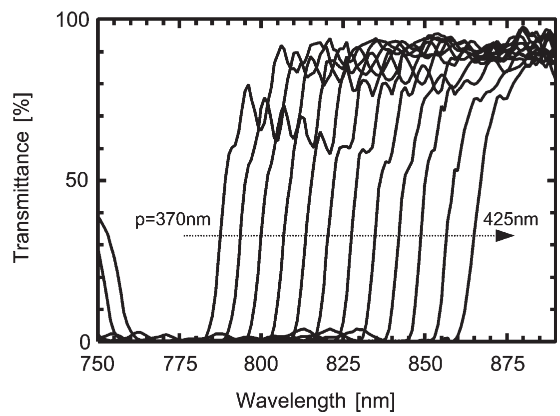

Fig. 7. Measured transmission spectra for each channel of the filter. Long-wave pass characteristics with almost equal spacing are obtained.

long-pass filters with cutoff wavelength spacing of about 7 nm are possible.

Note that by appropriately selecting the film materials and lattice constant, we can design a variety of filters with operation wavelength ranging from blue to short-wave IR. However, in this study, we begin with the demonstration of the filters for near IR (700–900 nm), as such wavelengths have become more important in various multispectral imaging purposes, as mentioned in Section I.

III. Fabrication and Evaluation

The photoresist for EB lithography (ZEP-520A, ZEON Co. Ltd.) was spin coated on a silica substrate. The line and space patterns of the period of about 400 nm are written on it by an EB lithography system (type CABL-8000, CRESTEC Co., Ltd.). Then, the substrate was dry etched through the photoresist by reactive ion etching. Finally, an alternating multilayer of 20 periods (40 layers in total) consisting of Nb_2O_5 ($n = 2.28$, $d = 180$ nm) and SiO_2 ($n = 1.47$, $d = 180$ nm) was deposited by RF bias sputtering. The plan view and cross section of the PhC are shown in Figs. 5 and 6, respectively. In this experiment, 12 square filter regions of 2.3 × 2.3 mm were formed. In-plane lattice constants ranged from 370 to 425 nm at intervals of 5 nm.

To control the lattice constant of the final PhC with resolution higher than that of EB scanning, we modulated the individual groove spacing on the initial substrate. For example, to fabricate a PhC region of $p = 375$ nm with minimum EB resolution of 10 nm, a line and space pattern of the period of 370 and 380 nm are placed alternately. Such microscopic structural fluctuation in the horizontal direction is smoothened as the bias sputtering proceeds, and as a result, a PhC having average lattice constant is produced. In this technique, we utilize the self-healing effect of the autocloning process [9], which automatically restores structural defects smaller than the lattice constant.

Fig. 7 shows the measured transmission spectra of each filter region for TE waves (electric field parallel to the grooves). As predicted by the dispersion calculation, cutoff wavelengths are almost equally spaced by 7.1 nm. The spectra of the modulated lattice regions ($p = 375, 385, 395$ nm, etc.) are as sharp as those of the nonmodulated ones ($p = 370, 380$ nm, etc.), which indicates that the former regions can be practically regarded as uniform PhC. Note that the ripples around the right side of the cutoff wavelength are caused by the multiple reflections between the surfaces of the multilayer and can be suppressed by inserting antireflection (AR) layers near the surfaces, as described in the following section.

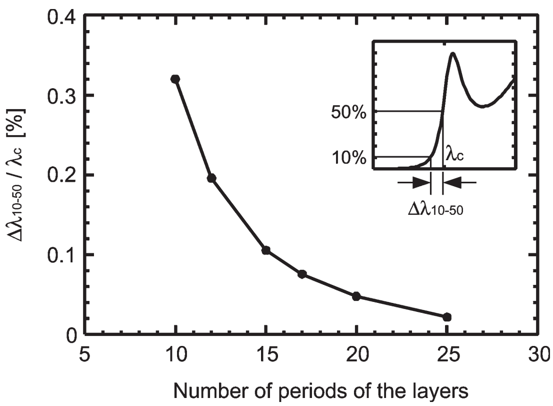

Fig. 8. Calculated relation between the sharpness of the cutoff and the number of periods of the multilayer. The horizontal pitch (p) is 370 nm. The vertical axis represents the ratio of the wavelength range from 10% to 50% of the maximum transmittance ($\Delta\lambda_{10-50}$) to the average cutoff wavelength (λ_c).

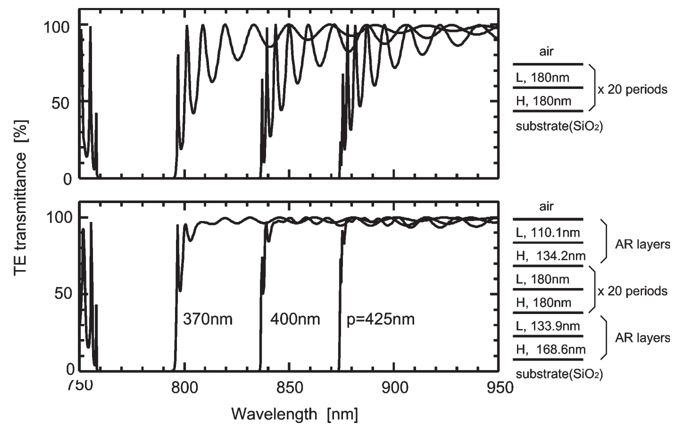

Fig. 9. Example of the calculation for AR coatings. Upper figure: Without AR layers. Lower figure: With AR layers consisting of two films on both air and substrate sides. "H" and "L" denote Nb_2O_5 ($n = 2.28$) and SiO_2 ($n = 1.47$), respectively.

IV. Discussion

In our filters, spectral selectivity (the sharpness of the spectral cutoff characteristics) can be adjusted by changing the number of multilayers. This is simply because the dependence of the feature of the spectrum near the cutoff wavelength of our 2-D structure upon the number of layers is basically similar to that of conventional flat multilayer. Fig. 8 displays the calculated relation between the number of periods and the "sharpness" of the cutoff, i.e., the wavelength range between 10% and 50% of the maximum transmittance for a typical lattice constant. On the other hand, the maximum transmittance in the passband can be raised over 90% as the films have almost no absorption. Therefore, if the number of layers is increased, the cutoff becomes sharper, while the maximum transmittance is almost kept constant. So, basically, the selectivity can be designed independently from the maximum transmittance.

Finally, we would like to discuss the possibility of AR coatings to reduce the ripples near the cutoff wavelength. As the ripples arise from the difference between the effective refractive index of the air, substrate, and multilayer, it can be reduced by properly inserting AR layers into the interface between the air and the top surface of the multilayer and the interface between the substrate and the bottom surface of the layer. The AR layers may consist of the same film materials as the main multilayers. Fig. 9 shows an example of the calculation for an AR coating. This example design was found by repeating finite-difference time-domain calculation and searching the optimum film thickness of the AR layers that gives the most flat transmission in the given wavelength range in the passband. Although it is difficult to perfectly eliminate ripples from all the filter channels as the effective index (slope of the dispersion curve) of each 2-D structure is not exactly the same, the improvement of the flatness of the total transmission is possible, as can be seen in the figure. It might be possible to establish designing rules for AR coatings on our 2-D structures by utilizing conventional theories such as impedance matching. It will be conducted in our future work.

V. Conclusion

We designed multichannel PhC wavelength filters for the near-IR band ($\sim$800 nm) and verified their operation through fabrication by the autocloning method. In the experiment, 12 long-pass-type filter regions with cutoff wavelength intervals of about 7.1 nm were integrated on a common silica substrate. To precisely control the effective in-plane lattice constant of the final PhC, a modulated lattice structure on a substrate was utilized. In a future study, we will reduce the reflection near the cutoff wavelength and apply this component to multispectral imaging.

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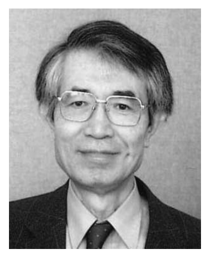

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