Random High-Q Cavities in Disordered Photonic Crystal Waveguides

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Abstract:
We present direct observations of electromagnetic fields localized in disordered photonic crystal waveguides and report the modal volumes and quality factors of the confined modes. Geometrical perturbations distributed uniformly throughout the crystal lattice were introduced by changing orientations of the polygonal lattice elements. Cavities in the disordered waveguides were excited by resonant coupling through a chain of random open resonators. Localized optical resonances with sub-((\lambda/n)^3 modal volumes and quality factors of up to ~ 150,000 were observed.

Summary:
Two-dimensional photonic crystal (PhC) slabs are periodic high-index-contrast structures that inhibit light propagation in bands of frequencies. Breaking the lattice periodicity by removing, shifting, or changing the size of the lattice components introduces local defects which can effectively guide, delay, and store light. In this work, we investigate a different form of lattice perturbations and provide further insight into the nature of light confinement in disordered PhC waveguides by presenting direct measurements of modal volumes (localization lengths) and quality (Q) factors of the localized fields [1].

The present design preserves the average PhC periodicity while replacing conventional circular patterns in the design files with randomly oriented polygons. This simple realization of disorder is different from the one described in our earlier publication, where shape perturbations of the lattice elements was achieved by applying random deflection jitter to the patterning electron beam (EB). The previous approach lacked analytic control over the superimposed roughness function and did not allow systematic introduction of long-range correlations for future studies of wave transport and localization. In the present work, the PhC platform is composed of a hexagonal array of pentagons, some of which are rotated around their centers by 24° in the clockwise or the anticlockwise direction, as shown in Figure 1.

The disordered PhCs were fabricated on silicon-on-insulator (SOI) substrates using EB lithography and two-step reactive ion etching (RIE). The SOI wafers were thermally oxidized to form a 220 nm thick Si layer clad by 30 nm of thermal oxide from above and 1 \mu m of buried oxide (BOX) from below. The polynomial patterns were then defined with a 100 kV EB (JEOL 9300) and transferred into the top oxide layer with a RIE process based on CHF_3/O_2 chemistry. The thermal oxide layer was then used in another RIE step as a hard mask to etch through Si with inductively coupled Cl_2/BCl_3/H_2 plasma. The BOX layer and the residual thermal oxide were eventually removed with buffered hydrofluoric...
The fabricated pentagons have rounded vertices with a curvature of $r \approx 10$ nm; the etched sidewalls are vertical within $4^\circ$ from the plane normal; and the fabrication-induced surface roughness is $< 5$ nm, as determined from scanning electron (SEM) and atomic force micrographs (AFM) of the processed structures shown in Figure 2.

TE-polarized output of a tunable infrared diode laser ($\lambda = 1475$–$1580$ nm, 100 kHz linewidth, and 2 pm tuning resolution) was coupled evanescently into the disordered W1s from an adiabatic taper prepared from a single-mode telecom fiber. The light leaking vertically out of the PhC waveguide was collected with an infinity-corrected 100× objective (numerical aperture of 0.80). The intensities and spatial profiles of the collected radiation patterns were monitored with an InGaAs camera (Sensors Unlimited, SU320MX-1.7RT) while the wavelength of the coherent laser was scanned. A LABVIEW program was used to generate two-dimensional intensity maps of the spatially resolved spectra which match the spectral features with the positions of sources of the detected light. Figure 3(a) shows the contour plot acquired from a typical, 110 $\mu$m long disordered W1. The spectral component of the displayed data shows an ~ 10 nm broad band filled with multiple pronounced peaks with effective $Q$'s ranging from several thousands to ~ 150,000. The $Q$'s were estimated from the full width at half maximum of the Lorentzian-shaped peaks shown in the spatially integrated spectra in Figure 3(b). Detailed scans of spectrally isolated modes of various $Q$'s and localization lengths, together with images of their field distributions on resonance, are presented in Figure 4. Resonance 1 extends far into the waveguide and contains several spatially separated intensity peaks. It has a relatively low $Q$ and can be explained with a series of coupled resonators.

In summary, our measurements show that engineered structural disorder superimposed uniformly throughout a PhC lattice results in efficient light confinement. Localized quasimodes with various $Q$'s and modal volumes were observed. The results can be useful for applications in sensing systems and low-threshold random nanolasers.

References: