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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. © 2012 American Institute of Physics.

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 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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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 \( r/a = 0.3 \) (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.\(^{22}\) 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 H1 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 behavior. These increases are in the range of 100–200°C.

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 ~ 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
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 line width 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. 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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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


