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In situ optofluidic control of reconfigurable photonic crystal cavities

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The mobile nature of fluids is fully exploited in planar photonic crystals to not only tune and reconfigure in situ optical microcavities, in a continuous and reversible manner, but also to create “a posteriori” spatially programmable cavities. Both the amount of liquid and the location of the selectively infiltrated area can be accurately controlled either mechanically, using a microfiber manipulator, or optically, using a laser-controlled evaporation and recondensation scheme. The wide applicability is illustrated by tuning a cavity resonance over 50 nm, adjusting the frequency splitting of an originally degenerate cavity mode, and by freely moving a liquid-induced cavity through dragging a microdroplet.

There has been a surge of interest in recent years to combine microfluidic circuits with optical circuits on a single chip, which defines a major part of the field of optofluidics.1,2 From the microfluidic point of view this is motivated by the potential to optically characterize the liquid content in lab-on-a-chip applications.3,4 From the optical point of view, not only the huge changes in local refractive index and the inherent mobile nature of liquids give rise to large dynamical tuning capabilities of optical circuits5 but also the fluids themselves can add functionalities by doping them with active elements.

The local infiltration of a two-dimensional photonic crystal (PhC) pattern with a resolution on a single hole level was first demonstrated by using an aqueous solution of a luminescent dye to make the infiltrated region visible.6 This work was motivated by the possibility to make rewritable photonic circuits, with the infiltrated sections acting as functional defects like cavities or waveguides. Recently, such liquid-induced waveguides were realized in practice.7 Using a solution with luminescent nanocrystals, the technique was exploited to create a local light source in a PhC.8 By careful local evaporation of infiltrated water, an accurate tuning mechanism for pre-existing PhC cavities was realized,9 which enabled detailed studies of coupled cavities.10,11 Selective liquid infiltration of planar PhCs was not merely used to tune pre-existing cavities and devices but also proposed12 and demonstrated13–15 as a way to create liquid-induced double heterostructure cavities. While reconfigurability is an important motivation for the local liquid infiltration,16,17 whether it is applied to tuning or liquid-induced devices, the associated demonstrations still lack flexibility and do not take full advantage of the mobile nature of the liquids. In Refs. 13–15, the reconfigurable liquid-induced devices were erased through cleaning the whole chip in a suitable solvent prior to its re-use. The more gradual water-removal by local laser-heating-induced evaporation demonstrated in Refs. 9–11 was performed while the whole chip remains fully functional, but does not provide a reversible tuning mechanism. In addition, the associated time scale is of the order of a day under continuous irradiation with a high laser intensity, which is not practical for many applications.

In the present work, a local infiltration technique is demonstrated that is continuously reversible and allows to create optical devices that are truly reconfigurable in situ on the chip, on a timescale of seconds to minutes. First, we show how to manipulate the infiltrated liquid to adjust, in real time, the mode frequency splitting of an initially degenerate PhC hexagonal cavity mode. Laser irradiation is used not merely for removing the liquid, but also for refilling a different area of the PhC device, thereby achieving a reversible tuning range for a cavity resonance greater than 50 nm. Finally, a type of droplet-induced PhC cavity is demonstrated that is movable by dragging the drop mechanically over the chip. The present findings not only expand the tuning opportunities within optical circuits, but also can be adapted for sensing strategies in optofluidic architectures.

The two-dimensional hexagonal photonic crystals are made in 220 nm thick InGaAsP membranes, with parameters that enable operation near the 1550 nm band, implying lattice constants around 450 nm.17 A 3 × 1010 cm−2 layer of InAs quantum dots, with an inhomogeneous photoluminescence (PL) spectrum broader than 200 nm and centered around 1500 nm, was grown in the middle of the membrane. The experimental arrangement is shown in Fig. 1(a). The PL emission is generated by a 660 nm laser, focused to a ∼2 μm spot

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on the sample by a numerical aperture of 0.45, 17 mm working distance, microscope objective. The PL emission is collected either from the same spot through the same objective or at an independent position from the evanescent field of guided emission with the apertureless tip of a scanning near-field optical microscope (SNOM). The sample is mounted on a piezo-controlled translation stage to select the excitation spot. The selective local liquid infiltration is performed using the method reported earlier. An optical fiber is pulled to a diameter less than 1 μm in a microflame and after breaking is mounted in an independent piezo-controlled nanomanipulator near the sample. The tip is wetted in the liquid from a macroscopic (~1 mm³) drop somewhere on the chip. By dragging the wet tip over the surface or touching at a single point, microstrips or microdroplets are created. The fluid manipulation with the microfiber infiltration tip can be done under near-simultaneous observation of the PL with the objective; the SNOM tip and the infiltration tip, however, cannot be used simultaneously. To avoid evaporation issues at room temperature, an extremely low vapour pressure oil was used (10⁻¹⁰ mbar at ~20°C), with non-noticeable evaporation at room temperature. The oil refractive index is 1.63, it wets well to both the glass and the semiconductor, and it is transparent to the visible and infrared light. A one missing row of holes waveguide with closed ends, known as W1, or a one missing hole cavity, with the surrounding holes modified in both position and radius, known as H1, are used in the present work, as shown in the scanning electron microscope images in Figs. 1(b) and 1(c). The typical view of an infiltrated sample, excitation spot, and fiber manipulator tip are shown in Fig. 1(d). To support the experiments, simulations were performed using three dimensional finite difference time domain calculations.

The in situ control is first demonstrated for an H1 cavity in a PhC with lattice constant a = 480 nm, nominal design of radius to lattice spacing ratio ra/a = 0.3 (see Fig. 1(c)). The six holes surrounding the defect are reduced in radius by 38 nm and radially shifted outwards by 15 nm to increase the quality factor (Q) of the cavities. Here, we deal only with the two low-frequency dipole modes, which are degenerate for truly hexagonal symmetry. The spectra of these dipole modes, labeled D1 and D2, are shown in Fig. 2(a) for different infiltration conditions. Curve 1 is obtained from the pre-existing cavity, before infiltration. Using the infiltration tip, an extended area around the defect is infiltrated with oil. In the infiltrated region, the oil is suspended in the holes by capillary forces, but the underetched void below the membrane is not filled. The associated spectrum (curve 2) is redshifted with respect to curve 1 due to the larger effective refractive index provided by the oil. The magnitude of the shift is consistent with the simulations.

Next, oil is selectively removed from around the defect by increasing the power of the excitation laser and systematically moving the focus position. It is observed that oil disappears at the focus position, which is attributed to evaporation under the increased local temperature. For clarity, the directly visible, albeit somewhat faint, infiltrated regions under the optical microscope are presented with sketches in the insets of Fig. 2(a). When liquid is removed in the horizontal direction in the sketches 2, 3 and 4 of Fig. 2(a), the dipoles are split in frequency, with one (labeled D1) shifting much more than the other (labeled D2). This behaviour is
readily understood from the spatial intensity distribution of both modes, for which the calculated magnetic field distributions are plotted in Figs. 2(b) and 2(c), respectively. Subsequently, oil is removed in the vertical direction, starting from top in the sketches. Both modes rapidly blueshift back to their original positions (i.e., for the dry cavity), as seen in curves 5 and 6 (sketches 5 and 6). From the mode profiles (b) and (c), it should be expected that when removing liquid in the vertical direction, mode D2 is more strongly affected than mode D1, so they should cross in between curves 4 and 5. A direct proof for the crossing is given in Fig. 2(d), with data from a different run, where the two resonances could be continuously monitored, during the laser-induced evaporation of the oil.

Selective tuning of the two $H_1$ dipole modes by selectively modifying the dry cavity has been done before by local oxidation or lithographic design. The present method, however, is reversible and reconfigurable, easier than the uniaxial strain method and more accurate than the liquid crystal temperature tuning method. For empty membranes, the local temperature rise under the present conditions is in the range of 100–200°C. The exponentially rising vapour pressure with temperature in this regime could explain the evaporation, which is observed to vary highly nonlinearly with power, effectively exhibiting a threshold value below which no oil removal is observed on time scales of tens of minutes. The present method appears very similar to the water removal procedure, but the different time-scales should be noted, minutes versus days. The lower temperature used for the water removal (~40°C) seems insufficient to explain the difference, in view of the vapour pressures of water and oil, so that the reason for the difference is not clear.

Although the previous cavity tuning demonstration was flexible and continuous, it was not fully reversible. We show next that the laser evaporation technique can also provide reconfigurable and reversible tuning, using an evaporation-recondensation scheme leading to an optically driven fluid transport on the chip. A similar $H_1$ cavity as above was used, with nominally the same host PhC, but slightly different parameters for the modified holes: the six inner holes’ radius is reduced by 15 nm and their positions radially shifted outwards by 30 nm. The empty cavity dipole resonance is displayed in curve 1 of Fig. 3(a). Then the cavity is completely infiltrated, including its undercut, by repeatedly dragging fluid to the cavity until saturation; any excess fluid on top is wiped off with the infiltration tip. The cavity resonance for this case is shifted by 50 nm, in agreement with simulations, to just beyond the detector cut-off at 1600 nm, so that the signal to noise ratio is small, see curve 2. Subsequently, the laser at increased power (~0.5 mW) is directed to the center of the cavity for two minutes several times, after which the image of Fig. 3(c) is obtained and the spectra strongly blue-shift as in the curves 3 and 4 of Fig. 3(a). The observations are interpreted as evaporation and recondensation of liquid. A large liquid reservoir (estimated ~10$^{-3}$ ml$^3$) is available in the undercut void below the PhC membrane. The laser heats the membrane and, through this, the oil then evaporates. Since the heating is very local and the oil very non-volatile, it immediately recondenses in the cold air and on the cold surface immediately next to the hot spot, where droplets form and coalesce. The resulting splashes of liquid are seen in Fig. 3(c). The removal of the liquid in the center part of the cavity causes the spectra to blue-shift. This process is analogous to that demonstrated in Ref. 27. The heating laser is then slowly moved from the cavity center to the boundary, evaporating more liquid, which recondenses in the near surrounding that now includes the cavity center. A liquid droplet near the cavity center can be distinguished in Fig. 3(d), where excess liquid has been wiped off. Most importantly, the signature of the re-infiltration mechanism can be seen from the redshift of curve 5. For the last step, curve 6, all liquid is removed again by laser-induced evaporation, including from the undercut. The dipole resonance has actually blue-shifted beyond its original position. This is a known effect and attributed to laser-induced oxidation of the semiconductor.

The on-chip reconfiguration capabilities of selectively liquid infiltrated PhC devices are now demonstrated in the context of liquid-induced cavities. It is shown that the concept can be extended to realize a movable, droplet-induced cavity on top of a W1 waveguide ($a = 425$ nm, $r/a \sim 0.3$). Fig. 4(a) displays the calculated W1 dispersion curves and the top of the PhC lower bands for several dielectric environments. Curve 1 is for the starting, un-infiltrated W1 waveguide, while curve 2 corresponds to the case with all holes infiltrated. With only a small section of the waveguide infiltrated (roughly 10 periods), a fluid-induced double heterostructure (DHS) cavity is created. This DHS cavity is
spectrum 4 is taken with the objective. Recorded with a SNOM tip, located near the infiltrated region for curve 2; infiltration status is sketched in the insets near the curves. Spectra 1 to 3 are part of the holes of the waveguide (2), all holes as well as undercut infiltrated, the DHS peaks obviously disappear and another reversible and adjustable “on-the-fly” are introduced and their relevance proven in a number of experiments. The versatility and flexibility of the method shows great potential for the control of PhC based optical circuits. The results offer perspectives for incorporating PhC devices in sensing circuits.

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also observed in the present experiments as follows from curves 1 and 2 of Fig. 4(b). The peak of curve 1 corresponds to the empty waveguide cut off. The four peaks beyond the empty waveguide cut off in curve 2 correspond to the Fabry-Perot like modes of the DHS cavity, occurring in the mode gap between the empty and infiltrated waveguide (see Fig. 4(a)). When the entire waveguide, including undercut, is infiltrated, the DHS peaks obviously disappear and another uniform W1 waveguide results, with a strongly red-shifted cut-off peak, see curve 3 in Fig. 4(b). Its dispersion is shown as curve 3 in Fig. 4(a). For these experiments, the SNOM collection was used as the modes scatter little and thus are very weak to observe in the far-field observation through the objective.

On top of the fully infiltrated waveguide a microdroplet is placed. This locally increases the average refractive index and thus should induce a droplet-induced DHS cavity. Following the DHS analysis, the W1 dispersion with a thick layer (~200 nm in practice) of oil below and above the membrane, with all holes filled is shown as curve 4 in Fig. 4(a). A “droplet mode gap” can be identified in the W1 dispersion curves, analogous to the “DH mode gap. In the experiment, again four resonances appear just beyond the infiltrated waveguide cut off, as shown by curve 4 in Fig. 4(b). This curve could be readily measured with the objective, indicating a larger scattering from the droplet, consistent with the broader lines. The width line of the droplet-induced cavity resonance has not yet been subject of study. The interesting property of this droplet cavity is that it can be continuously moved with the fiber manipulator, as proven when shifting it reversibly along the focus of the excitation laser. The droplet remains bound to the fiber by capillary forces. The oil lubrication enables the smooth movement of the microfiber along the surface, in contrast to the jumping movement caused by stick-slip behaviour when fiber and surface are dry. A microfiber in contact with a PhC waveguide can induce a cavity by itself.29 In the present experiments, there is no need for the permanent presence and accurately controlled position of the fiber, which can be withdrawn after the droplet is placed.

In conclusion, both mechanically and optically controlled infiltration techniques of photonic crystals that are reversible and adjustable “on-the-fly” are introduced and their relevance proven in a number of experiments. The versatility and flexibility of the method shows great potential for the control of PhC based optical circuits. The results offer perspectives for incorporating PhC devices in sensing circuits.
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