Strain-tunable silicon photonic band gap microcavities in optical waveguides

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We report the design, device fabrication, and measurements of tunable silicon photonic band gap microcavities in optical waveguides, using direct application of piezoelectric-induced strain to the photonic crystal. We show, through first-order perturbation computations and experimental measurements, a 1.54 nm shift in cavity resonances at 1.56 μm wavelengths for an applied strain of 0.04%. The strain is applied through integrated piezoelectric microactuators. For operation at infrared wavelengths, we combine x-ray and electron-beam lithography with thin-film piezoelectric processing. This level of integration permits realizable silicon-based photonic chip devices, such as high-density optical filters, with active reconfiguration. © 2004 American Institute of Physics.

Real-time reconfigurability is desirable for photonic crystal based telecommunication devices, as a means of provisioning optical networks and compensating for performance variations due to tight manufacturing tolerances or external disturbances. To this end, the modulation of photonic crystal optical properties through application of small strain was recently proposed. 1 Permanent deformations on the photonic crystal unit cell or defects have also been investigated for control of polarization, 2 coupled resonators field distributions, 3 and quality factors in microcavity lasers. 4

Here we demonstrate the design and experimental observations of tunable microcavity resonances through direct application of strain from integrated piezoelectric microactuators. The conceptual design of the strain-tunable platform is illustrated in Fig. 1. Four piezoelectric microactuators, each consisting of a tri-layer of platinum (Pt) top electrode, a lead zirconate titanate (PZT), and a Pt bottom electrode, are anchored onto the SiO2 deformable membrane. An optical waveguide with a photonic band gap microcavity 5 is located on the membrane between the microactuators. Active strain from the PZT microactuators, when placed under differential applied voltages, results in plane-strain deformation of the membrane and, hence, strain-induced perturbation of the microcavity. Compared with electro-optic 6,7 methods, piezoelectric strain-tuning is more practical toward silicon-based integrated photonic systems, given the weak Kerr nonlinearities in silicon. Moreover, compared with thermal 8,9 methods, piezoelectric strain-induced tuning permits nanowatt power consumption per active device as opposed to milliwatts, microsecond response times as opposed to milliseconds, and spatially localized tunability for high-density integration.

With the small-strain perturbation, order of 0.1%, the proposed device is expected to achieve at least greater than 109 repeated cycles, as performed on related deformable membranes, 10 without observable mechanical fatigue.

As shown in Fig. 2(a), the microcavity is formed by the introduction of a point defect into a periodic array of holes in the high-index contrast Si waveguide. The waveguide has submicrometer dimensions (t = 176 nm and w = 541 nm), is single-mode, and sits on a low-index SiO2 ridge (t = 296 nm). The periodic structure, with lattice constant a, splits the lower order guided mode at 1.56 μm wavelengths for an applied strain of 0.04%. The strain is applied through integrated piezoelectric microactuators. For operation at infrared wavelengths, we combine x-ray and electron-beam lithography with thin-film piezoelectric processing. This level of integration permits realizable silicon-based photonic chip devices, such as high-density optical filters, with active reconfiguration. © 2004 American Institute of Physics.

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in the band gap. The design has dimensions \( a = 429 \, \text{nm} \), \( a_d = 643 \, \text{nm} \), and \( d = 189 \, \text{nm} \). The electric field distribution is found through three-dimensional (3D) finite-difference time-domain (FDTD) computations. Figure 2(b) shows the electromagnetic energy distribution sliced through the middle of the microcavity. The observed strong field confinement gives a modal volume of \( 0.055 \, \mu \text{m}^3 \), about \( 5(\lambda/2n)^3 \), where \( \lambda \) is the resonant wavelength and \( n \) the silicon refractive index. The microcavity quality factor \( Q \), defined as \( \lambda/\Delta \lambda \) where \( \Delta \lambda \) is the full-width half-maximum of the microcavity transmission, is estimated to be 175. Applications of the microcavity include high-density optical filters and spontaneous-emission suppression. The design is predicted to be \( 2.1 \, \text{nm} \) from the more accurate 3D computation. Other effects such as index change due to applied stresses are found to be from changes in the defect length. A two-dimensional (2D) computation gives a similar final result for \( \Delta \lambda \), although the various contributions differ from the more accurate 3D computation. Other effects such as index change due to applied stresses are found to be secondary, changing \( \Delta \lambda \) by less than 1% fractional difference, for a strain of 0.1%.

Fabrication of the device necessitates the combination of x-ray and electron-beam lithography with thin-film piezoelectric microfabrication. X-ray lithography, with a \( \text{Cu}_x \) source at 1.3 nm, is used with a mask fabricated using electron-beam lithography to obtain 130 nm minimum feature sizes for operation at 1.55 \( \mu \text{m} \) wavelengths. A scanning electron micrograph of the fabricated microcavity is illustrated in Fig. 2(a). The fabricated thin-film microactuators have a piezoelectric dielectric constant of 1200 and a piezoelectric coefficient \( d_{31} \) about \( -100 \, \text{pC/N} \). The completed chip, before packaged for testing, is shown in Fig. 2(c).

To test the microcavities, two tunable laser diodes are used to provide a measurement window from 1430 to 1610 nm. A polarization controller and a fiber-coupled lens assembly were used to couple light into the structure. The resulting waveguide mode was imaged onto a photodetector and the signal was processed with a lock-in amplifier. The inset of Fig. 3 shows the top view of the coupled waveguides and the microcavity, captured with infrared cameras. Waveguide transmission losses were investigated through the Fabry–Perot resonance methodology using the cleaved facets of waveguides in devices without microcavities, and were determined to be between 5 and 7 dB/cm.

The measured microcavity transmission spectrum, with...
out active strain, is shown in Fig. 3. The higher-frequency band edge is at approximately 1450 nm, with excellent matching between experiment and theory without any fitted parameters. The microcavity resonance is observed at 1555.2 nm, with the FDTD predictions deviating by a 3.8% fractional difference. Although this represents a 59.3 nm deviation, the percentage deviation is well within the numerical resolution of the FDTD and the measurement accuracy of the device dimensions. The measured Q is 159, below the FDTD predictions of 175. This discrepancy is likely due to residual fabrication imperfections leading to increase in cavity losses. It should be possible to significantly increase Q to well over $10^5$ by well-known techniques, such as a small increase in the modal volume or a forced cancellation of the lowest order multipole term in the far-field radiation field.

When a dc bias is applied to the piezoelectric microactuators, the maximum $\Delta a$ is determined to be $+0.63$ nm for 16 V (tensile stress) applied and $-0.91$ nm for 15 V (compressive stress) applied. The tension and compression stresses are possible based on the location of the microcavity and the specific set of microactuators activated. Figure 4(a) shows the strain-tuned resonances for the various applied voltages. The fitted Lorentzians are generated through a trust-region nonlinear least squares algorithm with $R^2$ values of $0.94 \pm 0.03$. For the particular dimensions of the microcavity, $Q$ degrades by about 3% when under tension and improves when under compression. This is due to the dependence of $Q$ on the field profile and position in the band gap, both of which change under the applied strain.

Figure 4(b) compares the measurements with the first-order perturbation predictions. The applied strain is estimated through Computer Microvision, an instrument that can measure displacement with nanometer precision. The results are in excellent agreement: for an applied strain of 0.04%, first-order perturbation theory predicts a $\Delta a$ of 1.55 nm while our experimental measurements show a $\Delta a$ of $1.54 \pm 0.17$ nm. We expect, however, larger deviations for larger applied strains, since our predictions capture only the first-order perturbation.

In summary, we investigated the real-time configurability of silicon photonic band gap microcavities in optical waveguides, using direct application of piezoelectric induced strain. The tuning of the cavity resonance was first predicted theoretically through first-order perturbation theory on FDTD computations. By combining x-ray lithography, electron-beam lithography, and thin-film piezoelectric microfabrication, we built the tunable microcavities for operation at 1.55 $\mu$m. Experimental measurements demonstrate the cavity resonance shifts, within the band gap, when a strain is applied through the integrated microactuators, in agreement with our predictions. The results and analysis presented in this letter provide confidence that dynamic strain-tuning of photonic crystal devices is a realizable step toward practical photonic crystal implementations. Possible applications include postfabrication trimming for passive silicon-based integrated photonic systems, active feedback compensation for external disturbances, and device reconfiguration toward tunable optical filters. For the latter, a larger tuning range would be required, and it is possible for up to 8 nm (0.2% strain) at 1.55 $\mu$m optical wavelengths. This would be accomplished by delivering a larger force to the microcavity via a reduction in the membrane residual stress, wherein most of the elastic energy is dissipated, or in the membrane thickness.

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17. Higher-order perturbations suffer from the incomplete basis of our eigenproblem in terms of the electric field. However, we could cast the eigenproblem in terms of the magnetic field (such that $\mathbf{V} \times \mathbf{H} = 0$ is satisfied) to compute higher-order corrections. Issues of fast-convergence, however, would need to be solved.
18. A variational approach to the elastic strain energy in the double-anchored membrane suggests residual stress is the largest contributor, following the technique shown by Senturia, S. D., Microsystems Design (Kluwer Academic Publishers, Massachusetts, 2001).