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Optical Properties of Line-Defect Waveguides in Square-Lattice-of-Pillars Photonic Crystals for Optical Buffer Application

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1. Introduction

Square-lattice-of-Pillars photonic crystals (pillar-PCs) have collected much attention as platforms of integrated optical circuits [1]. Point defects in the pillar-PCs can act as high-Q cavities for filters, and line defects can act as waveguides for optical wiring. We focus on the line-defect waveguides to apply to integrated optical buffers, which can be used in photonic nodes in photonic telecommunication network. In this paper, we present properties of line-defect waveguides in pillar-PC. Structure and fabrication process of the PC are described. Calculated and measured optical losses of the waveguides including 90°-bends are presented. Also, small group velocities of guided light are demonstrated.

2. Structure and Fabrication

The structure of pillar-PC including line-defect waveguide is illustrated in Fig. 1 [2]. The PC consisted of circular silicon pillars arranged in square lattice, a silicon dioxide layer beneath the pillars and a polymer coating among and over the pillars. The refractive index of the silicon pillars was 3.48, and the refractive index of both the silicon dioxide and the polymer coating was 1.45. A line-defect waveguide was formed by reducing the diameter of the pillars in a single row in the Γ-X direction of the lattice as shown in Fig. 1. It should be noted that, optically, the PC structure has reflection symmetry in its thickness direction. The solid curve in Fig. 2 shows the dispersion relation of the guided mode. It was calculated for a pillar diameter of 0.533 a and a height of 2.98 a, where a is the lattice constant. The diameter of the defect pillars was set to 0.354 a. The only guided mode of the pillar-PC waveguide was a TM-like mode [3]. In Fig. 2, the gray region represents the PC's bulk propagation modes that have the same symmetry as the guided mode.

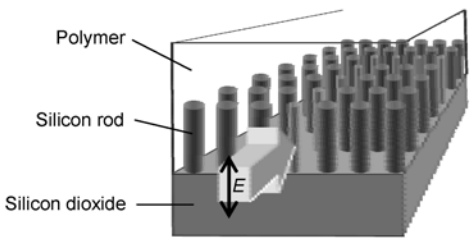

Fig. 1 Illustration of a pillar-PC including a bent line-defect as a waveguide.

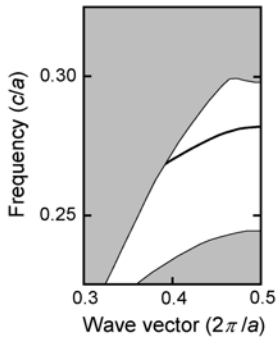

Fig. 2 Dispersion relation for a pillar-PC waveguide.

This pillar-PC waveguide was fabricated by using a silicon-on-insulator (SOI) wafer that had a 1.3-μm-thick silicon layer and a 4.0-μm-thick silicon-dioxide layer. After the top silicon layer was etched into pillars by electron-beam (EB) lithography and plasma etching, liquid polymer was spin-coated, and hardened by being irradiated with ultraviolet rays.

2. Transmission Properties

According to the diagram in Fig. 2, the frequencies of the guided mode of the straight waveguide range from 0.268 c/a (λ = 1603 nm) to 0.282 c/a (λ = 1525 nm) when a is 0.43 μm, where λ and c are respectively the wavelength and the speed of light in a vacuum.

Figure 3 shows a calculated electric field intensity distribution of a guided light in a 90°-bent waveguide. The electric field in Fig. 3 was numerically simulated by three-dimensional (3D) finite-difference time-domain (FDTD) method for a wavelength of 1.55 μm. The field was monitored at the reflection plane (the central plane bisecting the PC) in the thickness direction. In Fig. 3, it can be verified that light is confined tightly even around the corner of the line defect. This characteristic enables us to fold a line defect compactly in a PC at line intervals of 10-20 rows of pillars. The transmittance spectrum of a simple 90° bend of the pillar-PC waveguide was also calculated by 3D FDTD simulation. The spectrum indicated that light passed the 90°-bend efficiently over a wavelength range of at least 60 nm, which was large enough to include a whole range of telecommunication wavelengths.

We measured the transmittance of a 1.8-mm-long straight waveguide in the fabricated PC. The waveguide was cleaved to produce facets of waveguide ends. Light

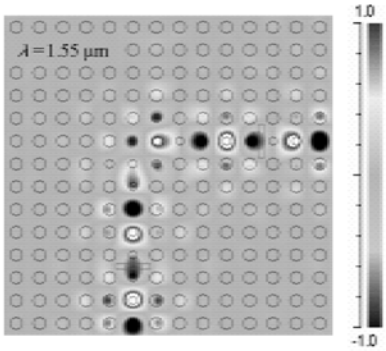

Fig. 3 3D FDTD simulation of a PC waveguide bend.

from a wavelength-tunable laser was passed through a polarization controller, and was led into a cleaved end of the waveguide by using a lensed optical fiber. The light from the waveguide was collected with another optical fiber at the opposite end and led into an optical power meter. A transmittance spectrum is shown in Fig. 4 (a). For Fig. 4 (a), the optical loss included the propagation loss of the waveguide and the input and output coupling losses. By subtracting the coupling losses, a minimum propagation loss of 4.8 dB/mm at a wavelength of 1550 nm was derived [2]. The fine oscillation in the spectrum shown in Fig. 4 (a) was caused by reflection at slight discontinuities of the PC waveguide. The discontinuities were every 80 μm along the line-defect and seemed to be the result of stitching errors of writing fields in the EB lithography. A group velocity of guided light v_g at a peak wavelength λ was calculated from this spectrum oscillation by using the equation,

$$v_g = 2cL\frac{\Delta\lambda}{\lambda^2}, \qquad (1)$$

where L is the period of the waveguide discontinuities, and $\Delta\lambda$ is the wavelength difference between the two neighboring peaks at λ. The group velocities for the peaks in Fig. 4 (a) were plotted in Fig. 4 (b). They ranged from 0.1 c to 0.2 c, which agreed with the range of group velocities calculated from the dispersion relation in Fig. 2.

To measure the optical loss of a 90° bend of waveguide, a set of waveguides in another pillar-PC was fabricated. Because a different SOI wafer with a 1.0-μm-thick silicon layer was available for it, the new pillar-PC was re-designed to have a pillar diameter of 0.580 a, a defect pillar diameter of 0.410 a and a height of 2.50 a, where a was 0.40 μm. Waveguides including different numbers of 90°-bends were arranged in parallel in the pillar-PC. The waveguides were cleaved to be 5 mm. Further, the waveguide ends were etched by focused ion beam, so that all the waveguide ends existed on the exact middle between the pillars along the waveguides. This treatment to the waveguide ends helped us to have the same optical loss for coupling of every waveguide to lensed optical fibers. By comparing optical losses among the measured waveguides, we obtained a minimum bending loss of 2.5 dB/bend.

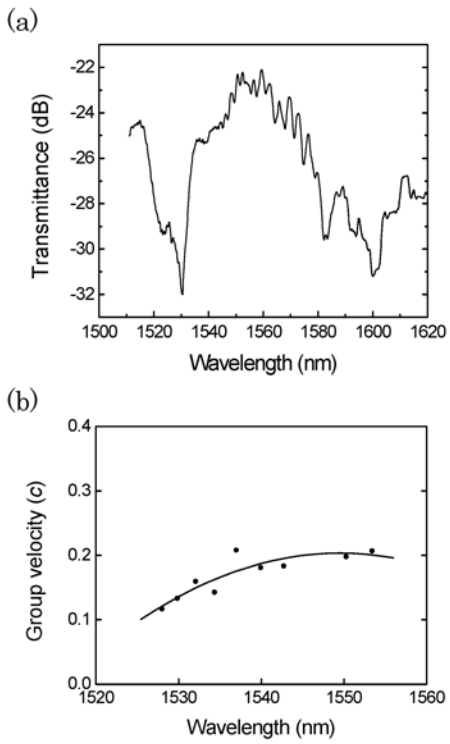

Fig. 4 (a) Measured transmittance spectrum; (b) calculated group velocities of light guided in a waveguide.

3. Conclusions

Optical properties of pillar-PC waveguides were described. Although measured optical losses were still large, they should be reduced by improving fabrication process. The group velocities of a guided light were as small as 0.1 c-0.2 c. Also, the guided light was confined tightly in the waveguide. A 5×5-mm PC chip, for instance, can contain a folded waveguide as long as 3 m. It is, thus, concluded that pillar-PC waveguide can work as an integrated optical buffer for a delay time of several tens of nanoseconds.

Acknowledgements

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References

[1] J. D. Joannopoulos, R. D. Mead, and J. N. Winn, Photonic crystals, (Princeton University Press, Princeton, NJ, 1995).

[2] Tokushima, H. Yamada, and Y. Arakawa, Appl. Phys. Lett. **84** (2004) 4298.

[3] In this paper, TE-like modes have only a lateral electric field in the reflection plane that bisects the PC pillars in the height direction. TM-like modes have only a lateral magnetic field in that plane.