Fabrication and Characterization of Nanobeam Resonators with Waveguides

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Introduction:

Photonics research involves the manipulation and characterization of light flow through materials with engineered geometries. Like electronics, which seeks to control the behavior of electrons, photonics seeks to control the behavior of photons. Photonic crystals employ periodic changes in refractive index to elicit specific behaviors from photons. Recently, photonics researchers have made progress in confining and guiding light at sub-wavelength scales in photonic crystal resonators with high quality factors. These devices have potential applications in chemical sensing, optical switching, nanoscale lasers, low power nonlinear optics, cavity quantum electrodynamics, and light-matter coupling [1].

This project involved the fabrication and characterization of silicon nanobeam cavities, a type of one-dimensional photonic crystal resonator, and its aim was to optimize a new method of probing the optical resonance modes of these cavities. Our cavity design extended the work done by Deotare, et al, who have improved fabrication quality of nanobeam cavities and have achieved quality factors as high as 7.5×10^5 [2].

The quality factor, Q, is related to how long a resonant photon remains contained within the cavity. Practically speaking, fabrication quality prevents the realization of the maximum theoretical quality factors which are on the order of 2.0×10^7. Typical near-IR resonators (see Figure 1) are approximately 500 nm wide, 10 μm long, and 220 nm deep.

The periodic, uniform holes along the silicon nanobeam are Bragg mirrors, which act as ideal mirrors over a range of frequencies and define the characteristic optical bandgap of the cavity. By introducing a defect in this series, typically done by perturbing the spacing at the center of the series of holes, resonance modes emerge. Thus, when the cavity is probed with an appropriately polarized resonant wavelength, photons are trapped near the defect for a relatively long period of time. Tapering the size and spacing of the holes nearby the defect allows for impedance matching which is necessary to achieve high Qs.

Currently, the group employs a resonant scattering technique to probe the optical properties of these cavities. However, the coupling of the laser light from free space at normal incidence restricts the number of modes available for excitation.

In order to probe modes with a wider range of polarizations, our new design incorporated waveguides, solid beams of silicon, onto both ends of the resonator. The waveguides provided a new way to direct the pump beam which excited the resonance modes to the cavity. It was then possible to couple the end of a waveguide to a pulled optical fiber-taper carrying a large evanescent field. We also inserted an intermediate SU-8 waveguide to reduce scattering losses between the silicon waveguide and the optical fiber.

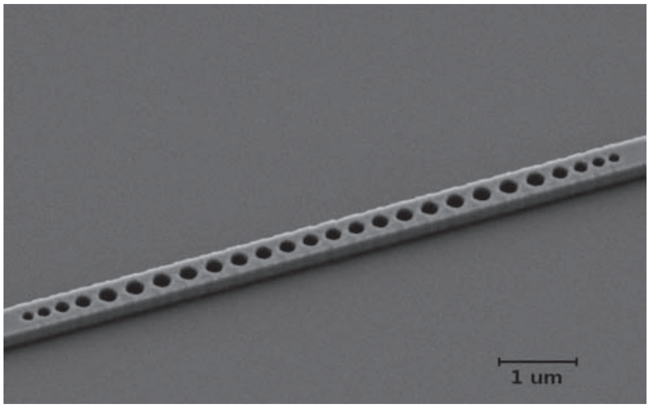

Figure 1: Fabricated resonator.

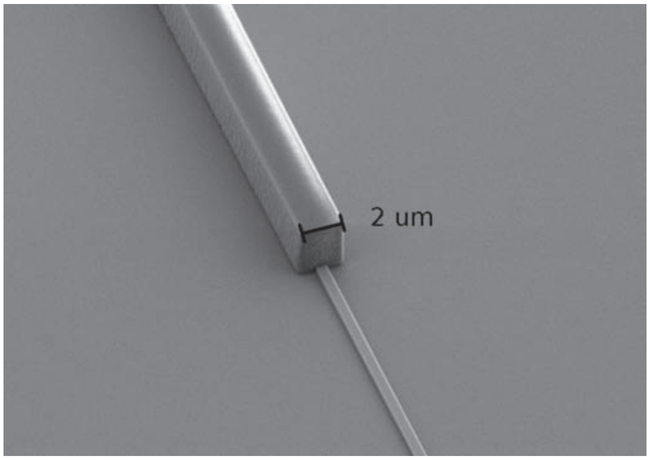

Figure 2: Fabricated waveguides.

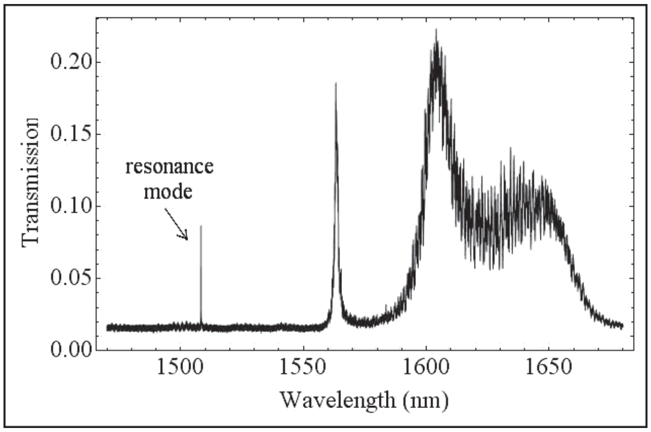

Figure 3: Transmission spectrum.

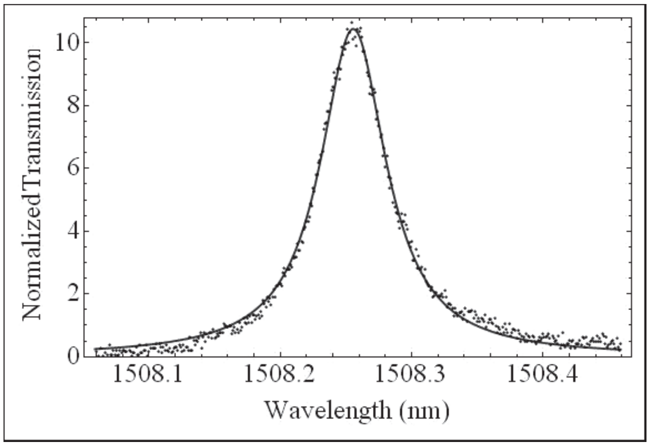

Figure 4: Resonance mode.

Experimental Procedure:

The cavity design was simulated using finite difference time domain (FDTD) software, and we expected a resonant wavelength around 1.51 μm. We transferred the design geometry to AutoCAD in order to produce a file readable by the Elionix electron-beam lithography tool. We wrote the pattern to an silicon-on-insulator (SOI) wafer covered in FOx-17 (HSQ), a negative electron-beam resist. Reactive ion etching (RIE) allowed us to transfer the pattern to the silicon device layer of the wafer. The RIE recipe consisted of C_4F_8, SF_6, and H_2 plasmas and had two steps, a silicon etch phase and a silicon oxide etch phase; this helped prevent undercutting which could become a problem when the substrate etched at uneven rates. Subsequently, we wrote SU-8 waveguides using a similar electron-beam lithography technique. We used scanning electron microscopy (SEM) to image the results of the fabrication procedure.

To characterize the fabricated cavities, we input a tunable near-IR laser beam into an optical fiber which carried the probe beam to our sample. We brought the probe beam from the fiber to the cavity through the SU-8 waveguide and the silicon waveguide. Resonant photons tunnel through the cavity and may emerge at the other side. Then, they pass through an identical series of waveguides and fiber to a photodetector where we measured the transmission spectrum of the cavity. Hence a peak in the spectrum indicated a resonance mode.

Results and Conclusions:

Figure 1 is an SEM image of a silicon resonator resting on an oxide substrate, taken at a 45 degree angle from the surface to inspect the quality of the silicon dry etch. Figure 2 shows the interface between a silicon waveguide and an SU8 waveguide.

We have demonstrated that it is possible to measure resonance modes by probing through waveguides. Figure 3 is a sample measured transmission spectrum, which has a resonance peak that is more easily detectable than typically observed using the resonant scattering technique. We fit the resonance peak to a Lorentzian distribution function in Figure 4, allowing us to determine the quality factor of this cavity to be 25000.

Future Work:

Future work includes continuing to optimize this characterization technique, through improving the waveguide fabrication procedure and investigating cavity resonance modes that have not been measured previously. This technique can also be applied to investigate the resonance modes of more complicated structures such as coupled resonators [1]. In this case, a hydroflouric acid (HF) vapor etch would be used to fabricate suspended cavities anchored to an oxide substrate via the extended silicon waveguides.

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References:

[1] P. B. Deotare, M. W. McCutcheon, I. W. Frank, M. Khan, and M. Loncar. Coupled photonic crystal nanobeam cavities. Applied Physics Letters, 95, 2009.

[2] P. B. Deotare, M. W. McCutcheon, I. W. Frank, M. Khan, and M. Loncar. High quality factor photonic crystal nanobeam cavities. Applied Physics Letters, 94:121106, 2009.