Strain-tunable Photonic Band Gap Microcavity Waveguides at 1.55 µm

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Concept and Key Idea
Photonic-bandgap microcavities in optical waveguides have demonstrated cavity resonances at wavelengths near 1.55 µm band, quality factors on the order of 300, and modal volume at 0.055 µm³ in high-index contrast Si,SiO₂ waveguides and GaAs air-bridge waveguides. Applications include zero-threshold microlasers, filters and signal routers. For tunability in Si microphotonic platforms, thermal actuation is often utilized. Compared to thermo-optics, the novel strain-tuning via thin-film piezoelectric micro-actuators provides a significantly faster response, lower power consumption and better localization of tunability. This level of integration would permit dynamic reconfiguration of the cavity resonance and band-edges, fine-tuning for fabrication mismatches, and active compensation of device arrays to external disturbances. We have designed and fabricated the first tunable photonic-bandgap microcavities in optical waveguides, with the strain modulation via thin-film piezoelectric actuators on deformable membranes. Cavity resonance tunability, with sub-nanometer lattice control, is designed through perturbation on FDTD computations. Device fabrication integrates X-ray nanolithography, piezoelectric micro-actuators and bulk micromachining.

Device Design
The conceptual design is illustrated in Figure 2. The Si microcavity waveguide is located on a deformable double-anchored SiO₂/Si membrane. The thin-film piezoelectric actuators provide sufficient driving force, under 5V actuation, for the sub-nanometer strain control of the geometric lattice in the microcavity. Comparative designs of the double-anchored membrane have been demonstrated for analog tunable diffractive gratings. Experimental effects of static strain on coupled vertical microcavity resonators and theoretical designs for shear-modulated 2D photonic crystals on bulk piezoelectric substrates have also been reported.

We employ first-order perturbation theory to obtain a semi-analytical result for the strain-induced shift in the cavity resonance; such methods ease the study of small modulations such as the 0.3% strain considered here. First, a closed-form solution for the hole boundary displacements is derived following classical mechanics. The material boundary displacements are then numerically meshed and employed in a perturbation-theory formulation, which involves surface integrals of the unperturbed fields (obtained by FDTD simulation) over the perturbed material boundaries. The result predicts a 0.8% shift in resonant wavelength (12.7 nm in the C-band) for a 0.3% mechanical strain from a 3D computation. This is illustrated in Figure 5a. While a 2D computation suggests similar final results in the resonant shift, the 3D computation highlights differences from the individual contributions – hole ellipticity, defect cavity length, and hole diameters – in the strain perturbation. Other effects such as photoelasticity and waveguide out-of-plane bending were found to be secondary.

Fabrication and Results
Encouraged by the theoretical suggestions, we proceed to integrate X-ray nanolithography with thin-film piezoelectric microfabrication to fabricate the device. X-ray nanolithography is used in order to pattern
feature sizes on order of 100 nm for operation at 1.55 µm. First, an X-ray mask – generated earlier through e-beam nanolithography – is brought in proximity to a poly-methyl-methacrylate resist on the wafer substrate. A CuL source at 1.3 nm generates the X-rays to transfer the microcavity pattern from the mask to the resist. The resulting pattern is inverted through lift-off into a 35 nm chromium hard mask for subsequent reactive ion etching into a 212 nm single crystal Si layer. The substrate is a Unibond silicon-on-insulator wafer. A scanning electron micrograph of the fabricated microcavity is illustrated in Figure 2b.

The integrated thin-film piezoelectric microactuators is fabricated through a sol-gel process where we develop a wet-etch method to pattern the sol-gel film before annealing. The etchant is a diluted HCl:HF solution and the annealing performed at 650 °C without any PZT cracks while maintaining a good perovskite phase. The completed piezoelectric film has a dielectric constant at 1200 and a piezoelectric d31 coefficient estimated at -100 pC/N. The sample is carefully cleaved to obtain waveguide input and output ports flushed with the substrate for testing. Lastly, a XeF2 isotropic Si etch is used to define the double-anchored membrane with high fabrication yield. The completed chip is shown in Figure 2c.

Experiments: static and dynamic

To test the microcavities, two tunable laser diodes are used to provide a measurement window from 1430 to 1610 nm. A fiber lens assembly, with polarization controllers and lock-in amplification, is used to the couple light into and out of the waveguides. Infrared cameras are also used in the setup to determine proper coupling into the waveguides and image the guided modes. The inset of Figure 3 shows the top view of the coupled waveguides and the microcavity.

The measured microcavity transmission spectrum, without active strain, is shown in Figure 3. The resonance is at 1555.2 nm, within a 0.2% fractional difference with the numerical FDTD predictions. The measured Q is 159, in good agreement with theory. This particular device had defect length a of 643 nm, lattice constant a of 429 nm, averaged hole diameters of 189 nm, and a waveguide width w of 540 nm. Waveguide losses were investigated through a Fabry-Perot resonance method using the end facets of the waveguide without the microcavity, and determined to be between 5 – 7 dB/km.

When a DC-bias is applied to the piezoelectric microactuators, the shift in resonance, Δλ, is determined to be -0.91 nm for 15 V (compressive stress) applied and +0.63 nm for 16 V (tensile stress) applied. These transmission measurements mark the first demonstration of active strain to dynamically tune the responses of silicon photonic crystals. The shifts in resonance for each applied voltage is averaged over multiple measurements, holding the voltage constant. The resonance wavelength noise, without any active tuning, is determined to be 0.02 nm from multiple measurements. The fitted Lorentzians are generated through a trust-region nonlinear least squares algorithm with R² values of 0.94 ± 0.03. Q also changes slightly when strain is applied to the microcavity.

Conclusions

The experimental verifications and theoretical predictions presented above provide confidence that dynamic strain-tuning is a realizable step towards practical photonic crystal implementations, be it in terms of post-fabrication trimming applications, active feedback compensation for external disturbances or device reconfiguration towards tunable optical filters. A larger tuning range, and larger applied strain, is readily possible up to 8 nm (0.5% modulation) at 1.55 µm optical wavelengths through a reduction in the membrane residual stress, wherein most of the elastic energy is dissipated, or in the membrane thickness.
Fig. 2 Device schematic of the tunable photonic-bandgap microcavity waveguide, with strain modulation via thin-film piezoelectric actuators on the deformable membrane.

Fig. 3 (A) Scanning electron micrograph of the embedded microcavity patterned by X-ray lithography. Inset: side-view of Si waveguide on SiO₂ ridge. (B) Electric energy distribution at middle 2D slice of microcavity, at resonance. (C) Top view of completed strain-tunable microcavity with integrated piezoelectric microactuators.