Chemical sensing in slotted photonic crystal heterostructure cavities

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We fabricated slotted photonic crystal waveguides and cavities supporting resonant modes in air. Their peculiar geometry enables the detection of refractive index changes in a given analyte with high sensitivity because of the large overlap between the optical mode and the analyte. This yields a high figure of merit for the sensitivity of the device and we are able to report values of $S=\Delta\lambda/\Delta n$ over 1500. By applying a photonic crystal heterostructure to the slotted geometry, we are able to create high quality-factor cavities essential for realizing low detection limits up to $Q=50\ 000$. © *2009 American Institute of Physics*. [DOI: 10.1063/1.3079671]

A key performance indicator of integrated optical devices for applications in sensing is the ability to detect small refractive index changes. For resonant devices, this ability is both expressed in terms of the wavelength change induced by a refractive index change, i.e., $S=\Delta\lambda/\Delta n$, as well as the sharpness of the resonance, typically described by the Q-factor. Intuitively, these two requirements are contradictory in guided-wave optics; in order to achieve a large wavelength change, the optical mode needs to overlap strongly with the analyte, yet in order to achieve a high cavity Q, the mode should be strongly confined in the waveguiding medium. This apparent contradiction can be resolved by confining light in what is known as a "slotted waveguide," whereby the discontinuity of the optical field at a dielectric interface is exploited to form a guided mode inside a narrow slot.[1] This geometry yields a strong overlap between the optical mode and an analyte that may be filled into the slot, resulting in a high figure of merit $S=\Delta\lambda/\Delta n$, e.g., 212 nm/RIU (refractive index units, RIU) for a ridge waveguide geometry.[2]

By implementing the slotted waveguide in a planar photonic crystal (PhC) platform,[3–6] the second requirement of high Q cavities can also be fulfilled. For example, by utilizing the heterostructure concept,[7] one can create cavities with very high Q-factors. Here we demonstrate the realization of such a cavity with a Q-factor of 50 000. In order to simplify the numerical modeling of the resonant mode shift due to the refractive index change, we assume that it is similar to the shift experienced by the slot mode cutoff.

The inset of Fig. 1 shows a scanning electron microscopy (SEM) image of a slotted PhC (SPhC) cavity, with zoomed views of two relevant sections of the slot, and the main figure shows the dispersion map for a silicon SPhC waveguide with a slot width of $0.3a$ and a silicon thickness of $h=220$ nm for two different background refractive indices, where a is the PhC lattice. The thick continuous lines represent the slot modes, the shaded areas the lattice modes, and the dashed lines are the light lines in the two cases. Since most of the electromagnetic field of the slot mode sits in air, it is subject to strong changes as the refractive index of the medium inside the slot is varied. The red lines and yellow shaded areas in the figure correspond to air ($n=1.0$), while the black lines and gray shaded areas are relative to a background refractive index of $n=1.315$, typical of de-ionized water at $\lambda=1550$ nm. A qualitative inspection of the dispersion curves highlights the strong effect that small changes in refractive index have on the slot mode. In order to assess this effect quantitatively, we monitored the wavelength shift of the slot mode cutoff against the background refractive index for different slot widths. Figure 2 shows the results obtained with standard plane wave analysis for width $\in[0.1a,0.4a]$, $h=220$ nm, $r=0.3a$, and $a=490$ nm. The geometrical (width, a, h, and radius) and material factors $(\epsilon_{Si},\epsilon_{bulk})$ are interlinked and result in a nonlinear dependence of the sensitivity on the slot width. Nevertheless, for a background index of $n=1.34$ and a slot width of $0.4a=196$ nm, we obtain an impressive sensitivity value of $\Delta\lambda/\Delta n=585$ nm/RIU.

We now move on to cavities, adapting the "heterostructure" approach[7] that is widely used to build cavities based on regular PhC waveguides. In contrast with the standard $W1$ line defect waveguide, where the cavity is realized by expanding the lattice pitch in direction of propagation, a SPhC heterostructure cavity requires a local compression of the lattice. This pulls the eigenstate *up* into the band gap (see Fig. 1) rather than *down* as in Ref. 7.

The best result we were able to achieve is shown in Fig. 3, which is over ten times larger than previously published experimental values of Q for air-confined cavities,[5,8] namely, a Q of 50 000. The geometrical parameters match the simulation, with $a=490$ nm, $r\simeq 0.3a$, and width$=0.3a$ with the lattice constant in the defect region reduced to 470 nm. The

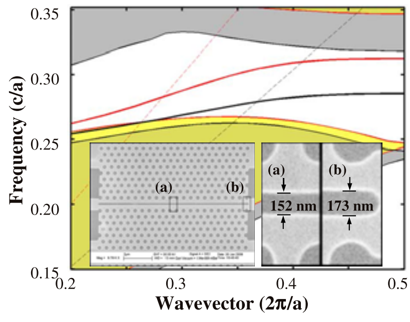

FIG. 1. (Color online) Dispersion properties of SPhC waveguide with different background refractive indices [yellow shade and red lines ($n=1$), gray shade and black lines ($n=1.315$)]. Inset: SEM image of a SPhC cavity, with zoomed view of the (a) central and (b) external part of the slot.

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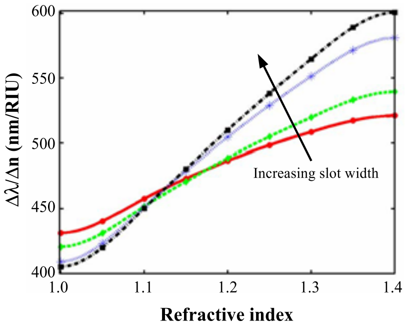

FIG. 2. (Color online) Sensitivity vs background refractive index for different slot widths: (red) $0.2a$(98 nm), (green) $0.3a$(147 nm), (blue) $0.4a$(196 nm), and (black) $0.5a$(245 nm).

fabrication procedure was carried out in the framework of the ePIXnet nanostructuring Platform[9] and the fabrication details are identical to the procedure used in Ref. 4. The inset shows the transversal (E_y) component of the electric field as obtained by three dimensional finite-difference time-domain simulations. Although a direct comparison between the numerical simulations and the experiment is spoiled by the actual shape of the slot region—as shown on the insets of Fig. 1 and further discussed below—the two are comparable and clearly indicating that the cavity is monomodal; the maximum Q we obtain from simulation is 70 000, which is reasonably close to the experimental value of 50 000 considering the experimental constraints.

In order to assess the sensing capabilities of our structures, we characterized them in an endfire setup using TE polarized (with respect to the plane of periodicity) light. The samples were infiltrated with solutions of caster sugar of varying concentrations via drop casting. The corresponding refractive indices of the solutions at a wavelength of 1.55 μm were determined with a refractometer.

The laser source used for the characterization had a wavelength span of 100 nm around $\lambda=1550$ nm. This posed some challenges in the experiment as the high refractive change between air (dry sample) and the solutions (infiltrated sample) shifted the resonant mode by >100 nm. We therefore designed different sets of samples, i.e, some to operate in the target wavelength range when wet and others when dry.

The result is shown in Fig. 4. We tracked the position of the cavity modes for three different slot widths of width $=0.31a$ (152 nm), $0.34a$ (166 nm), and $0.35a$ (171 nm) and solutions with different refractive indices, ranging between

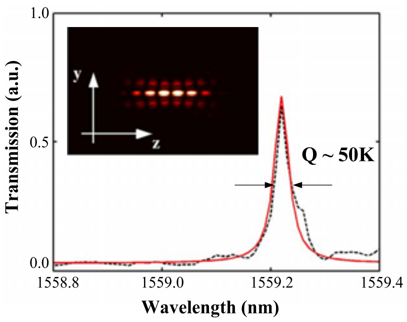

FIG. 3. (Color online) Transmission spectrum of the cavity mode with $Q=50\,000$, including a Lorentzian fit. Inset: calculated y component of the electric field of a slot cavity mode.

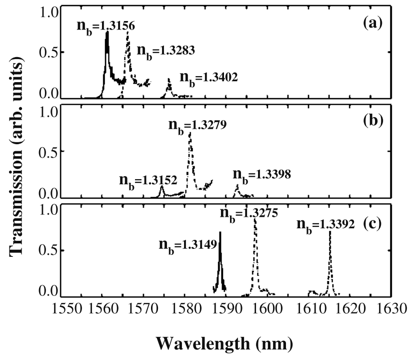

FIG. 4. Transmission curves of resonant modes for different void widths and solution background refractive index, reported close to the pertinent resonant peak. Slot widths: (a) 171, (b) 166, and (c) 152 nm. We obtain the maximum sensitivity from the rightmost peaks in (c), given their wavelength difference of $\Delta\lambda=18$ nm.

$n=1.315$ and $n=1.340$. We measured an average infiltrated $Q\simeq 4000$, which is lower than the average dry cavity value due to the lower refractive index confinement. The experimental results do not agree well with the numerical prediction, however, and we measured a maximum value for the sensitivity of $\Delta\lambda/\Delta n \simeq 1538$ nm/RIU [Fig. 4(c)].

This surprisingly high figure can be explained as follows.

(a) Wetting: It is difficult to infiltrate very small features with aqueous solutions due to the high surface tension. The surface tension decreases, however, as the concentration of dissolved sugar increases, thus improving the wettability.[10] We therefore believe that the high $\Delta\lambda/dn$ values are caused by increased penetration of the liquid into the slot with concentration; as the concentration changes, so does the refractive index of the solution, and also its overlap with the optical mode.

(b) Slot uniformity: SEM inspection reveals that the slots are not uniform but narrower in the center, with a variation in width of up to 10% (see the insets of Fig. 1). This suggests that the above argument of partial infiltration as a function of sugar content applies both in the vertical and in propagation direction; as the sugar concentration increases, more liquid enters the slot starting from both ends and moving toward the center. While the partial infiltration complicates the *ab initio* modeling of the device, the experimental results show without reasonable doubt that the sensing is evaluated tracking the same (and unique) resonant mode supported by the slotted heterostructure cavity.

We verified numerically that the experimental resonance frequencies are compatible with a partial infiltration of the device. While complete infiltration would shift the resonances to over $\lambda=1650$ nm, we observed the resonances around 1590 nm.

In conclusion, we presented and demonstrated chemical sensing operation in SPhC cavities. We report a sensitivity in excess of 1500 nm/RIU and a Q-factor of up to 50 000, both unprecendented values for PhC based refractive index sensors.[5,8,11–13] In terms of the detection limit (DL), which is defined as the ratio of the resolution (directly linked to Q of the cavity) and the sensitivity,[14] we obtain $\mathrm{DL}\simeq 7.8\times 10^{-6}$

from a $Q=4000$ and a sensitivity $S=1538$ nm/RIU from our experimental conditions.

By further increasing the Q-factor and properly understanding and controlling the partial infiltration issues, we believe that slotted PhC waveguide cavities could even exceed the present limit of $DL=10^{-7}$ (Ref. 14 and references therein), which would be quite a remarkable result, given that ours is an integrated device.

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