Random high-*Q* cavities in disordered photonic crystal waveguides

J. Topolancik and F. Vollmer[a)]
Rowland Institute at Harvard, Harvard University, Cambridge, Massachusetts 02142, USA

B. Ilic
Cornell NanoScale Facility, Department of Applied Physics and Field of Biophysics, Cornell University, Ithaca, New York 14853, USA

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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. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2809614]

Two-dimensional photonic crystal (PhC) slabs are periodic high-index-contrast structures that inhibit light propagation in bands of frequencies.[1,2] Breaking the lattice periodicity by removing, shifting, or changing the size of the lattice components introduces local defects which can effectively guide,[3–5] delay,[6,7] and store light.[8–11] We have recently explored a conceptually different approach to photon confinement in PhC structures. The design concept applies structural perturbations which are distributed uniformly throughout the artificial crystal by deliberately changing the shapes of lattice elements.[12] The nanometer-scale disorder introduced in this way effectively represents randomly distributed scatterers which impede propagation of Bloch waves through the underlying periodic structure. We have shown that highly dispersive guided modes propagating along line defects in disordered PhCs experience strong coherent backscattering which gives rise to Anderson localization. The effect was observed in a narrow band close to the guided mode's cutoff where light propagates with a slow group velocity and interaction with the superimposed disorder is the strongest. In this letter, 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.

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).[12] 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 Fig. 1(a). The orientation of the pentagon at a particular lattice point is chosen at random while the total numbers of features with a specific orientation are equal. The lattice constant a $=410$ nm and the average air fill factor of ~30% are fixed throughout the PhC. The disorder introduced this way goes beyond the usual surface roughness caused during fabrication, but the underlying lattice periodicity is mostly preserved. Single-line-defect waveguides (W1s) were defined in the hexagonal array by removing rows of pentagons along the Γ-*K* lattice symmetry direction. W1s formed in disorder-free PhCs composed of circular holes are known to exhibit a stop band (or mode gap), which is a band of frequencies where wave transport is prohibited. TE-polarized electromagnetic (EM) waves (electric field parallel to the crystal plane) are guided in the pass band of these structures by the photonic bandgap within the PhC plane and by total internal

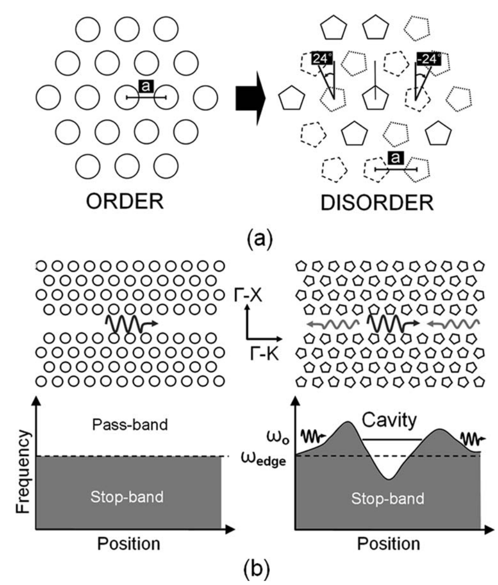

FIG. 1. (a) Description of the introduced lattice disorder. Circular lattice elements in the hexagonal array are replaced with pentagons with three specified orientations. (b) Schematic illustration of the effect of disorder on the band structure of Γ-*K* line-defect waveguides. Top: an extended propagating wave (black) is backscattered (gray) by disorder which results in its localization. Bottom: an alternative localization picture. Fluctuations of the stop band edge (ω_{edge}) create wells in which photons of certain energies (ω_0) are confined.

[a)]Electronic mail: vollmer@rowland.harvard.edu reflections in the out-of-plane direction. Introduction of disorder perturbs the translational symmetry of the waveguide causing slight fluctuations of the stop band boundary which effectively creates opaque barriers through which EM waves evanescently couple into transparent wells in which they become confined. This is illustrated schematically in Fig. 1(b) where a cavity with a resonant frequency ω_0 is formed in the proximity of the unperturbed mode edge (ω_{edge}) by disorder-induced backscattering of the propagating wave. Tuning of the barrier heights and well dimensions by design is an established way of photon localization by the so-called mode-gap effect which has been employed extensively to engineer high-Q nanocavities with ultrasmall modal volumes.[9,10] The system at hand can be essentially regarded as an experimental realization of mode-gap confinement in randomized PhCs. While sharing the conceptual origin, random resonators are different from designed nanocavities in the following way. Geometry of an engineered cavity is usually optimized with a systematic parametric search aimed to reduce the modal volumes and minimize losses. The cavity resonances are excited evanescently from a feeding waveguide and their Q's are dictated by the strength of the in-plane coupling to the waveguide and vertical coupling to the continuum. On the other hand, a cavity in a disordered W1 is excited by resonant tunneling through other cavities along the waveguide which form a chain of coupled random open resonators. The coupling process is a research topic in itself as it leads to interesting wave transport and localization phenomena.[13,14] The Q of a cavity in the random chain depends on its geometry, the strength of lateral coupling to its neighbors, and the fabrication-induced surface roughness which causes additional scattering. It is conceivable that disordered structures support low-loss cavity geometries which have so far not been discovered by parametric optimization. Deliberate introduction of random disorder could therefore further improve Q's of PhC-based nanocavities. Theoretical investigations of one-dimensional systems with various levels of disorder suggest that there is an optimum amount of defects which maximizes the quality of confinement.[15] These results therefore suggest that cavities in partially ordered structures should have Q-factors superior to those supported by completely random systems.[16]

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 μm 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 acid forming 220 nm thick freestanding PhC slabs. The fabricated pentagons have rounded vertices with a curvature of $r \cong 10$ nm; the etched sidewalls are vertical within 4° 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 Fig. 2.

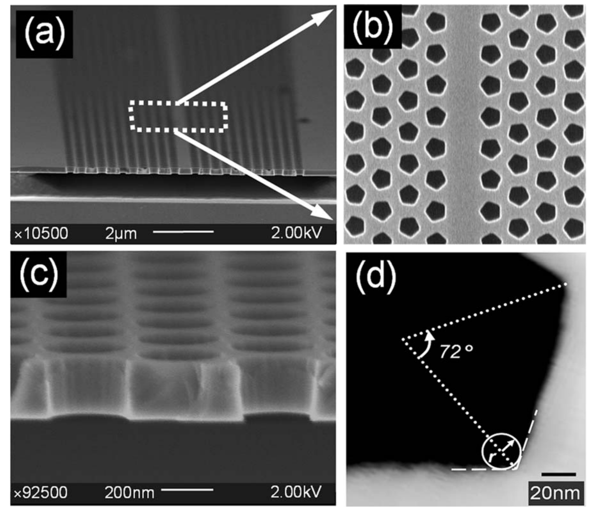

FIG. 2. (a) SEM image of the fabricated PhC slab, (b) top view of the randomized pattern, (c) detailed micrograph of the cleaved facet showing the tilt and the surface roughness of the etched wall, and (d) AFM image showing the top edge roughness and the rounded vertices of a pentagonal air hole.

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, as described elsewhere.[12] 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 μm long disordered W1. The x axis is the wavelength of the collected

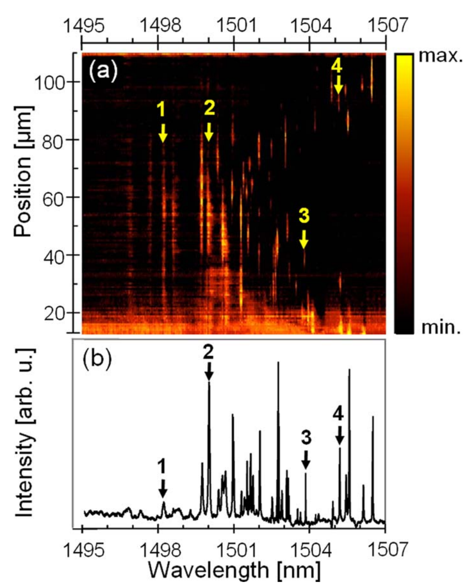

FIG. 3. (Color online) (a) Contour plot of spatially resolved spectra of the vertically dissipated light from a 110 μm long disordered waveguide. Wavelength-scan step size is 5 pm. Spatial positions up to $\sim$13 μm from the edge are not shown due to excessive surface scattering in that region. (b) Total, spatially integrated spectra of the same sample showing multiple Lorentzian-shaped resonances.

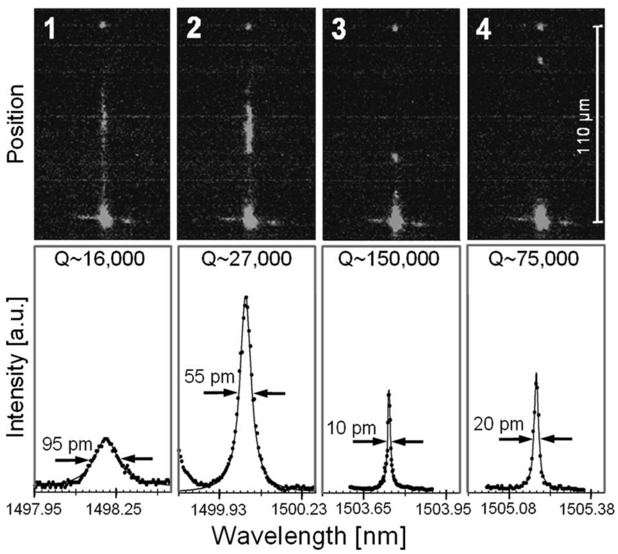

FIG. 4. Near infrared images of the scattered fields (top) and detailed spectra (bottom) for four wavelengths marked in Fig. 3. The light is incident from the bottom and the bright spot that marks the end of the waveguide and is present at all scanned wavelengths is caused by scattered light reflected to the waveguide's outlet from the other facet of the ~3 mm long cleaved sample.

light and the y axis is the distance from the edge of the waveguide. 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 Fig. 3(b). The contour plot shows that the vertically leaking light is emitted from "hot spots" of various sizes which are distributed randomly along the disordered waveguide. The observed resonances are localized in waveguide sections ranging from less than 2 μm to a significant fraction of the waveguide length. Although the size and the shape of the observed emission patterns could not be determined more precisely due to the limited resolution of our imaging system, the captured images are sufficient to conclude that the disordered W1 contains nanocavities with sub-$(\lambda/n)^3$ modal volumes. 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 Fig. 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. Resonance 2 is a textbook example of an exponentially localized wave in a random medium with the maximum field intensity at the center of the sample.[17] Resonances 3 and 4 are especially interesting as they are extremely well localized deeply in the waveguide and exhibit high Q factors. We would like to note that the effective Q of ~150 000 (Resonance 3) is less than an order of magnitude smaller than the record-high value measured in PhC cavities ($Q\sim 1\,200\,000$).[18] Having compared spatially resolved spectra of W1s with different realizations of disorder, we conclude that the quality of confinement improves with increasing excitation wavelength, i.e., the localization lengths shrink and the Q's rise as the spectral penetration into the stop band of the underlying periodic system increases.

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.

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