# Reduction of Propagation Loss to 0.1 dB/mm: Flat-Core Channel Waveguides Consisting of Periodic Structures

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***Abstract*—We successfully fabricated channel waveguides utilizing photonic crystal (PhC) dispersion having a very low loss of ∼0.1 dB/mm by the autocloning method. We achieved the loss reduction by improving the fabrication condition and adjusting the core width. The result of propagation loss can be regarded as a "milestone," and it enables us to realize practical PhC circuits that contain functional components such as chromatic dispersion equalizers and high $Q$ wavelength filters.**

***Index Terms*—Autocloning, optical waveguide, optical wiring, photonic crystal (PhC), propagation loss.**

## I. INTRODUCTION

PHOTONIC crystals (PhCs) have attractive properties such as wide photonic bandgap produced by strong multiple reflection of light and large chromatic dispersion around the band edges, which conventional silica planar waveguides do not have. Therefore, PhC are regarded as one of the most promising candidates for highly functional optical integrated circuits of the next generation.

Among a number of fabrication methods for PhC components so far proposed [1]–[3], the autocloning method [4] is one of the most suitable for industrial applications. By using the autocloning process, one can fabricate PhCs consisting of a number of crystal regions with various lattice constants, lattice orientations, etc., by a single film-deposition process [5]. With the help of such "heterostructure," various functional components as well as wiring waveguides can be created monolithically. We have so far developed in-line PhC resonators, as shown in Fig. 1, and demonstrated their wavelength filtering operation at $\lambda = 1.55\ \mu$m range [5]. These types of inline PhC devices usually consist of Bragg-reflection parts [Fig. 1(a)] as mirrors or delay elements, and passband parts as cavities [Fig. 1(b)] or wiring elements [Fig. 1(c)]. Although the latter parts do not need PhC to have photonic bandgap, they are indispensable to practical PhC circuits. For the past few years, we have developed straight and bent waveguides as a wiring element for this purpose by using Si–$SiO_2$ [6] and $Ta_2O_5$–$SiO_2$ [5], [7] material systems. Particularly, in the latter $Ta_2O_5$–$SiO_2$ material system, we reported the propagation loss of 0.56 dB/mm at $\lambda = 1.55\ \mu$m by utilizing flat-surface core structure [8].

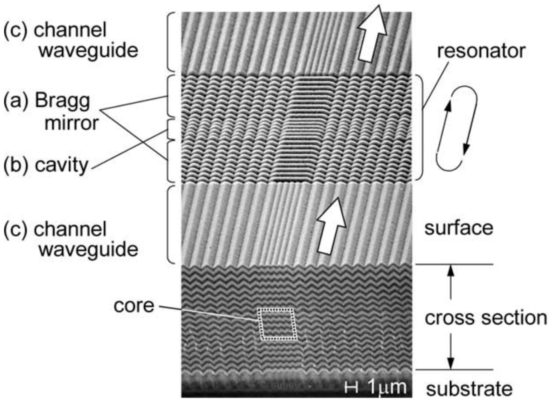

Fig. 1. SEM picture of an in-line resonator fabricated by the autocloning method [8]. The device consists of heterostructured PhC. The regions (a), (b), and (c) function as Bragg reflectors, a cavity, and connecting waveguides, respectively. Bright and dark layers correspond to $Ta_2O_5$ and $SiO_2$, respectively.

In this study, we successfully reduced the propagation loss of the wiring waveguides with the similar flat-surface core structure to the order of 0.1 dB/mm. Such reduction is achieved mainly by adjusting the core width and by optimizing the fabrication condition of the autocloning process.

## II. DESIGN OF CHANNEL WAVEGUIDE

Fig. 2 shows a schematic view of the waveguide. We first demonstrated the light propagation in the similar heterostructured waveguide structure in 2001 [7]. The waveguide has nine different regions in its cross section. The multilayer consists of $Ta_2O_5$ ($n = 2.1$) and $SiO_2$ ($n = 1.5$). Dispersion relation of light in the periodic structure determines the effective refractive index $n_{\text{eff}}$ ($n_{\text{eff}} = k_z/k_0$, where $k_z$ is the wave-number along $z$ and $k_0$ is the wave-number in vacuum) of each region. We designed the in-plane pitch and the thickness of the layers so that the horizontally polarized light (i.e., electric field is parallel to the substrate) at $\lambda = 1.55\ \mu$m is confined in a finite region by the difference of the effective refractive index. Note that our waveguide is an integrated optics analogue of holey fibers [9], as it

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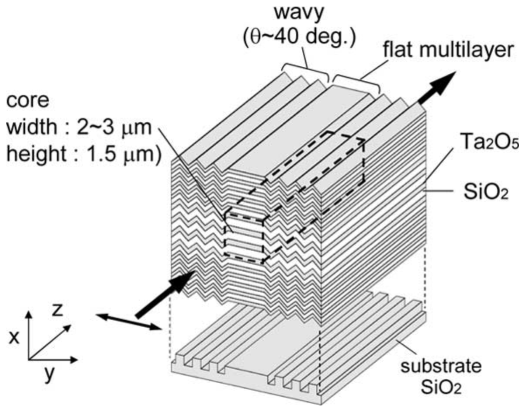

Fig. 2. Schematic illustration and the designed structural parameters of the channel waveguide.

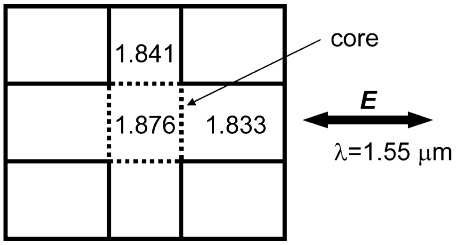

Fig. 3. Effective refractive-index distribution in the cross section of the waveguide for the horizontally polarized light at $\lambda = 1.55\ \mu$m.

is index-guiding one and does not have longitudinal periodicity. Fig. 3 shows the effective index profile in the cross section. In the horizontal direction, the flat region acts as a core, while the wavy regions with an in-plane pitch of 1.1 $\mu$m act as cladding. In the vertical direction, the core and the cladding layers have lattice constants of 0.73 and 0.41 $\mu$m, respectively. Light is confined in the center region of the cross section and propagates along the $z$ direction. In this kind of structure, we have made use of the effect that the flat multilayer has larger effective refractive index than that of wavy multilayers for horizontally polarized light. In this design, the effective index difference $(\Delta)$ between the core and the cladding in vertical and horizontal directions are approximately 2.3% and 1.9%, respectively.

## III. Fabrication of Channel Waveguides

On the basis of the above design, we formed an array of grooves on a fused silica substrate by electron-beam lithography and dry etching, and deposited multilayer onto it by the autocloning method. Fig. 4 shows a scanning electron microscope (SEM) image of the cross section of the fabricated channel waveguide. As seen in Fig. 4, a regular periodic corrugation of the cladding is perfectly replicated from the bottom to the top, and flat interfaces are maintained in the core region. A bias-sputtering process is partially utilized for the formation of $SiO_2$ layers in order to increase the film density and to suppress the small fluctuation of the layer shape. Furthermore, in order to reduce the propagation loss to less than 0.56 dB/mm, which we reported in the previous work [9], in the current study, we optimized the fabrication parameters. Table I summarizes the fabrication parameters for the waveguide. Among the parameters, the mixed gas pressure of Ar and $O_2$ plays an important role in increasing the film density and, thus, obtaining smooth layer interfaces at the flat core region. We found that optimum gas pressure for our present design was 0.5 and 1.0 Pa for $Ta_2O_5$ and $SiO_2$ layers, respectively. Also, we fabricated waveguides having three different core widths (2.0, 2.5, and 3.0 $\mu$m) while fixing the height of the core to 1.5 $\mu$m, to find the relation between the spot size and the propagation loss. Note that the maximum available core width for a single-mode propagation is about 3.0 $\mu$m, at which the corresponding $V$ parameter is 2.16.

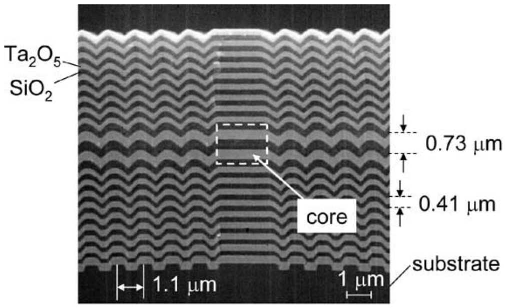

Fig. 4. SEM image of the cross section of the fabricated waveguide.

TABLE I
Fabrication Parameters for the Autocloning Process

| Fabrication parameters | $Ta_2O_5$ layer deposition | $SiO_2$ layer deposition |
|---|---|---|
| Gas pressure of Ar and $O_2$ [Pa] | 0.5 | 1.0 |
| $Ar/O_2$ flow rate [sccm] | 72/8 | 76/4 |
| RF power applied to the target [W] | 800 | 800 |
| Bias RF power applied to the substrate [W] | 0 | 20 |
| Substrate temperature [°C] | 200 | 200 |

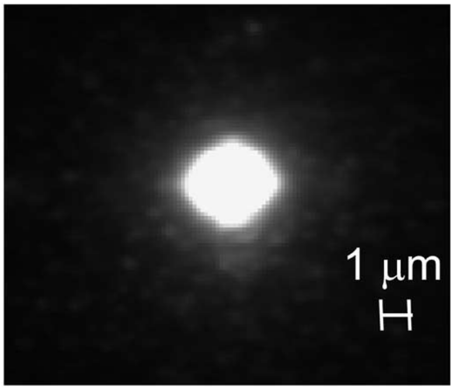

Fig. 5. Near-field pattern of the waveguide at $\lambda = 1.55\ \mu$m. The width of the core is 3.0 $\mu$m.

Fig. 5 shows a near-field pattern of the waveguide with the core width of 3.0 $\mu$m at $\lambda = 1.55\ \mu$m. The modal field diameter (MFD) is about 4.1 $\mu$m. The spot is almost circular, which indicates single mode propagation.

Insertion loss of the waveguides is measured by sandwiching it with a high-$\Delta$ single-mode fiber and a collimator lens. The

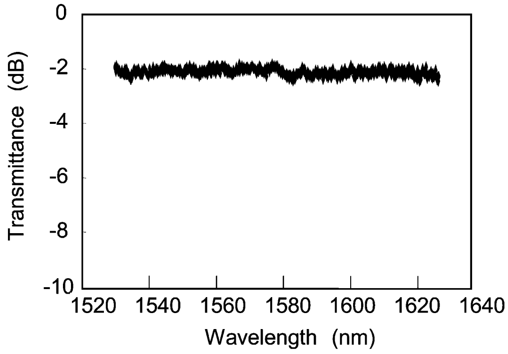

Fig. 6. Measured spectral characteristics of the total insertion loss. The width of the core is 3.0 $\mu$m.

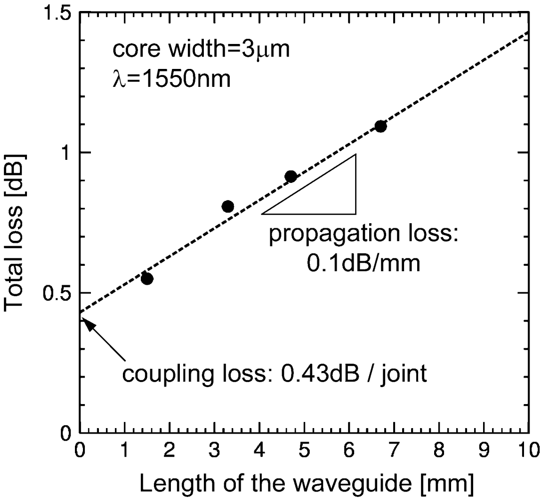

Fig. 7. Result of the loss measurement by cutback method at a fixed wavelength ($\lambda = 1.55$ $\mu$m). The width of the core is 3.0 $\mu$m.

high-$\Delta$ fiber ($\Delta = 1.5\%, \mathrm{MFD} = 4.0$ $\mu$m) is connected to a standard single-mode fiber ($\Delta = 0.3\%, \mathrm{MFD} = 10$ $\mu$m) by a thermally expanded core (TEC) splice method. The state of polarization of the incident light to the waveguide is adjusted to the horizontal one by a polarization controller inserted between the fibers and the tunable laser.

Fig. 6 shows the total insertion loss of the waveguide with the core width of 3.0 $\mu$m. The loss spectrum is almost flat from $\lambda = 1.5$ $\mu$m to $\lambda = 1.6$ $\mu$m. Fig. 7 shows a result of the loss measurement at a fixed wavelength of 1.55 $\mu$m by the cutback method. As can be seen, the propagation loss is 0.1 dB/mm and the coupling loss with the high-$\Delta$ fiber is 0.43 dB/joint.

## IV. CONCLUSION

By optimizing the fabrication condition and adjusting the core width, we achieved the propagation loss of 0.1 dB/mm, which is almost one sixth lower than the previously reported by us (0.56 dB/mm). The present result opens a door to the development of practical in-line PhC devices which require 60-ps/dB class lifetime of the light signal. Further loss reduction is possible by improving the quality of the patterned substrate and by optimizing the remaining process parameters for the autocloning deposition such as the schedule of bias power application.

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