Thermal tuning of silicon-based one-dimensional photonic bandgap structures

S. M. Weiss*1 and P. M. Fauchet1,2
1 Institute of Optics, University of Rochester, Rochester, NY 14627, USA
2 Department of Electrical and Computer Engineering, University of Rochester, Rochester, NY 14627, USA

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Thermal tuning of silicon-based one-dimensional photonic bandgap microcavities is demonstrated. Thermally induced spectral shifts are caused by both the host silicon matrix and the optically active material infiltrated inside the photonic bandgap structures. The active material leads to the dominant thermal tuning contribution but the effect of the silicon matrix cannot be neglected. The interaction of the temperature dependence of the host matrix with that of the active material is explored. The general trends revealed by the characterization should be relevant for two-dimensional silicon-based photonic bandgap structures as well as other photonic bandgap materials systems.

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1 Introduction

Photonic bandgap (PBG) structures have been investigated for many applications including mirrors [1], filters [2], waveguides [3], and lasers [4]. Enabling active devices makes PBG implementation even more attractive. The characteristic frequency range over which no light can be transmitted (i.e., the photonic bandgap) is defined by the length scale of periodicity and contrast of the dielectric functions of the PBG materials. Small perturbations of the dielectric function significantly affect the optical spectrum. Therefore, by changing the geometry or refractive index, light previously reflected at a particular wavelength can be transmitted.

Liquid crystals (LCs) have been investigated as a potential tuning agent for both thermal [5] and electrical [6] activation of PBG devices. A physical rotation of the LCs corresponds to a change in refractive index. The magnitude of thermal or electrical modulation can be used to tune the frequencies that fall within the PBG and actively control the operation of PBG devices.

Porous silicon (PSi) has proven to be a versatile medium for PBG structures. Passive one-dimensional PBG mirrors [1] and light emitting diodes [7] have been demonstrated. Infiltrating active material inside the PBG structure enables the formation of building blocks for tunable optical interconnects and light sources. These Si-based structures have the potential to be part of a microelectronics technology revolution [8].

Since spectral shifts control the performance of tunable devices, all factors that influence the optical properties of PBG structures must be considered. Temperature fluctuations often lead to changes in resonance positions and, hence, cannot be disregarded. It has been shown that the resonance position of PSi one-dimensional PBG microcavities (resonance near 1.5 μm) with no active material inside shifts by approximately 3 nm when the structure is heated from room temperature to 100 °C [9].
an optical interconnect where a microcavity resonance defines the passband for data transfer, the temperature range typically experienced by a computer processor may be sufficient to cause improper data transmission for very narrow resonances (e.g., < 1 nm [10]). Moreover, it has been shown that both the threshold pump power and operating wavelength of an InGaAsP-based photonic crystal laser depends significantly on the substrate temperature [11]. Therefore, a mechanism must be in place to account for the thermal drift introduced by the host PBG material in order to enable practical application of PBG devices.

2 Experimental

2.1 Porous silicon microcavity

The host structures for the thermal tuning investigation are PSi microcavities. Detailed procedures for the fabrication are published elsewhere [12]. PSi microcavities are formed by electrochemically etching highly doped (~0.01 Ω-cm) silicon in a solution of 15% hydrofluoric acid in ethanol. An alternating current density is applied to form the high and low refractive index layers. The current densities and etching times are carefully controlled to achieve the proper optical thickness for each layer of the microcavity. Alternating quarter wavelength optical thickness layers of 50% porosity and 75% porosity form the upper and lower Bragg mirrors. A half wavelength optical thickness defect layer (75% porosity) separates the two Bragg mirrors and creates a narrow resonance in the reflectance stopband. The resonance wavelength can be adjusted by appropriately modifying the thickness of each layer. Some of the microcavities are oxidized in a tube furnace with either flowing oxygen or nitrogen at temperatures ranging between 300 °C and 900 °C.

2.2 Liquid crystals

E7 nematic LCs are the active material infiltrated into the silicon matrix. To ensure uniform infiltration throughout the PSi microcavity, a vacuum technique is used for the infiltration [13]. E7 is chosen as the active material for its well-known high birefringence (Δn ~ 0.19 in the IR [14]). The magnitude of the active material birefringence is directly related to the tuning range of the photonic crystal structure.

3 Results and discussion

Experiments are performed to reveal the thermal tuning capabilities of one-dimensional PSi PBG microcavities. Thermal tuning contributions arise from both the host silicon photonic crystal and the LCs infiltrated inside the microcavities. In order to achieve practical device operation, both thermal contributions and interactions between the two contributions must be understood.

3.1 Tunable mirrors

Tunable mirrors have been fabricated for operation in the near IR. PSi microcavities serve as the host structure for the mirrors and LCs infiltrated throughout the microcavities enable active tuning. Figure 1 shows an example of thermal tuning of the mirrors. The signal is measured in reflectance using unpolarized light from a Perkin-Elmer Lambda 900 spectrophotometer with a spot size of approximately 3 mm. The resonance wavelength shifts by more than 7 nm. The magnitude of this shift indicates that a significant fraction of the LCs experience strong anchoring effects in the confined geometry of the PSi matrix [15]. For microcavities with narrower resonances, the on/off contrast will be significantly improved. The reflectance shift becomes most prominent near the phase transition temperature of E7 LCs (~59 °C). At the phase transition temperature, the LCs change from the ordered nematic phase to the disordered isotropic phase. Since the orientation of the LCs determines the refractive index, heating beyond the phase transition temperature will not lead to further resonance shifts. The maximum magnitude of the resonance shift is therefore determined by the initial LC alignment.
3.2 Tunable light sources

In addition to exhibiting high quality reflectance spectra that serve as the basis for tunable mirrors, PSi microcavities possess sharp photoluminescence (PL) peaks. Progress towards a tunable light source has been achieved by thermally modulating the PL spectra of LC infiltrated microcavities. An Ocean Optics HR2000 spectrometer with a spot size of approximately 1 mm is used for photoluminescence measurements. While the LCs appear to decrease the intensity of light emission, PL is not completely quenched upon infiltration. The basic mechanism for the PL shift is the same as that of tunable mirrors. However, the structure of the samples measured for PL and reflectance are different since the optical thicknesses of the layers must be adjusted appropriately to achieve resonances in the visible and near IR, respectively. Figure 2a shows that the spectral shift occurs over a narrow range of temperatures near the phase transition temperature of the E7 LCs. A large on-to-off contrast is achieved at 704 nm, as displayed in Fig. 2b. The initial emission wavelength can be set to any position within the standard PSi PL range (~600–900 nm) by adjusting the optical thicknesses of the PSi layers.

**Fig. 1 (a)** Reflectance redshift of tunable PSi microcavity resonance as a function of temperature. The shift saturates at the phase transition temperature of the infiltrated LCs. The schematics show the ideal LC alignment at temperatures below and above the phase transition. For lower temperatures, the LCs possess some alignment. At higher temperatures, the LCs lose their alignment and randomize. As the LCs rotate, the reflectance spectrum shifts. **(b)** Reflectance spectra of microcavity resonance at two different temperatures.

**Fig. 2 (a)** PL redshift of tunable PSi microcavity peak as a function of temperature. The shift saturates at the phase transition temperature of the LCs. **(b)** PL spectra showing peak at two different temperatures.
3.3 Influence of temperature on host PBG matrix
The implementation of tunable mirrors and light sources requires careful consideration of environmental factors that could lead to unwanted spectral shifts. Due to the temperature dependence of the refractive index of silicon, the optical spectra of all silicon-based PBG structures suffer from thermal drift. For the PSi one-dimensional PBG microcavity with no infiltrated active material, a resonance in the near IR will drift by 3 nm to longer wavelengths as the ambient temperature is increased from room temperature to 100 °C. In order to compensate for this drift, a simple oxidation treatment has been developed [9]. The annealing temperature and ambient oxygen content are adjusted to obtain a variable oxide thickness. 

As shown in Fig. 3, secondary ion mass spectrometry measurements indicate that oxidation in flowing nitrogen simply implies a lower oxygen concentration. Thermal desorption spectrometry measurements also support this claim. The surface stress induced by the oxide coverage of the silicon matrix provides a counterforce which serves to decrease the refractive index as a function of temperature. Therefore, depending on the degree of oxidation achieved, a redshift, no shift, or a blueshift of the resonance wavelength can result when the silicon-based PBG structure is heated (Fig. 3). The ability to control the thermal effects of the host PBG matrix allows for overall control of the tuning of these structures.

Fig. 3 (a) Reflectance resonance shifts of host PSi microcavities having various oxidation levels measured during subsequent heating of each sample. Depending on the level of oxidation, the resonance wavelength either redshifts, blueshifts, or remains nearly constant with heating. (b) Secondary ion mass spectrometry measurements show the relative percentages of silicon, oxygen, and nitrogen in microcavities for two different oxidation conditions. Flowing nitrogen instead of oxygen decreases the percentage of oxygen in the microcavities. There is only a minimal amount of nitrogen found in the microcavities.

3.4 Combined thermal effect of active material and host PBG matrix
The complete thermal response of the LC infiltrated PSi microcavities is a combined effect of the host PBG matrix and LC thermal dependencies. However, this combined effect is not straightforward. Preliminary experiments suggest that the oxidation treatment not only changes the host PBG matrix thermal response, but also affects LC alignment. Since surface tension and surface morphology play a significant role in determining the LC alignment, LCs may be positioned at different angles depending on the oxida-
tion conditions. Further analysis and experiments are necessary to quantify the effect that a specific oxidation treatment has on LC alignment.

3.5 Thermal tuning of two-dimension PBG structures

For two-dimensional PBG structures in silicon and other materials, the overall thermal response of the system will again be due to both the host PBG matrix and the LCs. The heating effect due to LCs will be more substantial in these structures since the host PBG matrix openings are much larger than those in the one-dimensional structures. Therefore, a greater number of LCs will rotate and contribute to the resulting spectral shift. The general trend for the temperature dependence of the host one-dimensional PBG matrix can likely be extended to two-dimensional PBG structures. Depending on the ratio of silicon to oxide, the PBG spectrum will blueshift, redshift, or remain constant as a function of temperature. However, in contrast to analysis of the one-dimensional PBG microcavities, there is likely a method of decoupling the thermal effect due to the host PBG matrix from that of the LCs. Since the host PBG matrix openings of the two-dimensional PBG structures are relatively large with smooth sidewalls, a surface alignment layer can be used to set the desired initial LC alignment, irrespective of the oxidation conditions for the structure [16]. In this case, the LC thermal response would be independent of the host PBG matrix preparation.

4 Conclusions

Tuning of one-dimensional PSi PBG microcavities is demonstrated. The reflectance and PL spectra of these structures are modulated based on the infiltration of LCs into the PSi matrix. The thermal response of the microcavities is adjusted by using an oxidation treatment to vary the magnitude and direction of the thermal drift caused by the host PSi matrix.

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