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Thermal Modulation of Group Delay of Pillar-Photonic-Crystal Waveguide

Masatoshi Tokushima

NEC Corporation, Nano Electronics Research Laboratories
34, Miyukigaoka, Tsukuba, Ibaraki 305-8501, Japan
Phone: +81-29-850-2625 E-mail: m-tokushima@cd.jp.nec.com

1. Introduction

The guided mode of a single-line-defect waveguide in square-lattice-of-pillars photonic crystal (pillar-PC waveguide) has small group velocities and also small group-velocity-dispersions in a wavelength range of more than several tens of nanometers. These features mean that the pillar-PC waveguide is suitable for "slow light" applications. We demonstrated large modulation of group delay of a pillar-PC waveguide. This capability suggests that a pillar-PC waveguide can be used in efficient tunable delay elements and in micro phase-modulators, which are in Mach-Zehnder interferometers and optical switches.

2. Waveguide Structure and Guided Mode

There have been few reports of successful measurement of pillar-PC waveguides. This is because an elaborated structure, a high-aspect-ratio etching technique and a no-void coating technique are required. Figure 1 shows an oblique scanning electron micrograph of a pillar-PC waveguide that we have fabricated [1]. In Fig. 1, circular silicon pillars are arranged in a square lattice on a silicon dioxide layer. Dielectric polymer is coated between and over the pillars. The refractive index of the silicon pillars is 3.48. The refractive indices of the silicon dioxide and the polymer coating are 1.442. As shown in Fig. 1, the core of the pillar-PC waveguide is a single row of pillars that are thinner than the others

This pillar-PC waveguide was fabricated using a silicon-on-insulator (SOI) wafer that had a 1.0-μm-thick silicon layer and a 3.0-μm-thick silicon-dioxide layer. After electron-beam (EB) lithography, the top silicon layer was etched into pillars with a dry etcher. Then, ultraviolet (UV) resin was spin-coated and hardened into a polymer using UV irradiation.

Since the silicon dioxide and the polymer have the same refractive index, the pillar-PC waveguide has optical

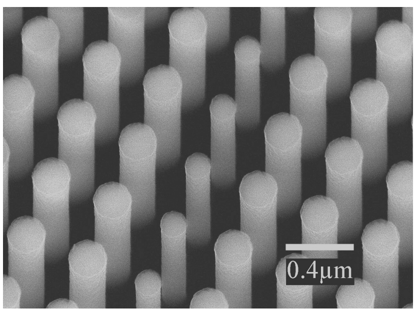

Fig. 1 Oblique scanning-electron-micrograph of an as-etched pillar-PC waveguide.

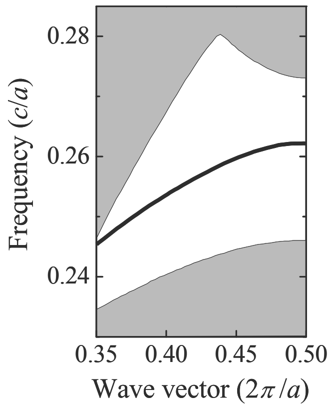

Fig. 2 Dispersion relation diagram of a pillar-PC waveguide.

reflection symmetry in its thickness direction, which allows the waveguide to have a TM-like guided mode [2]. The solid curve in Fig. 2 shows the dispersion relation of the guided mode. It was calculated for a pillar diameter of 0.605 a and a height of 2.50 a, where a is the lattice constant. The diameter of the defect pillars was set to 0.440 a. In Fig. 2, the gray region represents the PC's bulk propagation modes that have the same symmetry as the guided mode.

2. Theoretical Analysis of Group Delay Modulation

The dielectrics used in our pillar-PC waveguide are silicon, silicon dioxide and polymer. Of all the dielectrics, the polymer has the biggest thermo-optic coefficient $\Delta n_{\mathrm{poly}}/\Delta T \approx -7.0\times10^{-4}$ /K, where n_{poly} is the refractive index of the polymer and T is the temperature of the pillar-PC waveguide. As a result, thermal variation of group delay t of the pillar-PC waveguide is dominated by refractive index variation of the polymer Δn_{poly}. The group delay variation rate $\Delta t / t\Delta T$ of a pillar-PC waveguide is calculated by

$$\frac{\Delta t}{t\Delta T} \approx \Gamma_{\mathrm{poly}} \cdot \frac{\Delta n_{\mathrm{poly}}}{n_{\mathrm{poly}}\Delta T}. \qquad (1)$$

In Eq. (1), Γ_{poly} is defined by

$$\Gamma_{\mathrm{poly}} = -\frac{n_{\mathrm{poly}}\Delta v_g}{v_g \Delta n_{\mathrm{poly}}}, \qquad (2)$$

where v_g is the group velocity of the guided mode. This is a figure of merit representing an efficiency with which refractive index variation of a dielectric is converted to group velocity variation of a waveguide containing the dielectric. In the case of propagation in a homogeneous

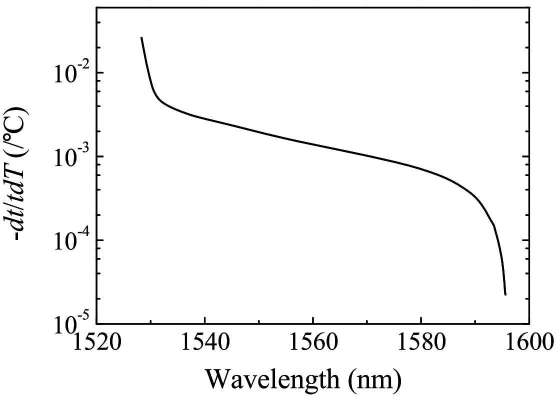

Fig. 3 Calculated wavelength dependence of the group delay variation rate.

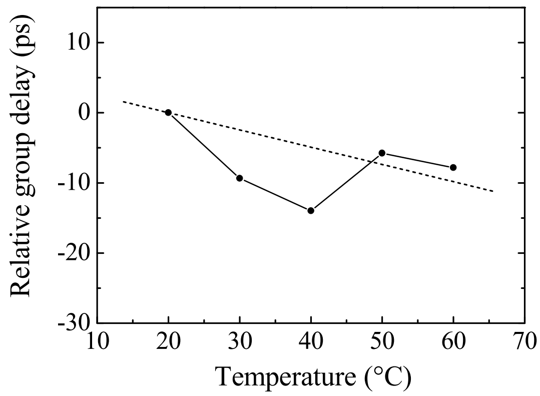

Fig. 4 Temperature dependence of the relative group delay. The broken line represents a theoretical estimation of the group delay.

dielectric polymer, Γ_{poly} = 1. At a wavelength of 1546 nm, which is 20nm longer than the cutoff wavelength of 1526 nm, group velocity is small, about *c*/20, where *c* is the speed of light in the vacuum, and also group velocity dispersion is small enough for the pillar-PC waveguide to be used for processing high-speed optical signals. From the dispersion diagram shown in Fig. 2, Γ_{poly} of the pillar-PC waveguide can be calculated to be as large as about 10 at 1546 nm. Wavelength dependence of the group delay variation rate $\Delta t / t\Delta T$ of the pillar-PC waveguide is shown in Fig. 3. From Fig. 3, the group delay of the pillar-PC waveguide is expected to decrease by about 9% when its temperature is increased by 40°C.

3. Experiment

The designed diameter of the pillars of the pillar-PC waveguide that we measured was 0.246 μm, and that of the defect pillars was 0.174 μm. The height of the pillars was 1 μm. The length of the pillar-PC waveguide was 1.6 mm. On a substrate, the pillar-PC waveguide was coupled to silicon wire waveguides on both ends of the pillar-PC waveguide. Waveguide ends of the measure sample were made by cleaving the substrate in the midst of the silicon wire waveguides. The total length of the waveguide including the silicon wire waveguides was 12.7 mm. The temperature of the pillar-PC waveguide was increased from 20 to 60°C using a Peltier thermo-electric element.

Group delay was measured using the phase shift method at an amplitude modulation frequency of 3 GHz. TM-polarization light from a laser diode was input to the waveguide using a lensed optical fiber. Light output from the waveguide was collected using another lensed optical fiber. After eliminating residual TE-polarization light, the output light was introduced to a photo detector, and then phases of the input and output lights were compared to calculate group delay.

4. Results and Discussion

The cutoff wavelength of the fabricated pillar-PC waveguide was 1560 nm, which was 34 nm longer than the cutoff wavelength of the waveguide model analyzed in Section 2. Therefore, measurement wavelengths were set to be around 1580 nm so as to be 20 nm longer than the actual cutoff wavelength.

The waveform of the modulated signal that was propagated through the pillar-PC waveguide was verified using a sampling oscilloscope. At 20°C, the group delay of the 1.6-mm pillar-PC waveguide (not including the silicon wire waveguides) was 112 ps. Figure 4 shows temperature dependence of the relative group delay, which was measured from the group delay at 20°C. The broken line in Fig. 4 represents a result calculated based on the theoretical analysis in Section 2. As seen in Fig. 4, the overall behavior of the measured data is similar to the calculated line. We think that the measured data's deviation from the calculated line was caused by initial relaxation of the polymer stress. By applying linear fitting to the measured data in Fig. 4, we derived a group delay variation rate of -4.5% for a temperature increase of 40°C. This rate is on the same order of -9% that was expected in the theoretical analysis in Section 2.

3. Conclusion

Large group-delay-modulation of the guided mode of our pillar-PC waveguide was demonstrated through theoretical analysis and experimentation. It was strongly suggested that the group delay modulation rate can reach more than 10% by heating the pillar-PC waveguide by about 100°C. Thus, the pillar-PC waveguide can be applied in efficient tunable delay elements and in micro low-voltage phase-modulators that can be used in integrated optical circuits.

Acknowledgements

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References

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

[2] In this paper, TM-like modes have electric fields predominantly parallel to the pillars.