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Disorder-induced high-Q cavities in photonic crystal waveguides

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ABSTRACT

We demonstrate experimentally that random departure from high-index-contrast periodicity in photonic crystal waveguides gives rise to spectral features that bear signatures of Anderson localization. Disorder-induced high-Q cavities are observed in a narrow frequency band close to the guided mode’s cut-off where the light propagates with slow group velocity. Spectrally distinct quasi-states with Qs as high as $\sim$250,000 are distributed at random locations along the waveguide and can find applications for example in optical sensing systems.

Keywords: photonic crystal waveguide, Anderson localization, random media, slow light, optical cavity, coherent scattering

1. INTRODUCTION

Optical cavities defined by point defects in photonic crystal (PhC) slabs localize light in sub-$\left(\lambda/n\right)^3$ modal volumes by distributed Bragg scattering within the 2D plane and by total-internal reflection (TIR) in the out-of-plane direction. The Q-factor is primarily limited by leaky $k$-space components that do not satisfy condition for TIR. Since the Fourier transform of $k$-space components corresponds to the field distribution, Q-factor of particular cavity geometry can be optimized by shifting the location or changing the size of lattice elements that surround the defect. Systematic parameter space searches aimed for cavity designs that exhibit small modal volumes produced Qs $\sim$100,000-1,000,000, and analytic relations were derived to solve the inverse problem of finding cavity geometry that supports a select high-Q cavity. One of the highest Q-values ($\sim$1,200,000) was reported for mode-gap confinement in double-heterostructure PhC waveguides formed by a missing row of air-holes within the hexagonal lattice (W1). Mode-gap confinement relies on the fact that increase of lattice constant tunes the cut-off frequency of the W1 waveguide mode. By introducing a local dislocation of lattice constant in W1, light of specific frequency can only reside in the so created transparent region and is otherwise reflected by the neighboring waveguide segments forming a high-Q cavity with sub-wavelength modal volume $\lambda$.

A different mechanism for localization was predicted for waves in disordered 3D media where coherent multiple scattering can lead to strong localization (Anderson localization). The theory was originally developed for matter-waves (electrons in disordered atomic crystals), but it can be directly extended to classical waves and light in particular. Experimental evidence for strong photon localization has been difficult to demonstrate as it requires strongly-scattering materials with minimum absorption. Only few experiments in random media and, more recently, in a disordered two-dimensional lattice reported experimental signs of localization. It has been proposed by John that conditions for localization should be easier to attain by superimposing the disorder on a high-index-contrast periodic structure that exhibits photonic band gap (PBG). Compared to random media, coherent scattering from superimposed disorder in a PBG material should result in strong localization at frequencies close to a band edge where the Ioffe-Regel condition for localization is satisfied. A W1 waveguide that exhibits random departure from perfect-index periodicity can essentially be regarded as a quasi-1D realization of such a disordered PBG system. Here we show experimentally that superimposing disorder on W1 waveguides by randomly changing the shape or orientation of lattice elements produces a new type of coherent localization analogous to that observed in strongly-scattering random media. The localization phenomenon with Q's of up to $\sim$250,000 is observed in a narrow ($\sim$5-30 nm) bandwidth close to the cut-off of the slowly guided Bloch-mode. The localization mechanism is reminiscent of that observed in engineered double-heterostructure cavities where light of specific frequency is confined in a ‘well’ created by enclosing a transparent waveguide segment.

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between two opaque sections. For the case of disordered W1s, transparent and opaque waveguide segments are formed randomly from a fluctuating stop-band boundary in the slow-light regime.

2. RESULTS

2.1 Photonic crystal waveguide fabrication

Two different strategies are employed to introduce disorder in W1s defined in a hexagonal PhC lattice formed by patterning of air-holes in a silicon slab (Fig. 1 (a)). In a first approach\textsuperscript{17}, small structural perturbations are introduced by applying current jitter to the patterning high energy electron beam (EB, JEOL 9300 operated at 100kV). As result, the shapes of the fabricated holes are slightly distorted from ideal circles of the original design files while the area of each disordered lattice element remains approximately constant. More specifically, the air-holes form an array with a lattice constant \( a = 410 \) nm; their size (\( \text{Area} = \pi \left( \frac{a}{2} \right)^2 \)) is fairly constant with a standard deviation of \( \sim 3.5\% \); but their circular shape carries a significant geometrical disorder in addition to the usual surface roughness introduced during fabrication as illustrated in the scanning electron micrograph (SEM) in Fig. 1(b). The image analysis of the patterns fabricated this way did not reveal any significant long-range correlations. In a second approach\textsuperscript{15}, circular patterns in the design files are replaced with higher-order polygons, e.g. pentagons, squares, and triangles (SEM micrographs of fabricated lattices are shown in Fig. 1 (c)-(e)). All the polygons in the design files have their surface areas equal to that of a circle in the perfect lattice; the orientation of the feature at a particular lattice point is chosen at random and the total numbers of features with a specific orientation are the same. In both approaches, the disordered PhCs are fabricated on silicon-on-insulator (SOI) substrates using EB lithography and two-step reactive ion etching (RIE). Thermal oxidation of the SOI wafers creates a 30 nm layer of thermal oxide above the 220 nm-thick Si layer which rests on a 1 \( \mu \)m thick layer of buried oxide (BOX). EB defines the circular and polynomial patterns in photoresist which are then transferred into the top oxide layer using the first RIE step based on CHF\textsubscript{3}/O\textsubscript{2} chemistry. The thermal oxide layer is then used as a hard mask in the second RIE step which etches through Si using inductively-coupled Cl\textsubscript{2}/BCl\textsubscript{3}/H\textsubscript{2} plasma. The BOX layer and the residual thermal oxide are removed with buffered hydrofluoric acid forming free-standing PhC slabs. W1s are defined in the disordered PhC lattices by removing rows of circular or polygonal features along the \( \Gamma-K \) lattice direction.

2.2 Experimental setup

TE-polarized output of a tunable infrared diode laser (\( \lambda = 1.475-1.580\)nm, 100 kHz linewidth, 2 pm tuning resolution) is coupled evanescently into the disordered W1s from an adiabatic taper\textsuperscript{19}. The taper, prepared by pulling a melted fiber and etching its tip down to the W1 dimensions (\( \sqrt{3} \times a \)), is positioned on top of the PhC-slab as illustrated in Fig. 1(a). The arrangement allows the light to leak out of the taper and to evanescently couple into W1. Once excited, the PhC modes propagate in the waveguide and interact with cavities which leak the light vertically out of the slab. The scattered light is collected with a microscope equipped with an infinity-corrected 100\( \times \) objective (NA=0.80).
Fig. 1. Experimental setup: (a) an adiabatic smf-28 fiber taper evanescently couples the light from the tunable laser source to the photonic crystal (PhC) waveguide where the guided mode interacts with disorder. Light scattered vertically from the PhC slab is collected with a 100× objective (Obj.1) and imaged through a field stop (FS) on a photodetector (PD1) using two lenses (L). Alternatively, the transmitted light can be collected from the cleaved edge of the PhC waveguide (objective Obj. 2 and photodetector PD2) or backscattered light can be rerouted with a circulator (Circ.) on photodetector PD3. Several realizations of fabricated disordered PhC lattices are shown in the insets (scanning electron micrographs): weakly disordered circles (b), randomly oriented pentagons (c), squares (d) and triangles (e).

2.3 Disorder-induced localization

Fig. 2 shows an example of a spectrum recorded from a W1 with PhC lattice composed of weakly disordered circles. Random cavities are observed in a narrow, ~5 nm frequency band close to the cut-off of the waveguide mode calculated for a perfect lattice. The Lorentzian-shaped features are spectrally well separated since their average level spacing ($\Delta \nu$) is large enough compared to the average level width ($\delta \nu$) so that the modes do not overlap. This essentially says that a fundamental localization condition, the Thouless criterion ($\delta \equiv \delta \nu / \Delta \nu < 1$)$^9$, is satisfied. One of the spectrally distinct quasi-states exhibits a particularly large Q value ~250,000, which is less than an order of magnitude smaller than the record Q-value measured in engineered double-heterostructures$^6$. 
The calculated dispersion diagram of the W1 waveguide ($r/a=0.28$, with $r$ being the effective radius of circles in the design file), is obtained by using computational methods that employ 3D plane-wave expansion algorithms\textsuperscript{20}. Computational results and the corresponding density of states (DOS) are shown in Fig. 3. TE-polarized optical modes (electric fields parallel to the crystal plane) are guided below the light line by the total internal reflections in the out-of-plane direction and by distributed Bragg scattering (or PBG) within the PhC plane. The W1 waveguide mode that is examined here (gray circles in Fig. 3) has an even symmetry and exhibits anomalous dispersion unique to PhC waveguides\textsuperscript{21,22}. Its group velocity ($v_g = \frac{d\omega}{dk}$) gradually decreases as the wave-vector approaches the zone boundary (the slow-light regime). Slow light in the highly-dispersive W1 waveguide is susceptible to coherent backscattering which can block the transport if certain conditions are met. It has been proposed by John\textsuperscript{9} that the standard Ioffe-Regel criterion for localization ($k\ell \leq 1$) should be reinterpreted for disordered periodic-index media in the following way: $k$ is the wave vector of a coherent Bloch wave and $\ell$ is its scattering mean free path. The magnitude of $k$ is limited by PhC periodicity attaining the maximum at the zone boundary $|k_{\text{max}}| = \pi/a$. $\ell$ represents the lengthscale at which the mode is scattered by structural imperfections of the lattice. In the classical regime (large $v_g$) $\ell$ is large since the light is well confined within the waveguide and interacts only weakly with disorder. However, in the slow-light regime ($v_g \rightarrow 0$) the guided mode probe the crystal with progressively increasing evanescent fields, which enhances scattering from disorder and reduces $\ell$ as $k$ approaches the zone boundary. The strong-localization window opens when $v_g$ (and therefore $\ell$) becomes sufficiently small to satisfy the modified Ioffe-Regel criterion. Then, cavities are formed in the proximity of the unperturbed mode-edge by disorder-induced backscattering of the propagating wave\textsuperscript{17}. In another interpretation, introduction of structural disorder perturbs the waveguide’s translational symmetry causing fluctuations of the stop-band boundary. This effectively forms opaque barriers through which waves in the slow-light regime evanescently couple into transparent wells (cavities) in which they become confined\textsuperscript{18}. Tuning of the barrier heights and well dimensions by optimizing local dislocations in otherwise ideal PhC lattices is an established way of photon localization by the so-called mode-gap effect which has been employed extensively to design high-Q nanocavities with ultra-small modal volumes\textsuperscript{9}. The system at hand can be essentially regarded as an experimental realization of mode-gap confinement in randomized PhCs.
In another experiment, intensities and spatial profiles of the collected radiation patterns were imaged 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 2D intensity maps of the spatially-resolved spectra (Fig. 4). It is seen that the quality of confinement commonly improves for quasi-states excited at longer wavelengths, i.e. the localization lengths shrink and the Qs rise as the spectral penetration into the stop-band of the underlying periodic system increases. High-Q cavities have been observed with sub-$\left(\lambda/n\right)^{3}$ modal volumes$^{18}$.

![Diagram](image)

**Fig. 3.** Calculated band structure (a) and corresponding density of states (b) of a W1 waveguide. Gray circles depict the guided mode of the W1 below the light line. The disorder-induced localization phenomenon, shown in the inset of (b), is observed in a narrow frequency band close to the guided mode’s cut-off.

![Image](image)

**Fig. 4.** Contour plot of spatially-resolved spectra of the vertically-dissipated light from a 110μm-long disordered waveguide. Wavelength-scan step-size is 5pm. Spatial positions up to ~13μm from the edge are not shown due to excessive surface-scattering in that region.

### 2.4 Different realizations of disorder and sensing applications

We further investigate the mechanism of disorder-induced photon localization by comparing localization bandwidth and maximum Q-factor for disordered lattices composed of weakly disordered circles, pentagons, squares and triangles. For increasing departure from circular symmetry of lattice elements it is observed that the maximum Q-factor drops from ~250,000 to ~10,000 (Fig. 5 (a)), and localization bandwidth increases from ~5 nm to ~35 nm (Fig. 5 (b)); at least for the realizations of disorder examined here. A rigorous study is underway where measurements are averaged over several realizations of disorder for the same lattice elements so that general conclusions can be drawn. The trend observed here, however, already indicates that higher-Q values may be found for realizations of disorder that preserve the overall
translational symmetry of the crystal. To characterize the disorder superimposed on an ideal lattice it may be helpful to define a disorder function $\Delta \varepsilon (r)$ of the dielectric permittivity $\varepsilon$ at location $r$, where $\Delta \varepsilon (r)$ is defined as the difference between the permittivity of ideal periodic structure $\varepsilon_{\text{ideal}}(r)$ (e.g. hexagonal array of circular air-holes) and the permittivity found in the disordered structure $\varepsilon_{\text{real}}(r)$. The disorder function can be visualized as columns of materials with positive- and negative contribution to the permittivity as shown schematically in Fig. 6. Further investigations are underway to determine experimentally and computationally (by finite-difference-time-domain algorithms) whether there exists an optimal disorder function for light confinement in W1s - which may even outperform quality of confinement in engineered defect structures. Such random cavities can find various applications in lasers and optical sensing systems. For the latter purpose, we examine perturbations to random cavities by changing the temperature of PhC slabs mounted on a thermoelectric element. The resonance wavelength of a disorder-induced cavity was monitored for different temperatures (Fig. 7). Rising the temperature primarily affects the refractive index of silicon via thermooptic coefficient. The temperature induced change in refractive index shifts the edge of the waveguide mode to longer wavelength. The measured shift in resonance wavelength of a temperature-tuned random cavity, $\delta \lambda / \delta T = 0.0780$ (Fig. 7 inset). Continuous measurement of resonance wavelength shift opens the possibility to track perturbations imposed on the PhC structure by e.g. bulk changes of refractive index or by adsorption of biomolecules. Although the individual resonance wavelength of a cavity defined in disordered W1 is at random value within the narrow localization band, the relative wavelength shift can be evaluated computationally by comparison to the mode edge shift expected for a perfect crystal, assuming that the fraction of field localized within the slab material does not differ significantly from cavity to cavity.

Fig. 5. (a) Plot of the localization bandwidth for four types of disorder; and (b) corresponding maximum recorded Q-factors.

Fig. 6. Schematic representation of a disorder function.
3. CONCLUSION

We described a conceptually new approach to photon localization in PhC structures. The design preserves the average PhC periodicity while replacing conventional circular patterns in the design files with randomly oriented polygons or disordered circles. Such nanometer-scale disorder effectively introduces randomly-distributed strong scatterers that affect propagation of Bloch-waves through the otherwise periodic lattice. We show that the guided modes in line-defect waveguides defined in such disordered PhCs experience coherent backscattering that leads to Anderson localization. The effect is observed in a narrow frequency band close to the guided mode’s cutoff where the light propagates with a slow group velocity. Optical cavities with Qs of $\sim 2.5 \times 10^3$ and small (micro- to nanoscale) modal volumes were observed along the disordered waveguides. The results can be useful for applications in sensing systems and low-threshold random nano-lasers.

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