High-Quality Confinement of Visible Light in Disordered Photonic Crystal Waveguides in the Anderson-Localized Regime

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Abstract: We demonstrate Anderson localization of visible light in silicon nitride photonic crystal waveguides. We measure photoluminescence resonances due to disorder-induced light localization showing quality factors of ≈10 000 that exceed engineered 2D photonic crystal cavities.
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1. Introduction

Confining light in optical cavities is of tremendous interest for a variety of applications, spanning from the investigation of fundamental light-matter interactions to applications in sensing, imaging and quantum information technology [1]. The development of efficient optical cavities operating at visible wavelengths is particularly important for the study of cavity quantum electrodynamics effects with defect centers in diamond and two-dimensional (2D) materials, and to control and boost the emission dynamics of organic molecules and colloidal quantum dots.

Engineered 2D photonic crystal cavities in silicon nitride, however, have shown quality factors limited to values of the order of 1000 [2,3]. Such low confinement efficiencies, compared to longer wavelength devices, can mostly be attributed to losses due to fabrication imperfections that are difficult to avoid when dealing with the small features required to trap visible light on a nanophotonic chip.

We use a different approach that makes use of fabrication imperfections to trap light via multiple scattering and give the first demonstration of Anderson localization of visible light on a nanophotonic chip. By using the intrinsic photoluminescence of silicon nitride, we observe sharp resonances, a signature of the trapping of light in optical cavities, and measure quality factors approaching 10000 [4], far exceeding values reported for engineered 2D photonic crystal cavities.

2. Discussion of the results

We carry out micro-photoluminescence measurements of silicon nitride photonic crystal waveguides in which disorder is introduced by perturbing, with respect to the perfectly periodic structure, the position of the air holes next to the waveguide channel (see Fig. 1a). The displacement distances are obtained from a Gaussian distribution with a varying standard deviation, expressed as percentage (0-9%) of the photonic crystal lattice parameter.

We apply a nanoscale imaging technique [5] to directly image the confined optical modes, by illuminating the sample with a wide-area 455 nm LED, and imaging the emitted light with an electron multiplying charge coupled device (EMCCD) (Fig. 1b). Even though the position where the cavities appear is not controlled, given the multiple scattering process at the basis of their formation, we are able to locate with nanometer-scale accuracy the position of the optical cavities. This is important for the deterministic coupling of emitters to the disorder-induced optical cavities and for assessing the far-field modes extensions (see right panels of Fig. 1b).

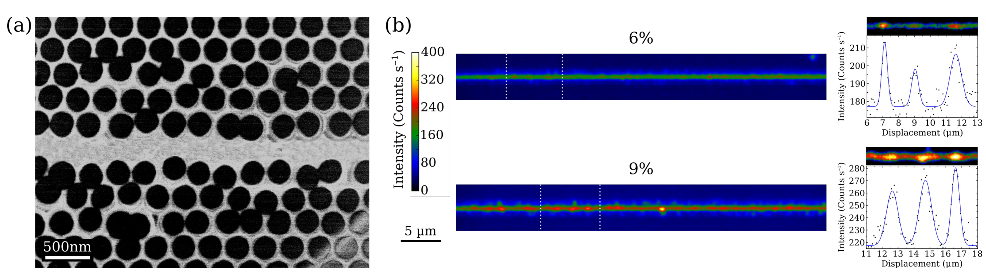

Figure 1: (a) Scanning electron micrograph of a suspended photonic crystal waveguide where disorder is introduced by displacing the three rows of holes on either side of the waveguide. (b) Photoluminescence images of the emission from waveguides with different degrees of disorder (6%, 9%), collected at room temperature, under 455 nm-LED illumination with a power density of 40 W/cm^2. Right panels: Enlargements of sections highlighted in the left panels and horizontal linecuts along the center of the waveguides (circles) and their Gaussian fits (solid lines).

Using a laser emitting at 473 nm, selected optical cavities are addressed individually and the confined light is characterized using a grating spectrometer. We observe sharp spectral resonances in the photoluminescence spectra (Fig. 2a-d), a signature of light confinement, and a distribution of confined wavelengths and quality factors (see inset of Fig. 2e), that follows the log-normal distributions expected in the Anderson-localized regime.

We study the dependence of the quality factor of the resonances as a function of an increasing amount of disorder and observe a decrease in the measured quality factors (see Fig. 2b). This trend can be explained by an increase of the out-of-plane scattering that results in greater losses when more disorder is present. For the lowest degrees of disorder, including samples where no intentional disorder is introduced (0%), we measure quality factors far exceeding the previous reported values of 1000, reaching a record value of 9300±800 (see Fig. 2a). These results prove that using disorder as a resource can provide quality in the light confinement exceeding that of engineered 2D photonic crystal cavities.

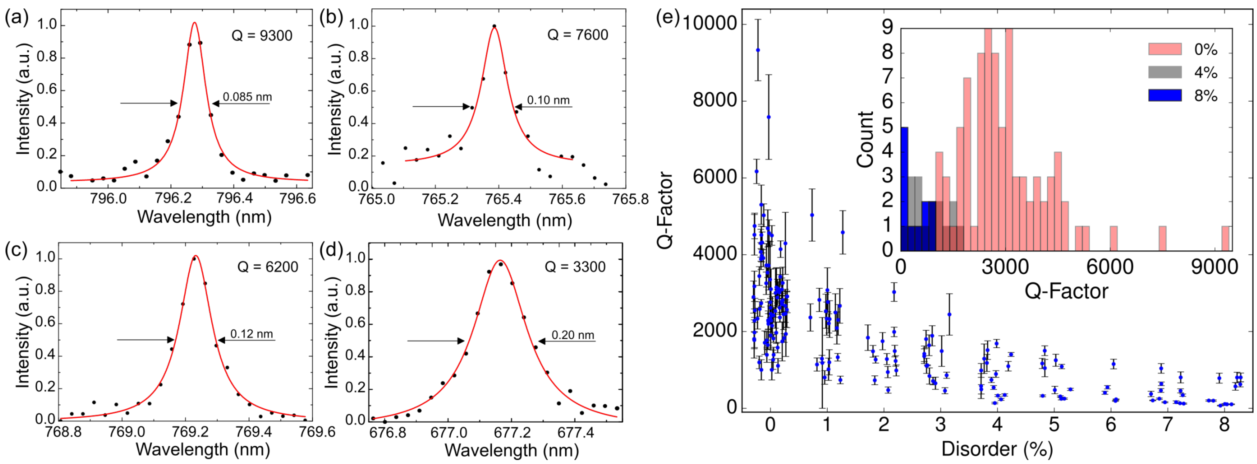

Figure 2: (a−d) Examples of normalized photoluminescence spectra, showing Anderson-localized resonances (symbols) and their Lorentzian fits (solid lines). The arrows indicate the FWHM of the peaks. (e) Statistics of the quality factors of Anderson-localized cavities as a function of degree of disorder (horizontally offset for clarity). The values are extracted from Lorentzian fits, like the ones shown in panels (a-d). The inset shows histograms of the number of events (count) as a function of quality factor, for different degrees of disorder (0%, 4%, and 8%).

3. Conclusions

We have provided the first demonstration of Anderson localization of visible light on a nanophotonic chip, and, by means of photoluminescence imaging, we have visualized the confined optical modes. Despite the lack of control on the position of the optical cavities, due to the multiple scattering process fundamental to the formation of the disorder-induced localized modes, we have shown that once the devices are fabricated, our technique allows the location of the optical cavities with nanometer accuracy. This represents an important step toward the deterministic addressing of disordered photonic cavities. Photoluminescence imaging also allows the far-field spatial extension of localized modes to be extracted, an important parameter in characterizing light localization.

The spectral characterization of the disorder-induced localized modes in our nanophotonic devices has revealed confinements with record quality factors reaching ~10 000: for the first time, to our knowledge, the quality of disorder-induced confinement exceeds that of engineered two-dimensional photonic crystal cavities. High quality in the confinement of visible light can find applications in energy harvesting, imaging, sensing, and fundamental research in light–matter interaction, cavity quantum electrodynamics experiments with emitters in the visible range, such as colloidal quantum dots, and defect centers in two-dimensional materials and in diamond.

4. References

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