MEMS-Actuated Photonic Crystal Switches

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***Abstract*—A compact guided-wave optical switch is realized by integrating one-dimensional photonic crystals with microelectromechanical systems (MEMS) actuators. The ON–OFF switching is achieved by physically moving a photonic crystal defect. Experimental results show an extinction ratio of 11 dB at 1.56-μm wavelength and a 0.5-ms time constant of the step response.**

***Index Terms*—Microelectromechanical (MEMS) devices, optical switches, waveguide switches.**

I. Introduction

THERE HAS been increasing interest in using photonic crystals (PCs) as a platform for compact integrated photonic integrated circuits because of their ability to tightly confine and localize optical energy. Many building blocks of such photonic circuits have been demonstrated, including PC waveguides with sharp bends, spectral filters, add–drop multiplexers, and superprisms [1]–[3]. Most of the PC circuits reported to date are static; their functionality is fixed by fabrication. It is desirable to include dynamic switching or reconfiguration functions.

Tunable PCs are promising for implementing optical switches with small footprints. Several tunable PCs have been reported. PCs filled with liquid crystals [4] can be adjusted electrically and thermally. However, the response time is on the order of tens of milliseconds. Free-carrier injection [5] and electrooptics [6] have been shown to directly modulate the refractive index of the host materials. However, the tuning range is limited, due to the small refractive index change. Other mechanisms include mechanically deforming the PC structures using the piezoelectric effect or sheer strain [7]. But, the tuning range is still not large enough for use in optical switches. Utilizing microelectromechanical system (MEMS) actuators to physically move one or a group of "photonic atoms" in the host PC has a stronger optical effect. PCs integrated with MEMS actuators have been proposed [8]. However, only optical simulation and fabrication were reported. Previously, we experimentally demonstrated a one-dimensional (1-D) PC switch actuated by MEMS [9]. In this letter, we present the detailed analysis and experimental results of the 1-D PC switch.

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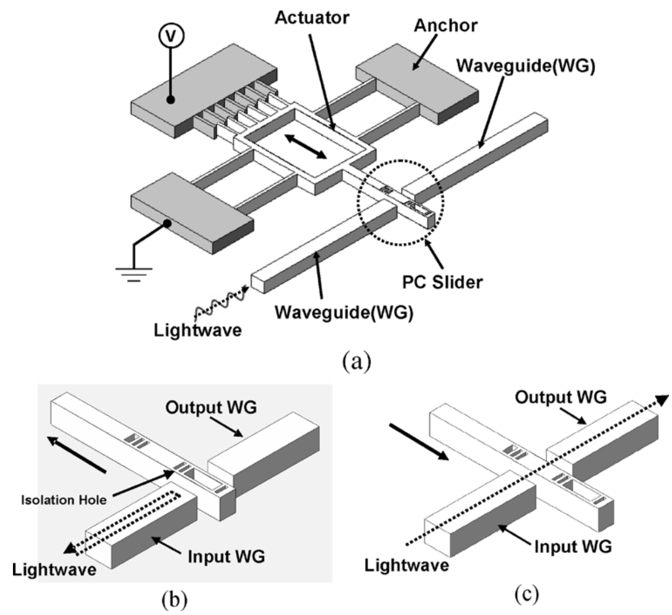

Fig. 1. (a) Schematic of MEMS-actuated PC switch. Lateral comb-drive actuator connects with PC slider inserted between two waveguides. Two states are defined on tip of PC slider: (b) reflection state and (c) transmission state.

II. Device Design and Operation

Fig. 1 shows the schematic of a MEMS-actuated PC switch. The 1-D PCs, usually referred to as periodic slab structures with alternating high- and low-index materials, are used in this design. In Fig. 1(a), a PC slider connected to a comb-drive actuator is inserted between two waveguides. Two PC states are patterned side by side on the slider. One is a reflection state consisting of two Si quarter-wave slabs separated by a quarter-wave air gap. The gap spacing between the slider and waveguides is also equal to one-quarter of the wavelength. The other is a transmission state made of a silicon piece, which mimics two periods PCs filled with silicon in the central gap as a defect. When the reflection state is moved in between the waveguides, as shown in Fig. 1(b), it forms a forbidden wavelength band (or photonic bandgap). Input light is reflected by the crystal. On the other hand, when the transmission state is positioned between the waveguides [Fig. 1(c)], it creates a narrow passband within the photonic bandgap. Signals at the center wavelength, which is determined by the size of the defect, can thus be switched dynamically between these two states by the MEMS actuator, achieving an ON–OFF switching function.

Since the slider itself is made of high-index material (Si), care must be taken to minimize lateral leakage of light energy. We have incorporated several isolation holes around the PC structures. This will be discussed further in the simulation.

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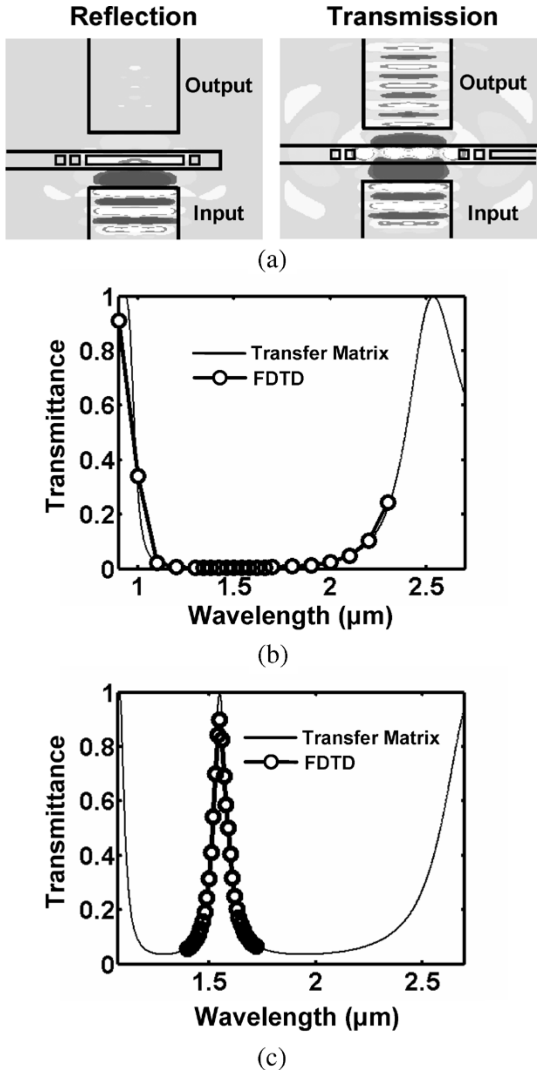

Fig. 2. (a) 2-D FDTD simulation at transmission state and reflection state. Calculated transmission spectra for (a) transmission state and (b) reflection state.

The forbidden bandwidth and the reflectivity of PCs are proportional to the index contrast. With the high index contrast, semiconductor PCs can confine light within just a few periods of crystal. In our device, single-crystalline silicon is used for the waveguides, the PC slider, and the MEMS actuator because of its transparent optical transmission at 1.55 μm wavelength and robust mechanical properties. The input and output waveguides are 4 μm wide and 1.5 μm in height. The gap spacing between the slider and the waveguide is 385 nm, and the thickness of silicon slabs in the PC is 110 nm, both corresponding to one-quarter of the guided wavelengths. In the transmission state, the thickness of the silicon region is fine tuned to achieve a peak transmittance at 1.55-μm wavelength.

The optical transmission of the MEMS PC switch is analyzed both by transfer matrix method (TMM) [10] and two-dimensional (2-D) finite-difference time-domain (FDTD) simulation. TMM is utilized to calculate the transmission spectra of the finite periods of 1-D PCs, and FDTD is used to simulate the electric fields and verify the calculated results. Fig. 2(a) shows the electric fields of the reflection and transmission states by 2-D FDTD simulations. A strong optical resonance, at the transmission state, occurs in the PC defect and the optical waves are coupled to the output waveguide. With isolation holes, the lateral power leakage is only about 0.4 dB. At the reflection state, most power is reflected by the PC structure. Fig. 2(b) and (c) plots the transmission spectra calculated both by TMM and FDTD simulation at the transmission and the reflection states, respectively. The forbidden band in the reflection state extends from 1.1 to 2.0 μm. The suppressed transmittance in the band is about 25 dB. The full-width at half-maximum (FWHM) of the band in the transmission state is 70 nm, sufficient to cover the entire C band in dense wavelength-division multiplexed (DWDM) systems.

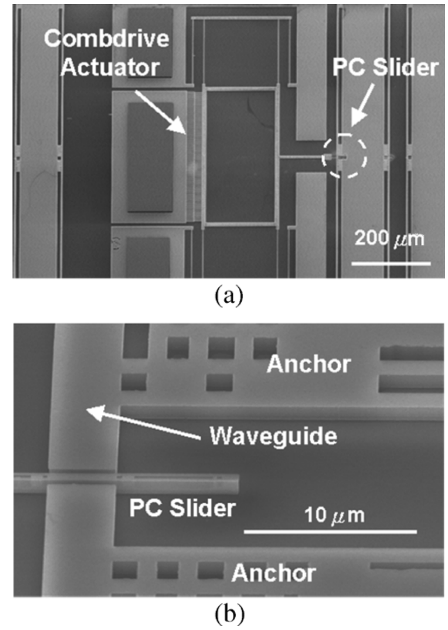

Fig. 3. (a) SEM image of fabricated MEMS PC switch. (b) Close-up view of PC slider. Two anchors support suspended waveguides.

III. Fabrication

The device was fabricated on a silicon-on-insulator (SOI) substrate with silicon layer of 1.5 μm and buried oxide (SiO2) of 0.5 μm. First, 100-nm thermal oxide was grown on the top of the silicon layer as a hard mask for silicon etching. Because the minimum feature of the PC slabs is 110 nm, but the mechanical structure is hundreds of micrometers in size, two-step lithography was employed to individually pattern the PCs and the actuators. The PC structures and the waveguides were patterned by e-beam lithography, and the microactuator was patterned by optical lithography. After the overlap e-beam and optical lithography patterns were transferred to the top thermal oxide, the silicon layer was etched down to the buried oxide by deep reactive-ion etching (DRIE) [11] to achieve a vertical sidewall. Finally, the microactuators, PCs, and waveguides were released by immersing the sample in hydrofluoric acid (HF). The scanning electron micrograph (SEM) of the finished device is shown in Fig. 3.

IV. Experimental Measurement

An experimental setup is constructed to measure the optical transmittance. Two lensed fibers are aligned to the input and

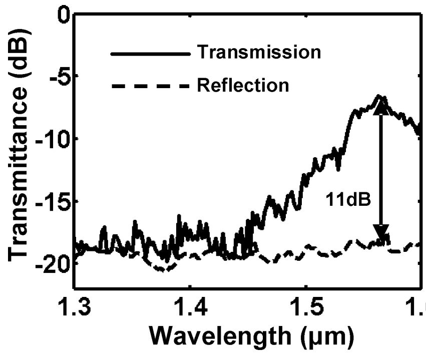

Fig. 4. Measured optical spectra at transmission (solid curve) and reflection states (dashed curve).

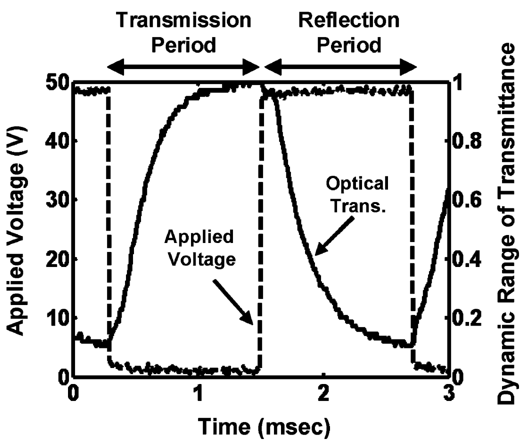

Fig. 5. Measured dynamic response of switch. Applied voltage is a square wave with period of 2.5 ms (dashed curve). Optical signal is measured by photodetector (solid curve).

output waveguides, respectively. The input fiber was connected to a white light source to launch a broad-band optical signal for test. The output fiber was connected to an optical spectrum analyzer. Without bias, the PC slider is initially at the transmission state. As the applied voltage increases to 50 V, the PC slider is moved to the reflection state. Fig. 4 shows the measured transmittance spectra at the reflection and transmission states, respectively. The measured spectra are normalized to the reference spectrum obtained from a straight waveguide. At the transmission state, a peak transmittance is shown at 1.56 μm. An 11-dB extinction ratio is achieved by comparing the transmittance at the reflection state. The transmission bandwidth is measured to be 65 nm, which agrees well with the theoretical prediction. An 8-dB optical loss is observed at the transmission state. This excess loss primarily results from surface roughness and vertical diffraction loss in the air gap due to shallow depth (1.5 μm). It can be improved by optimizing the process and increasing the height of the PC.

In order to measure the switching time, a square wave (0$\sim$50 V, 400 Hz) was applied on the combdrive actuator. The input fiber was connected to a laser with wavelength of 1.56 μm, which achieves the maximum transmittance contrast. The dynamic response of transmitted power is illustrated in Fig. 5. The time constant of the step response was measured to be 0.5 ms, which is primarily limited by the mechanical dynamics. The natural frequency of the comb-drive actuator is estimated to be 10 kHz. A shorter time constant can be achieved by scaling down the size of the actuators and increasing the thickness of buried oxide (reducing the damping effect).

V. Summary

We have proposed, fabricated, and experimentally tested a MEMS-actuated 1-D PC switch. An ON–OFF switching functionality is demonstrated with an extinction ratio of 11 dB, an excess optical insertion loss of 8 dB, an optical bandwidth of 65 nm, and a switching time of 0.5 ms.

References

[1] M. Loncar, T. Doll, J. Vuckovic, and A. Scherer, "Design and fabrication of silicon photonic crystal optical waveguides," *J. Lightw. Technol.*, vol. 18, no. 5, pp. 1402–1411, May 2000.

[2] F. Shanhui, P. R. Villeneuve, J. D. Joannopoulos, and H. A. Haus, "Channel drop tunneling through localized states," *Phys. Rev. Lett.*, vol. 80, pp. 960–963, 1998.

[3] O. Painter, A. Husain, A. Scherer, P. T. Lee, I. Kim, J. D. O'Brien, and P. D. Dapkus, "Lithographic tuning of a two-dimensional photonic crystal laser array," *IEEE Photon. Technol. Lett.*, vol. 12, no. 9, pp. 1126–1128, Sep. 2000.

[4] S. W. Leonard, J. P. Mondia, H. M. Van Driel, O. Toader, S. John, K. Busch, A. Bimer, U. Gosele, and V. Lehmann, "Tunable two-dimensional photonic crystals using liquid-crystal infiltration," *Phys. Rev. B, Condens. Matter*, vol. 61, pp. R2389–R2392, 2000.

[5] S. W. Leonard, H. M. van Driel, A. Birner, and U. Gosele, "All-optical ultrafast tuning of two-dimensional silicon photonic crystals via free-carrier injection," presented at the Tech. Dig. Summaries Papers Quantum Electronics Laser Science Conf., Opt. Soc. Amer., Washington, DC, 2001, p. 159.

[6] P. Kopperschmidt, "Tunable band gaps in electro-optical photonic bi-oriented crystals," *Appl. Phys. B, Lasers Opt.*, vol. B73, pp. 717–720, 2001.

[7] S. Rajic, J. L. Corbeil, and P. G. Datskos, "Feasibility of tunable MEMS photonic crystal devices," *Ultramicroscopy*, vol. 97, no. 1–4, pp. 473–479, Oct.–Nov. 2003.

[8] Y. Kanamori, K. Inoue, K. Horie, and K. Hane, "Photonic crystal switch by inserting nano-crystal defects using MEMS actuator," in *Proc. 2003 IEEE/LEOS Int. Conf. Optical MEMS (Cat. 03EX682)*, Piscataway, NJ, 2003, pp. 107–108.

[9] M. C. Lee, H. Dooyoung, E. K. Lau, W. Ming, and H. Toshiyoshi, "Nano-electro-mechanical photonic crystal switch," in *Proc. Optical Fiber Commun. Conf. (OFC). Postconf. Tech. Dig. (IEEE Cat. 02CH37339). Opt Soc. Amer.*, vol. 1, Washington, DC, 2002, pp. 94–95.

[10] P. Yeh, *Matrix Formulation for Isotropic Layered Media*. New York: Wiley, 1988.

[11] M. Naydenkov and B. Jalali, "Fabrication of high aspect ratio photonic bandgap structures on silicon-on-insulator," *Proc. SPIE—Int. Soc. Opt. Eng.*, vol. 3936, pp. 33–39, 2000.