Optical Sensing with Anderson-Localized Light

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Abstract: We demonstrate optical sensing with Anderson-localized visible light on scalable silicon nitride photonic crystal waveguides. For a refractive index change of ≈0.38, we measure 15.2 nm wavelength shifts of an optical resonance 0.15 nm broad.
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1. Introduction

Optical sensing is of preeminent importance for a variety of applications [1]: it can enable detection of harmful or desired contaminants, it can confirm that expected reactions have taken place and it can be used for quantitative analysis of the processes under study.

To this end, several kind of devices have been developed: in particular they have been based on plasmonic resonances [2] that have the advantage of relatively easy production and high yield, and photonic crystal cavities [3] that posses much sharper spectral resonances, but suffer from low scalability due to the highly engineered processes required. To overcome this issue, we propose to follow a different approach based on multiple scattering of light on imperfections as a means to achieve high-quality light confinement in the Anderson-localised regime [4].

Here, we show that we can make use of fabrication imperfections as a means to add functionalities to the fabricated devices. We report on photonic crystal optical sensors based on disorder-induced light confinement in photonic crystal waveguides in silicon nitride. We prove their suitability for the detection of liquid contaminants at room temperature and investigate their response to refractive index changes. We also show that temperature can be used to tune and modify the quality factor of the cavity resonances, allowing local temperature sensing [5]. Compared to engineered photonic crystal cavities, making use of disorder as a resource allows the spontaneous formation of tens of high-quality optical cavities in a fabricated device that does not require time-consuming optimizations or exact repeatability of the fabrication process - an important result in view of scalability of photonic crystal sensors.

2. Discussion of the results

The samples are composed of a 250 nm-thick silicon nitride layer deposited on a silicon substrate via plasma-enhanced chemical vapour deposition. By means of electron-beam lithography, we write the photonic crystal pattern that is transferred onto the silicon nitride layer via an inductively coupled plasma reactive ion etch, a wet etch is used to undercut the silicon nitride, creating a free-standing photonic crystal membrane (see Fig. 1a). Disorder is introduced in the position of the three rows of holes above and below the waveguide (for more details see Ref. 4).

Confocal photoluminescence spectroscopy, under 407 nm continuous-wave laser excitation, is used to characterize the Anderson-localized optical modes. Sharp spectral resonances, a signature of light confinement by disorder, are visible in the spectra collected when moving the excitation/collection spot along the waveguides [4].

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 (see Fig. 1b). The largest wavelength shift that we observe is of 15 nm more than 100 times the spectral linewidth of 0.15 nm (see inset of Fig. 1b), showing the high sensitivity of our system to small refractive index variations.

The process is entirely reversible: when the contaminant evaporates, the resonance shifts back, as shown in Fig. 1b-c. 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.

We have then tested the temperature dependence of the optical resonances: the sample is placed in a liquid-Helium flow-cryostat where the sample temperature, measured by a three point calibrated rhodium iron temperature sensor placed in the cold finger where the sample is mounted, can be varied from 300 to 10 K. Photoluminescence spectra are collected while the temperature is varied in defined steps. When varying the sample temperature, the refractive index of silicon nitride is modified, and given the sensitivity of photonic crystal structures to small refractive index variations, this results in a spectral tuning of the optical resonances. As shown in Fig. 2a, we

observe a blue-shift of the spectral peak of up to ~2 nm, when changing the temperature from 300 to 10 K. Such a shift is fully reversible and provides a local probe of the sample temperature in correspondence to the specific optical mode under examination. The temperature tuning of the optical resonances can also be used for tuning an optical mode into and out of resonance, for instance, with the emission line of defect centers in diamond and two-dimensional materials that emit in the visible and near-infrared range of wavelengths, thus allowing to carry out cavity quantum electrodynamics experiments.

Furthermore, we observe a variation of the quality factor of the optical resonance that increases of about a factor 2 when going from 300 to 10 K (see Fig. 2b). This can be explained by reductions in cavity losses, showing that the light-matter interaction can be further enhanced at cryogenic temperatures.

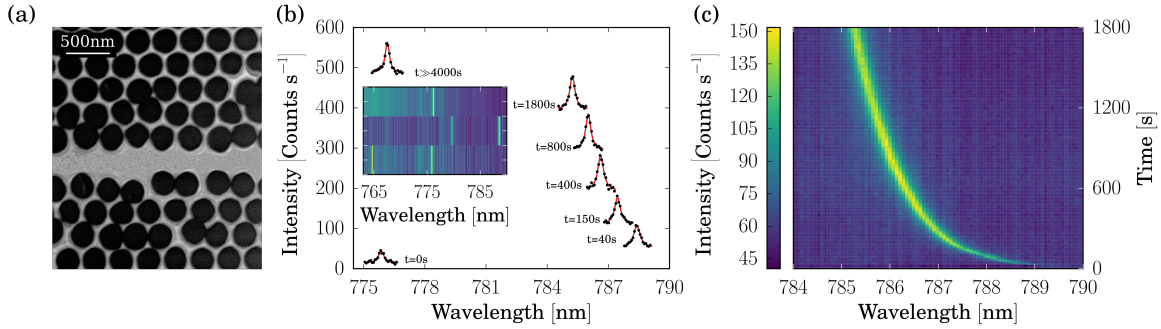

Figure 1: (a) Scanning electron micrograph of a disordered photonic crystal waveguide. (b) Example of photoluminescence spectra (vertically offset for clarity), collected under a laser excitation power density of 28 kW/cm^2, at room temperature (symbols) and their Lorentz fits (red lines), before IPA is applied to the photonic crystal waveguide (t = 0) and as a function of time after IPA deposition. Inset: Zoom in of spectra collected before IPA deposition (lower panel), 40 s after deposition (middle panel), and ≫4000 s after deposition (top panel), proving reversibility. (c) Color plot showing the full set of photoluminescence spectra, collected in the same conditions as for panel (b), as a function of time after IPA deposition.

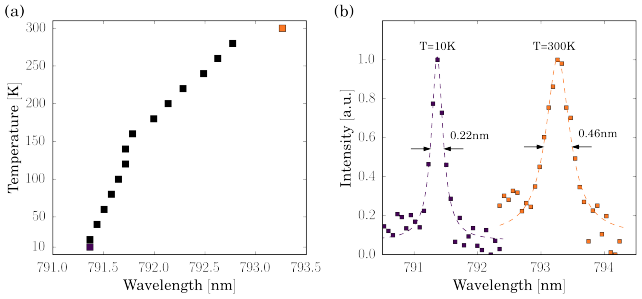

Figure 2: (a) Central wavelength of the cavity peaks, extracted by the Lorentzian fits of the photoluminescence spectra, collected under a laser excitation power density of 28 kW/cm^2, as a function of the sample temperature, varied with steps of 20 K (the error bars are too small to be visible). (b) Normalised photoluminescence spectra collected at temperatures of 10 (purple symbols) and 300 K (orange symbols) and their Lorentzian fits (solid lines). The full width half maximum of the resonances is also shown.

3. Conclusions

We have 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. We have also shown temperature shifts of up to ~2 nm when varying the temperature from 300 to 10 K, accompanied by a cavity quality factor increase of ×2. 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.

4. References

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