Thermo-optic photonic crystal light modulator

Mark T. Tinker[a] and Jeong-Bong Lee
Department of Electrical Engineering, University of Texas, Dallas, Texas 75083-0688

(Received 21 December 2004; accepted 29 April 2005; published online 27 May 2005)

A device concept is proposed for modulating light in silicon-based photonic crystal devices by using highly localized high-temperature modulation of a compact device to vary the position of the cutoff frequency in a photonic crystal waveguide and modulate light. The position of the cutoff frequency can be varied by up to 60 nm at the telecommunication wavelength of 1550 nm by locally increasing the temperature of the device. Modulators of a few to several micrometers in width can be designed that can modulate light with extinction ratios up to 50 dB and low insertion loss. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1944212]

Photonic crystals offer the potential for developing ultrasmall optical circuits in future generation optical devices. The large majority of the work in this area has necessarily been focused on the realization of passive devices essential to the operation of the basic technology. However, as the technology continues to mature, increasing focus is now being placed on the development of active devices. Light modulation is one key component of such devices. Although much of this work has been targeted at the direct implementation of standard optical devices, most notably the Mach-Zehnder interferometer,[1–6] within photonic crystal systems, device concepts relying exclusively on the inherent properties of the photonic crystal itself may offer significant advantages over simply using standard optical devices. This Letter discusses the potential for developing such a device in silicon at the telecommunication wavelength of 1550 nm.

Thermal actuation of silicon microactuators using microelectromechanical systems (MEMS)-based technologies have routinely and reliably been used to cycle silicon up to 700 to 800 °C on a regular basis for a number of years.[7–9] Although the maximum temperature of operation of any optical device in silicon will ultimately be limited to around 650 °C because of optical absorption,[10] localized heating of static photonic crystal devices up to these temperatures should still be capable of driving substantial changes in the refractive index through the thermo-optic effect. Since the thermo-optic coefficient of silicon is approximately $2.4 \times 10^{-4}\ K^{-1}$ over this temperature range, the refractive index of silicon can be increased by up to 0.15 by increasing the temperature of silicon to 650 °C.[11]

Changes in the refractive index of this magnitude can cause a significant shift in the photonic crystal band structure that can be used to modulate light by altering the cutoff frequency[12–14] in a photonic crystal linear waveguide. The basic concept of such a device is shown in Fig. 1, where an optical modulator centered in the middle of the device has been designed to operate around the cutoff frequency. The remainder of the waveguide is designed to minimize the loss of light as it enters and leaves the waveguide. Light is modulated by locally heating the device, shown in light blue, to increase the temperature of the modulator in order to change the cutoff frequency. Response times are expected to be around 10 μs, comparable to other silicon-based thermal modulators.[6,15]

A detailed spectroscopic analysis of linear waveguides oriented in the Γ-K direction of a triangular lattice of air holes in silicon reported a distinct cutoff range around the telecommunication wavelength of 1550 nm, starting at around 1510 nm and extending up to the upper band gap of the device at 1580 nm.[14] A modulator similar to this device was developed by simulating the behavior of a 20-column-wide linear waveguide oriented in the Γ-K direction near the telecommunication wavelength by using two-dimensional finite-difference-time-domain (2D FDTD) analysis. The photonic crystal was designed using a triangular lattice with a diameter of 180 nm and a lattice spacing of 320 nm. TE light was input into the waveguide using a single frequency Gaussian light source and the intensity of the output light sensed by a detector placed at the output of the waveguide. The normalized intensity of light at the output was then plotted as a function of wavelength.

Simulation results showing the intensity of the transmitted light at wavelengths ranging from 1200 to 1650 nm are shown in Fig. 2(a). The intensity of the transmitted light begins to fall abruptly at around 1510 nm and begins to rise again at around 1580 nm near the upper band gap of the device. This is in almost exact agreement with the detailed spectroscopic data from Ref. 14 discussed above. The effect of temperature on the position of the cutoff range was then simulated using these same dimensions at 235, 440, and 650 °C, and the data shown in Fig. 2(b). The wavelength of the cutoff frequency is increased by approximately 20, 40, and 60 nm at these three different temperatures. These devices gradually lose up to 5 dB of intensity before rapidly falling off at the cutoff frequency to around −40 dB. The intensity ultimately begins to increase as the wavelength approaches the upper band gap of the device. This type of behavior clearly provides the capability of modulating light over a wide range of wavelengths by simply changing the temperature.

FIG. 1. (Color online) Schematic diagram of thermo-optic modulator showing a six-column-wide modulator subjected to localized heating.

[a]Electronic mail: mtinker@utdallas.edu

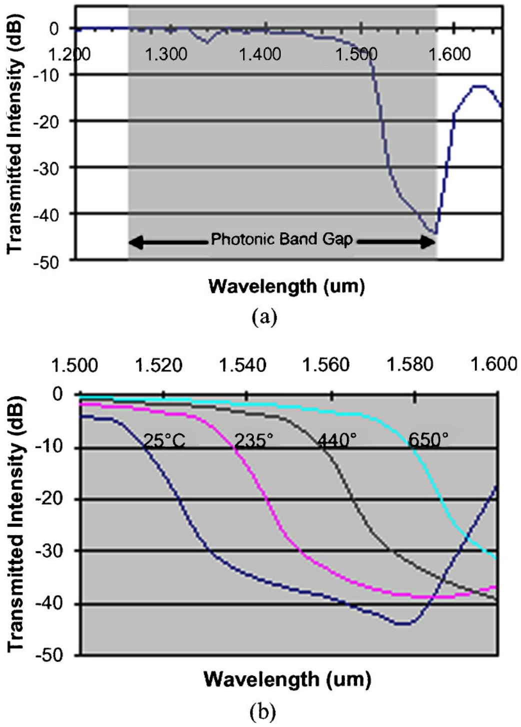

FIG. 2. (a) (Color online) Output intensity vs wavelength across the photonic band gap. (b) Shift of the cutoff frequency with temperature.

The magnetic amplitude of the light transmitted within these waveguides at both 25 and 650 °C is shown in Fig. 3 at 1500, 1550, and 1600 nm in order to provide a clearer understanding of the operative mechanism behind the device. At 25 °C, the transmission of light begins to weaken at 1500 nm as the light begins to spread out into the photonic crystal as it approaches the upper band gap. By 1550 nm, the device goes into strong cutoff as the extended modes can no longer be supported within the waveguide, causing the light to be reflected back out of the waveguide at the input. Finally, by 1600 nm the light actually begins to penetrate through the photonic crystal as it exceeds the band gap of the device. Consequently, the photonic crystals on each side of

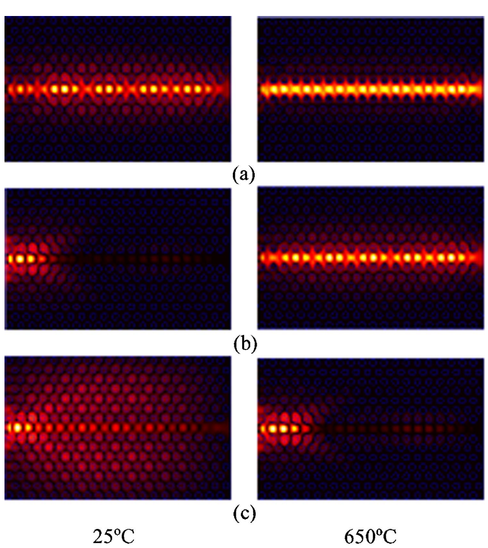

FIG. 3. (Color online) (a) Magnetic amplitude at 1500 nm, (b) 1550 nm, and (c) 1600 nm at 25 and 650 °C. Light input from the left side of waveguide.

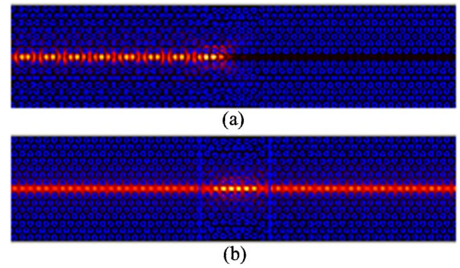

FIG. 4. (Color online) (a) Magnetic amplitude of light input into the modulator shown in Fig. 1 at 25 °C. (b) The magnetic amplitude with the modulator heated to 440 °C.

the waveguide no longer continue to act as two highly reflective mirrors that constrain the flow of light to the waveguide but begin to allow the light to penetrate into the photonic crystal itself. However, at 650 °C, the transmission of light is still strong at 1500 nm since the light is 60 nm farther away from the upper band gap than at 25 °C. However, by 1550 nm the transmission of light also begins to weaken, and by 1600 nm the device goes into strong cutoff. Note that cutoff is typically very abrupt, suggesting that devices can be designed using a much narrower width.

A device was designed to modulate light by varying the cutoff frequency at the telecommunication wavelength of 1550 nm by using the design shown in Fig. 1. The six-column-wide modulator in the center of the device was designed near the cutoff frequency with a lattice spacing of 320 nm and a diameter of 180 nm so that the device can be modulated by changing the cutoff frequency by the thermo-optic effect. The remainder of the waveguide was designed using a lattice spacing of 330 nm and a diameter of 180 nm in order to minimize the additional loss of light down the rest of the waveguide. This necessarily slows down the group velocity of the light through the modulator relative to the waveguide during transmission since the light is closer to the cutoff frequency in the modulator than in the rest of the waveguide but otherwise should have no notable effect on the operation of the device. The center of the device was heated to 440 °C within two columns widths of each side of the modulator in order to simulate the highly localized heating of the device to modulate the light. The modulator itself was only 1.92-μm wide and the width of the heat effected zone only 2.94 μm.

Simulation results shown in Fig. 4 clearly demonstrate that this device strongly modulates light at the telecommunication wavelength of 1550 nm. Note the increased intensity of the light in the modulator caused by the decrease in the group velocity of the light as it passes through the modulator, as shown in Fig. 4(b). However, this has no adverse effects on the modulation of the device as exemplified by the excellent ON/OFF characteristics of this device. The extinction ratio of this particular modulator is approximately 25 dB with an insertion loss of 1 dB. Increasing the width of the modulator to 12 columns wide increases the extinction ratio to almost 50 dB with almost the same insertion loss. Note that the insertion loss is significantly less here than that which would be estimated from the data acquired from the test devices shown in Fig. 2, suggesting that the insertion loss of modulators embedded in photonic crystal linear waveguides may perform much better than in the test devices. A number of other devices were designed with high extinction ratios and low insertion loss by varying the lattice spacings and diameters of the modulators and waveguides.

In summary, the thermo-optic effect can be used to modulate the position of the cutoff frequency in order to modulate light by designing short linear waveguides with optical characteristics close to the cutoff frequency. Small compact devices with widths of only a few to several microns can be designed with extinction ratios ranging from 25 to 50 dB with low insertion loss.

The authors gratefully acknowledge the financial support from the National Science Foundation through Grant No. ECS-0304442.

[1] T. F. Krauss, Phys. Status Solidi A **197**, 688 (2003).
[2] A. Martinez, A. Griol, P. Sanchis, and J. Marti, Opt. Lett. **28**, 405 (2003).
[3] M. H. Shih, W. J. Kim, W. Kuang, J. R. Cao, H. Yukawa, S. J. Choi, J. D. O'Brien, and W. K. Marshall, Appl. Phys. Lett. **84**, 460 (2004).
[4] E. Camargo, A. S. Jugessur, I. Ntakis, and R. M. De La Rue, Proc. SPIE **4944**, 376 (2003).
[5] Y. Sugimoto, N. Ikeda, N. Carlsson, K. Asakawa, N. Kawai, and K. Inoue, J. Appl. Phys. **91**, 3477 (2002).
[6] E. Camargo, H. M. H. Chong, and R. M. De La Rue, Opt. Express **12**, 588 (2004).
[7] Q.-A. Huang and N. K. S. Lee, J. Micromech. Microeng. **9**, 64 (1999).
[8] Q.-A. Huang and N. K. S. Lee, Microsystem Technologies **5**, 133 (1999).
[9] L. Que, J.-S. Park, and Y. B. Gianchandani, J. Microelectromech. Syst. **10**, 247 (2001).
[10] D. E. Ackley and J. Tauc, Appl. Opt. **16**, 2806 (1977).
[11] G. E. Jellison and H. H. Burke, J. Appl. Phys. **60**, 841 (1986).
[12] T. Baba, D. Mori, K. Inoshita, and Y. Kuroki, IEEE J. Sel. Top. Quantum Electron. **10**, 484 (2004).
[13] J. Yonekura, M. Ikeda, and T. Baba, J. Lightwave Technol. **17**, 1500 (1999).
[14] M. Notomi, K. Yamada, A. Shinya, J. Takahashi, C. Takahashi, and I. Yokohama, Phys. Rev. Lett. **87**, 253902 (2001).
[15] M. Iodice, P. M. Sarro, and M. Bellucci, Opt. Eng. (Bellingham) **42**, 169 (2003).