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著者	Umemori Ken-ichi, Kanamori Yoshiaki, Hane Kazuhiro
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Photonic crystal waveguide switch with a microelectromechanical actuator

Ken-ichi Umemori, Yoshiaki Kanamori, and Kazuhiro Hane[a)]
Department of Nanomechanics, Tohoku University, Sendai 980-8579, Japan

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A photonic crystal waveguide switch with a movable slab is proposed and fabricated by silicon micromachining. The switch structure consists of in-line input and output photonic crystal waveguide slabs and a switching slab to bridge gap between the waveguides. Driving the switching slab with a microelectromechanical actuator, the transmission between the waveguides is modulated. The switching characteristics can be explained by calculations using the finite-difference time-domain method. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2219996]

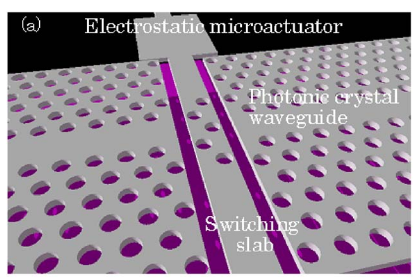
One of the advanced research topics in micro/nano-optics is the photonic crystal (PC). Especially, the PC waveguide attracts intensive interest in the research field of integrated optical circuits because of the promise of light confinement in a small area.[1] In most of the reported devices, the functions of the PCs are not variable. PCs with variable mechanisms have recently been proposed and modeled. Electronic tunable functions of PCs were demonstrated using optical polymer[2] and semiconductors,[3] and liquid crystals also studied theoretically.[4,5] Temperature tuning of PC is also attractive.[6,7] Furthermore, control of the transmission in photonic crystal waveguides was proposed by applying mechanical stress on the waveguide.[8,9] However, the combination of photonic crystal with those mechanisms is still in progress.

Control of PC devices using microelectromechanical systems (MEMS) is also a promising technology for introducing functionality to PC waveguides. Although several devices with variable mechanical structures of PCs were considered, there have been very few reports on the experimental studies for the combination of PC waveguide with MEMS due to the difficulty in the fabrication of hybrid structures.[10–12] In this study, we fabricate a PC waveguide switch with a MEMS actuator.

Figure 1(a) shows the schematic diagram of the proposed PC waveguide switch. A two-dimensional photonic band gap structure with a triangular lattice cell is used for the waveguide. The structure makes use of the effect of a two-dimensional photonic band gap to confine the light in the in-plane direction for transverse-electric (TE)-like mode. The proposed PC has air holes 0.30 μm in diameter with a lattice constant of 400 nm. The PC slab is 205 nm thick. The stop band of the designed PC has been calculated by the plane wave expansion method to be from 1.02 to 1.64 μm. The air gap between the top silicon layer and the substrate is 3.0 μm, which is equal to the thickness of the SiO_2 layer of the silicon-on-insulator (SOI) wafer.

The proposed device is divided into three parts: an input waveguide slab, an output waveguide slab, and a central movable slab (switching slab). In the centers of the input and output slabs, the line-shaped defects (three PC line defects) are introduced to form the straight waveguides. The switching slab is an interaction plate acting as a switching element between the input and output waveguides, and it can be moved downward by a parallel-plate electrostatic microactuator (MEMS) connected to the slab. The design layout of the proposed device is shown in Fig. 1(b). The PC regions in the input and output slabs are 20 μm long and 9 μm wide, respectively.

From an intuitive consideration, the switching slab is expected to operate as a transmission bridge between the input and output waveguides. The light wave passes through the gap between the input and output PC waveguides when the switching slab locates between them, and the light wave is stopped if the switching slab is removed. The actual wave propagation property, however, is not so simple. If there is no switching slab between the two waveguides, the transmittance across the air gap is dependent on the gap width between the waveguides. The air gap and the edges of the waveguides work similarly to a Fabry-Pérot-type filter with low reflectance. For gaps smaller than 2λ (λ: wavelength), calculations using a finite-difference time-domain (FDTD) method show that the transmission light intensity has maxima and minima of period $\lambda/2$ although the average intensity decreases as a function of the air gap. The smallest gap to obtain the minimum transmission intensity was around $\lambda/4$. The third minimum was obtained around 2 μm, which was roughly equal to $5\lambda/4$. Considering the calcula-



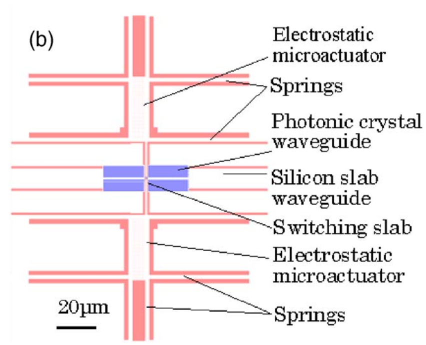


FIG. 1. (Color online) (a) Schematic diagram of the photonic crystal waveguide switch and (b) the whole design of the device.

a)Electronic mail: hane@hane.mech.tohoku.ac.jp

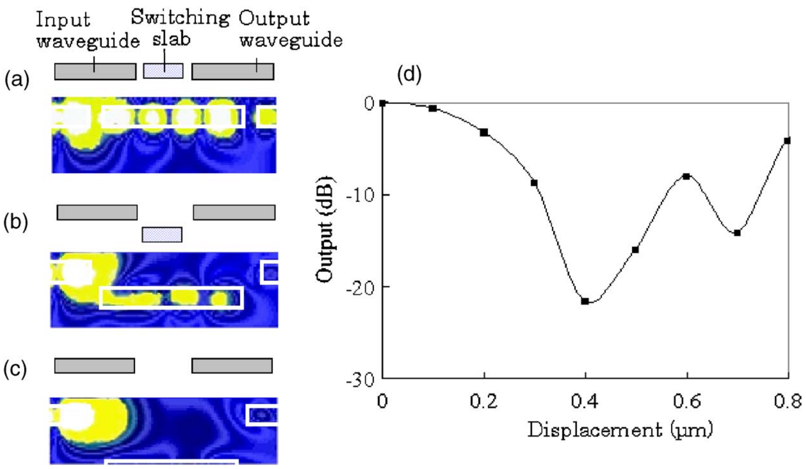


FIG. 2. (Color online) Cross-sectional intensity distribution of the electric at the slab displacements of (a) 0 nm, (b) 400 nm, and (c) 800 nm, respectively, and (d) the normalized output intensity as a function of the displacement.

tion results and the fabrication conditions, the gap between the input and output waveguides was set to 2 μm to obtain the minimum transmittance under the switch-off condition in our experiment. Here, the "switch-on" condition corresponds to the state that the switching slab is not moved (i.e., in the same plane as the input and output PC waveguides), while under the "switch-off" condition, the slab is lowered below the plane. The switching slab is 1.6 μm wide and the gap between the input and output waveguides is 200 nm.

We calculated the switching characteristics of the proposed structure using a three-dimensional FDTD method as a function of the vertical displacement of the switching slab. Lowering the switching slab in the displacement range from 0 to 400 nm, the light wave propagating from the input waveguide to the switching slab decreased, but still interacted with them and passed to the output waveguide. This was caused by the fact that the silicon slab had a high refractive index (3.48), and thus the light wave interacted strongly with the slab even if the slab was lowered. The pull-in voltage of the electrostatic microactuator also limited the displacement of the switching slab (<1 μm). Therefore, the light wave propagation could not be shut out completely by a small displacement of the switching slab. However, to eliminate light propagation during the "off" condition could be achieved by introducing the holes in the switching slab at the expense of some loss in the transmittance under the switch-on condition.

Considering the above results, we further simulated several structures for the switching slab and the air gap under our experimental conditions. As a compromise of the switch structure, we utilize a small number of PC holes (ten holes) in the switching slab as shown schematically in Fig. 1(a) to shut out the light leaking from the input waveguide to the output waveguide through the switching slab under the switch-off condition, although it generates a loss under the switch-on condition. Figure 2 shows the light transmission properties calculated by the FDTD method. Figures 2(a)–2(c) schematically show the cross-sectional intensity distribution of the (TE-like) electric field propagating through the switch structure for displacements of the modified switching slab of 0, 400, and 800 nm, respectively. The bright regions in the figure correspond to regions where the electric field is strongest. Figure 2(d) shows the normalized output intensity as a function of the switching slab displacement.

Under the switch-on condition, i.e., without the displacement of the switching slab, the light propagates from the input to the output waveguide with a loss, which was calculated to be 8.7 dB. This value is used for the normalization in Fig. 2(d). Lowering the switching slab from 0 to 400 nm, the light emitted from the input waveguide flows to the switching slab as shown in Fig. 2(b). Due to the PC holes in the switching slab, the scattering effect of the light is strong so that much of the light does not propagate to the output waveguide. At the displacement of 400 nm, a minimum output of about 22 dB is obtained as shown in Fig. 2(d). Large displacements cause the output intensity to increase due to the direct propagation path through the gap between the input and output waveguides. Therefore, the wave propagation between the waveguides can be strongly prevented by leaking the light to the switching slab than by removing the switching slab completely under our experimental conditions.

In the case of the switching slab without the PC holes, the output intensity varied similarly to that shown in Fig. 2(d) except that the transmittance was higher by 0.4 dB. However, the difference in the output between the switch-on and the switch-off conditions was smaller by 0.5 dB than the case of the switching slab with PC holes.

To fabricate the structure we used electron beam patterning. The top silicon layer was etched by fast atom beam (Ebara Co. Ltd.), and the SiO_2 layer was removed partially using HF vapor. Figure 3 shows the electron micrograph of the fabricated device. The diameter of the photonic crystal holes was measured to be from 0.297 to 0.303 μm. The

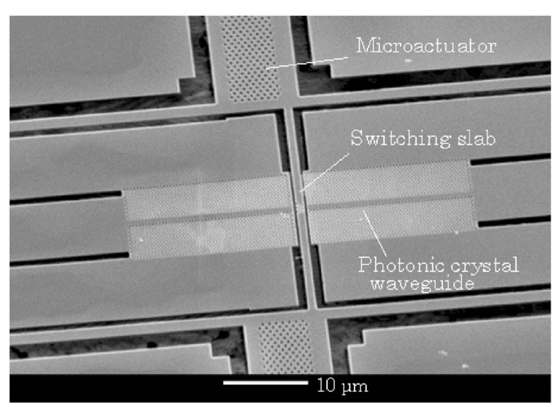


FIG. 3. Electron micrograph of the fabricated device.

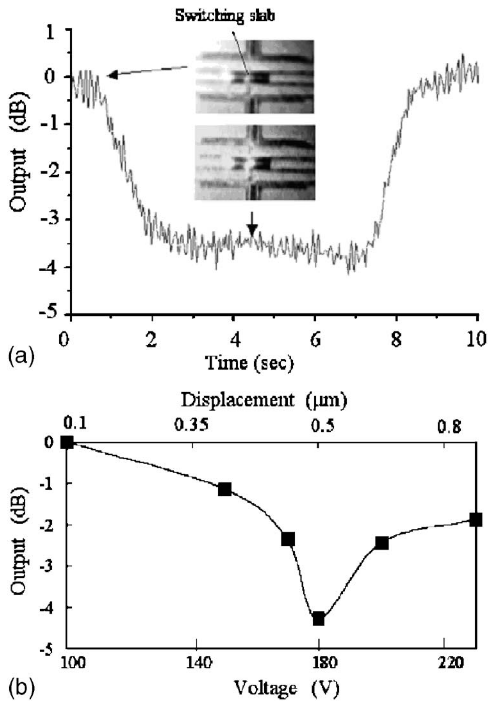


FIG. 4. (a) Output intensity as a function of time and (b) the output intensity as a function of voltage and corresponding displacement.

switching slab, which is connected to the microactuator, was fabricated without sticking to the substrate.

The value of the switching slab displacement was measured from that of the parallel plate of the microactuator. The displacement increased up to 0.8 μm at the voltage of 230 V. The pull-in voltage was around 250 V at a displacement of 1 μm, which agreed with the numerical calculation of the mechanical response of the fabricated structure. The lowest mechanical resonant frequency was calculated to be 649 Hz.

The optical measurements of the fabricated device were carried out using a laser diode with wavelength of 1.55 μm. The laser light was introduced to the slab waveguide of the PC switch through a single-mode fiber with a tapered lens at the end. The output from the PC waveguide was measured through a similar kind of fiber optics and a detector.

Figure 4(a) shows the output light intensity measured as a function of the time. When the voltage is varied rectangularly from 0 to 180 V, the output light intensity is modulated according to the applied voltage. The device in operation was observed with an infrared camera; the images are shown in the inset. When the voltage is applied, the intensity of the light spot from the switching slab becomes brighter due to the scattering of the stopped light under the switch-off condition.

Figure 4(b) shows the output light intensity measured as a function of the applied voltage. The corresponding displacement is also shown on the upper axis. The output intensity gradually decreases with the increase of the voltage and becomes minimum at the voltage of 180 V (at 0.5 μm). Further increases in the voltage cause the output to increase as shown in Fig. 4(b). This behavior of the output intensity agrees well with that predicted by the numerical calculation shown in Fig. 2(d). The absolute value (4 dB) of the output change between the switch-on and switch-off conditions is much less than that predicted (22 dB) by the numerical calculation. This may be caused by our experimental setup, in which the stray light from the input fiber to the sample slab is included in the measured output because of our in-line waveguide configuration.

In conclusion, a PC waveguide switch with a movable slab connected to a MEMS actuator has been fabricated by silicon micromachining. It has been shown that the combination of the PC waveguide and a MEMS actuator is a promising technology for introducing variable functions in PC devices.

[1]K. Inoue, Y. Suginmoto, N. Ikeda, Y. Tanaka, K. Asakawa, T. Maruyama, K. Miyashita, K. Ishida, and Y. Watanabe, Jpn. J. Appl. Phys., Part 1 **43**, 6112 (2004).
[2]M. Schmidtr, M. Eich, U. Huebner, and R. Boucher, Appl. Phys. Lett. **87**, 121110 (2005).
[3]T. Baba, M. Shiga, K. Inoshita, and F. Koyama, Electron. Lett. **39**, 1 (2003).
[4]C.-Y. Liu and L.-W. Chen, Phys. Rev. B **72**, 045133 (2005).
[5]E. P. Kosmidou, E. E. Kriezis, and T. D. Tsiboukis, IEEE J. Quantum Electron. **41**, 657 (2005).
[6]H. M. H. Chong and R. M. De La Rue, IEEE Photonics Technol. Lett. **16**, 1528 (2004).
[7]H. Takeda and K. Yoshino, Opt. Commun. **219**, 177 (2003).
[8]N. Malkova, S. Kim, and V. Gopalan, Appl. Phys. Lett. **83**, 1509 (2003).
[9]N. Malkova, J. Phys.: Condens. Matter **16**, 1523 (2004).
[10]W. Park and J.-B. Lee, Appl. Phys. Lett. **85**, 4845 (2004).
[11]C. W. Wong, P. T. Rakich, S. G. Johnson, M. Qi, H. I. Smith, E. P. Ippen, L. C. Kimerling, Y. Jeon, G. Barbastathis, and S.-G. Kim, Appl. Phys. Lett. **84**, 1242 (2004).
[12]M.-C. M. Lee, D. Hah, E. K. Lau, H. Toshiyoshi, and M. Wu, IEEE Photonics Technol. Lett. **18**, 358 (2006).