Hybrid Photonic Crystal Microcavity Switches on SOI

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ABSTRACT

We report the development and characterization of 2-D photonic crystal (PC) microcavity devices on silicon on insulator. The transmission of light through a 2-D PC microcavity near resonance can be switched on and off by modulating the refractive index of the PC. Because silicon has poor electro-optical properties, it is advantageous to insert electro-optic materials inside the air holes. In this work, we report the design, fabrication, and characterization of such hybrid PC microcavity switches using liquid crystals as the electro-optic material. In addition, we demonstrate an electrode geometry that eliminates electric field screening by the more conducting silicon host, and thus enables switching.

Keywords: SOI, photonic crystals, polymers, liquid crystals, silicon, switching, optical interconnect, electric tuning

1. INTRODUCTION

Increasingly, the computation speed of modern computers is limited not by the performance of the individual computing elements, but by the rate at which they can communicate with one another. In fact, the International Technology Roadmap for Semiconductors (ITRS) identifies interconnect performance improvements as one of its grand challenge areas going forward.1 One way to address this bottleneck is through the use of optical interconnects, which have the ability to provide a data path that has both greater bandwidth and lower latency than are possible using electrical interconnects.2, 3 Although there are several important components necessary to produce a fast and efficient optical interconnect, recent work has shown that a fast, silicon-based optical modulator is the most critical.3

A variety of modulator designs have been proposed or demonstrated, including Mach-Zehnder-based approaches 4, 5 and those based on resonant structures such as rings.6 A design based on a photonic crystal microcavity, however, offers unique advantages in terms of size and power consumption, both of which are crucial concerns for optical interconnects. Furthermore, the use of a hybrid structure, such as one incorporating electro-optic materials like liquid crystals or polymers into the pores of the photonic crystal, can help to fully leverage the power of the device. Compatibility with current and future CMOS processing can be preserved by infiltrating the electro-optic material at the last stage of fabrication.

2. METHODOLOGY

The design we propose in this work is based on a two-dimensional photonic crystal microcavity. A resonant approach was chosen because it offers significant advantages over other approaches, in terms of both device size and power consumption.7 We chose to implement the resonator as a microcavity in a photonic crystal because of the unique advantages photonic crystals offer over other resonant structures, especially in terms of size. Specifically, whereas the minimum physical extent of a microring resonator is determined by its operating wavelength, a photonic crystal microcavity can be made almost arbitrarily small with the only result being a reduction in the cavity’s Q-factor. This drawback can be overcome, however, by incorporating into the microcavity an electro-optic material that experiences a greater index contrast $\Delta n$. In fact, the photonic crystal microcavity can be designed to concentrate the optical field in the region of the electro-optic material, in order to increase operating efficiency and further reduce power consumption. In this way, photonic crystal microcavities are ideally suited for use in hybrid electro-optic switch designs.

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It should also be noted that reducing the Q of the microcavity may actually be desirable in many cases: by allowing the resonant mode to cover a broader range of wavelengths, greater tolerance can be permitted in manufacturing the devices. Manufacturability is often the ultimate deciding factor in what is implemented in modern chip designs.

Design of the photonic crystal microcavity was carried out using the MIT Photonic Bands (MPB) software. MPB was used to calculate the band structure and mode profiles of the microcavity. Two criteria were used in assessing the viability of candidate microcavity designs. First, the design had to concentrate the optical field inside the pore region, where the electro-optic material will be located, rather than in the silicon host material. Second, changing the refractive index of the electro-optic material by $\Delta n$ must produce a shift in at least one of the structure’s optical bands. The first criterion assures that the optical field will ‘see’ the electro-optic material. The second criterion assures that changing the index of the electro-optic material will result in a shift in the transmission spectrum of the microcavity, since the band structure corresponds to the photon density of states and thus to the transmission spectrum of the structure.

The design ultimately chosen consists of a two-dimensional triangular (hexagonal) array of round holes, with a single defect cavity in the center. The cavity concentrates the optical field such that it overlaps with the electro-optic material. In order to apply an electric field to the electro-optic material, we used a geometry proposed in previous work, wherein electrical contacts are fabricated on opposite sides of the photonic crystal. This configuration allows the electric field to flow laterally across the structure and ensures that the electric field is felt by the electro-optic material inside the pores, rather than being screened by the silicon. Figure 1 shows a finite element simulation of the electric field distribution in such a structure, and clearly indicates that the electric field is able to enter each pore, including the defect cavity. This work is the first we know of employing this geometry.

![Figure 1](image.png)

**Fig. 1.** Finite element simulation showing the electric field distribution in the photonic crystal structure. The rectangular strips are the electrodes across which voltage is applied. Lighter color corresponds to higher electric field.

### 3. EXPERIMENTAL

#### 3.1 Fabrication of the photonic crystal structure

The photonic crystal structure in this work is fabricated in SOI using standard silicon processing techniques. The SOI wafers used had an active silicon layer 300–450 nm thick, and a buried oxide layer 1 $\mu$m thick. Two different process flows were used, depending on the type of structure desired. In the first process, a layer of oxide approximately 150 nm thick is thermally grown on the SOI at a temperature of 1000$^\circ$C. PMMA e-beam resist is then spun onto the wafer, and a JEOL 9300 electron beam lithography system is used to define the structure of the photonic crystal, as well as that of the waveguides and couplers. Developing the PMMA removes any material that has been exposed by the JEOL, and a fluorine-based plasma etching process is used to transfer the pattern from the PMMA to the oxide layer by etching away
Fig. 2. Schematic showing the fabrication process flow for the photonic crystal microcavity in this work. First, a layer of silicon dioxide is thermally grown on a piece of SOI at approx. 1000°C. PMMA e-beam resist is spun onto the piece, and the desired pattern is exposed using a JEOL 9300 electron beam lithography system. The piece is developed, and the pattern is then transferred to the oxide layer using a fluorine plasma etch, and the PMMA is removed with an oxygen plasma ash. Next the pattern is transferred to the silicon layer using a chlorine plasma etch, and the remaining oxide is removed with a BOE solution.

Fig. 3. SEM image of the microcavity structure fabricated with the first method, using PMMA as the resist, and with a larger (800 nm) defect cavity.
Fig. 4. Schematic showing an alternate fabrication process flow for the photonic crystal microcavity in this work. First, a negative e-beam resist XR-1541 (HSQ-based) is spun onto a bare SOI piece, and exposed in the JEOL 9300. The piece is developed, and then etched in a chlorine plasma to transfer the pattern to the silicon.

Fig. 5. SEM image of the microcavity structure fabricated with the second method, using the negative e-beam resist XR-1541, and having a smaller (100 nm) defect cavity.
any oxide not covered by the remaining PMMA. The remainder of the PMMA is then removed using an oxygen-based plasma etch, leaving only the patterned oxide layer on the silicon. The oxide layer then acts as a mask during a subsequent chlorine-based plasma etch, which transfers the oxide’s pattern into the silicon. The oxide mask is then removed using a buffered oxide etchant (BOE) solution, resulting in the desired structure defined in silicon, and resting on the buried oxide layer of the SOI. This process is illustrated in Fig. 2, and Fig. 3 shows an SEM image of one of the resulting devices.

An alternate process that does away with the oxide pattern transfer step was also used. In this process, a spin-on-glass negative e-beam resist is spun onto bare SOI, and then exposed in a JEOL 9300 electron beam lithography system. Developing the resist removes those regions that were not exposed, such that the remaining exposed resist acts as a mask. A subsequent chlorine-based plasma etch is used to remove any silicon not covered by the resist, leaving behind the desired structure defined in silicon, and once again resting on the buried oxide layer of the SOI. Figure 4 illustrates this process, and Fig. 5 shows an SEM image of one of the resulting devices.

3.2 Definition of electrical contacts and infiltration of liquid crystal

Once devices have been fabricated using either of the above processes, electrical contacts must be defined in order to facilitate the application of an electric field to the photonic crystal region. The first step in this process is to evaporate 100–200 nm of aluminum onto the devices. A layer of photoresist is then spun on top of the aluminum, and exposed through a chrome mask containing the pattern for the electrical contacts. The photoresist is then developed and used as a mask during chemical etching of aluminum. The result is the desired aluminum pattern aligned to the device structure in silicon. Figure 6 is an SEM image showing a closeup of the contacts in the region of the microcavity. After contact definition, the facets of each device are polished to allow for more efficient coupling between the waveguides and fiber, which is outlined in section 3.3.

![SEM image of a microcavity after definition of aluminum electrical contacts. The contacts consist of a layer of aluminum 100–200 nm thick and deposited using e-beam evaporation. The contacts were patterned using photolithography followed by a chemical aluminum etch.](image)

Once the electrical contacts are defined, liquid crystals can be infiltrated using a relatively straightforward approach. First, the devices are heated to approximately 70°C. A micropipet is then used to deposit a small amount of LC onto
each device in the region of the photonic crystal, and the devices are left at temperature for approximately 5 minutes, after which they are cooled back to room temperature. The high initial temperature is used to ensure that the liquid crystal molecules are oriented isotropically, which enables them to infiltrate the pores more effectively.

3.3 Setup for measurement of transmission spectrum

In order to measure the transmission spectrum of each device, we used a tunable laser and a liquid-nitrogen-cooled germanium detector. Tapered fibers are used to couple to and from the device under test. In this setup, the device is placed on a stage and adjusted such that the device’s waveguides are aligned to the fibers. The input and output fibers are each aligned to the device using a three-axis (x,y,z) stage. Before coupling, however, the polarization of the light is verified using a Glan mirror and, if necessary, adjusted with a three-ring polarization controller. Once coupling has been achieved, the tunable laser is simply stepped through the entire range of wavelengths of interest, and the output from the germanium detector is recorded. The transmission spectrum of each device is calculated by dividing the germanium detector’s output by a spectrum taken while the Glan mirror was in place. A schematic of the setup is shown in Fig. 7.

Fig. 7. Schematic of the measurement setup showing the photonic crystal structure and waveguides. A tunable laser is used as the light source, and coupling is accomplished using tapered, lensed fibers.

4. RESULTS AND ANALYSIS

To observe the switching function of the device, we apply a voltage to the electrical contacts while the transmission spectrum is being measured. A square-wave signal at a frequency of 1 kHz was used, with the voltage ranging from 0–60 V peak-to-peak. As the electric field inside the pores of the photonic crystal increases, the LC molecules reorient such that they are parallel to the plane of the device, along the electric field lines. The result is a change in the index of refraction inside the pores, and thus a shift in the transmission spectrum of the device. Specifically, in the case of positive anisotropy LC such as Merck E7, light with horizontal (TE) polarization experiences an increase in the refractive index in the pores, while vertically (TM) polarized light would experience a slight decrease.

Simulations of the microcavity performed in MPB show that switching should be strongest for TE-polarized light. Since TE light experiences an increase in the pore refractive index with increasing applied electric field, we expect the transmission spectrum of the device to redshift when a voltage is applied. This behaviour is demonstrated in Fig. 8, which shows the transmission spectrum as it shifts in response to different levels of applied voltage. As can be seen, the central transmission peak redshifts by approximately 4 nm, from 1514 nm at zero voltage to 1518 nm at 15 V. Figure 9 shows a summary of the results obtained from a single device infiltrated first with positive-anisotropy (Δn > 0) Merck E7.
LCs mentioned above (triangles), and then with a negative-anisotropy LC, Merck ZLI-4788 (circles). The negative-anisotropy LC exhibits a negative index change upon the application of voltage, and thus causes a blueshift in the transmission spectrum. The same device with no LC exhibits no shift in its transmission spectrum (squares).

Our results demonstrate that a hybrid photonic crystal microcavity is a feasible basis for an electro-optic switch. This behavior is not limited only to liquid crystal as the active material, but should be applicable to other active materials such as electro-optic polymers. Polymers are especially attractive because they should allow very high switching speeds, whereas the switching speed with most LC is limited to the kHz range. Experiments to confirm and extend these results are currently in progress.

![Graph showing transmission spectra at different voltages](image)

**Fig. 8.** Transmission spectra of the photonic crystal microcavity structure at several different levels of applied voltage, measured for TE polarization. A redshift is observed because of the increase in refractive index due to the liquid crystal molecules’ realigning in response to the applied voltage. The high frequency oscillations are Fabry-Perot fringes due to reflection at the waveguide facets and at the waveguide/PC interface.

![Graph showing resonance shift as a function of applied voltage](image)

**Fig. 9.** Resonance shift as a function of applied voltage for a structure containing Merck E7 positive anisotropy liquid crystal (triangles), the same structure containing Merck ZLI-4788 negative anisotropy liquid crystal (circles), and the same structure again containing no liquid crystal (squares). A positive wavelength shift corresponds to a redshift.
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