# Efficient confinement of visible light in disordered photonic crystals

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**Summary**

We demonstrate Anderson localization of visible light in silicon nitride photonic crystal waveguides. We measure photoluminescence resonances due to disorder-induced light confinement showing quality factors of ≈10 000 that exceed engineered two-dimensional photonic crystal cavities and prove their sensing capabilities.

## 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, two-dimensional (2D) materials and organic molecules. 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 10 000 [4], far exceeding values reported for engineered 2D photonic crystal cavities, and show how such devices can be used for optical sensing of contaminants.

## Discussion

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 light-emitting diode (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 prior to device fabrication, 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

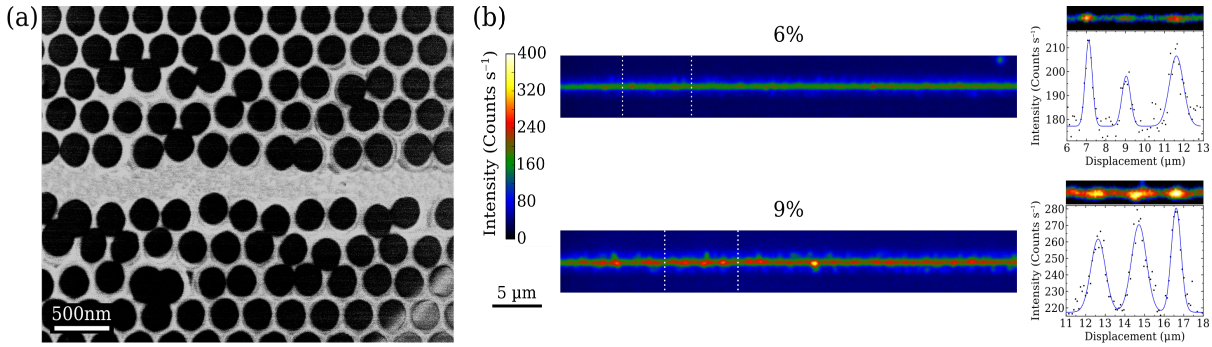


Figure 1: (a) Scanning electron micrograph of a suspended photonic crystal waveguide where disorder is introduced by displacing the three rows of holes on either side of the waveguide. (b) Photoluminescence images of the emission from waveguides with different degrees of disorder (6%, 9%), collected 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).

emitters to the disorder-induced optical cavities and for assessing the far-field modes extensions (see right panels of Fig. 1b).

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, a signature of light confinement, and a distribution of confined wavelengths and quality factors, 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. 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 reaching a record value of 9300 ± 800. These results prove that using disorder as a resource can provide quality in the light confinement exceeding that of engineered 2D photonic crystal cavities.

In order to characterize the response of our device to the presence of contaminants, we deposit an amount (estimated to be ~20 pℓ, on the photonic crystal waveguide area of approximately $10^3$ μm$^2$) of isopropyl alcohol (IPA), with refractive index 1.38, on the sample's surface and monitor the emission wavelength of selected resonances throughout the process. When the contaminant is deposited on the sample, producing a local refractive index change of ~0.38, we observe a spectral shift of the cavity resonance. The largest wavelength shift that we observe is of 15 nm more than 100 times the spectral linewidth of 0.15 nm, showing the high sensitivity of our system to small refractive index variations [6]. The process is entirely reversible: when the contaminant evaporates, the resonance shifts back. Therefore, a calibration of the system would allow, not only the verification of the presence of a contaminant, but also the evaluation of its quantity and/or its refractive index.

## 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 at the basis of the formation of the disorder-induced localized modes, we have shown that once the devices are fabricated, our technique allows locating 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, like 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.

We have also demonstrated optical sensing with disorder-induced optical cavities in photonic crystal waveguides in the Anderson-localised regime. We have observed reversible spectral shifts up to 100 times the linewidth of the spectral resonances, for liquid contaminants providing a refractive index change of ~0.38. Our experiments take advantage of the spontaneous formation of tens of high-quality optical cavities along the fabricated photonic crystal waveguides, allowing simultaneous sensing with different optical resonances. Since there is no need for multiple iterations of the fabrication process, our results show that disorder-induced light confinement in silicon nitride photonic crystals is suitable for the development of high sensitivity, scalable, optical sensors.

## References


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