Tuning of a cavity in a silicon photonic crystal by thermal expansion of an elastomeric infill

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We use an elastomer as infill material for a photonic crystal. As a result of the thermal-expansion-induced strongly negative thermal optical coefficient, this material is highly suitable for thermal tuning of the transmission of a cavity. This is demonstrated by global infilling of a hole-type silicon photonic crystal slab and global thermal tuning. In the temperature range 20-60 °C the cavity peak shows a pronounced elastomer-induced blue shift of 2.7 nm, which amply overcompensates the red shift arising from the thermo-optic property of the silicon. These results qualify the elastomer for tuning by local optical heating. © *2011 American Institute of Physics*. [doi:10.1063/1.3640235]

Photonic crystals (PhCs) are dielectric materials with a periodic modulation of the dielectric constant. The most striking property of a PhC is the photonic bandgap, i.e., a wavelength range where the PhC is opaque.[1] Cavities in a PhC, for light confinement and transmission tuning, are highly attractive for applications such as optical switches,[2] add-drop filters,[3] and low-threshold lasers.[4] Tuning of the refactive index of the PhC, which can be done with optical,[5] mechanical,[6] and electric[7] methods, is very important for applications. Another approach is infilling the air holes of a PhC with a liquid crystal, of which the index is tuned by driving it through the phase transition.[8]

Here, we apply an elastomer as infill material to tune the transmission of a PhC cavity. Elastomers, owing to the weak bonding between the polymer chains, exhibit a strong thermal expansion and consequently a high negative thermo-optic coefficient (TOC) dn/dT. The ultimate tuning on the basis of an elastomer is by local optical heating of the elastomeric infill, by applying laser pulses, resulting in a resonance-wavelength shift. Local heating can be accomplished by doping the elastomer with dye molecules or quantum dots, provided that these mainly decay non-radiatively, to ensure efficient conversion of locally deposited optical energy into heat.[9] With the present experiments we qualify Kraton SEBS G 1657[10] (further just called "elastomer"), a highly stable and durable elastomer, for tuning by local heating. This is done by demonstrating global infilling of a hole-type silicon PhC slab with the elastomer and global thermal tuning of its refractive index. We study the tuning properties of the elastomer by measuring the transmission of a cavity in the infilled PhC as a function of temperature. Our infilled PhCs operate in another regime than athermal waveguides,[11] which are clad by a polymer with a negative TOC that exactly compensates the positive TOC of the silicon waveguide to make the properties temperature insensitive. The TOC of the elastomer, on the contrary, amply overcompensates the TOC of the PhC material, enabling thermal tuning.

The PhCs are fabricated in silicon-on-insulator (SOI) material. The device layer is 220 nm thick; the buried oxide is 2 μm thick. The lithographic pattern is written in ZEP 520 resist with an e-beam writer and is transferred to the silicon using plasma etching in an SF_6-based plasma. Membrane PhCs result from underetching the patterned silicon. The PhCs have a triangular lattice with nine rows of holes between 2.5 μm wide waveguides and are oriented for light propagation in the ΓM direction. The designed ratio r/a of the hole radius to the lattice constant is 0.3, while a is litho-tuned in the range 490-510 nm. Having measured the empty crystal (i.e., holes not infilled), the chip is cleaned to prepare for infilling, which is done by applying a droplet of a 2% solution by weight of elastomer in cyclohexane. The low viscosity and good wetting properties of the solution make it quickly spread over the PhCs, flow through the holes and fill the space below the membrane, resulting in infilled PhCs with elastomeric upper and lower cladding. Fig. 1(a), a scanning electron microscope (SEM) image of an infilled PhC, demonstrates that infilling of the holes indeed has proceeded in this way. The measurements are performed after a certain time ($\geq$0.5 h), to make sure that the solvent has completely diffused out of the elastomer, as indicated by stabilization of the spectral features.

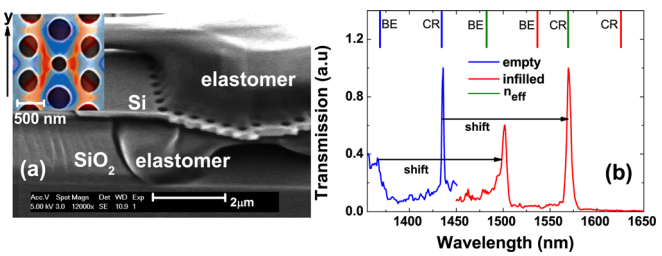

FIG. 1. (Color online) (a) SEM image of a cleaved elastomer-infilled PhC. The inset shows a SEM image of the cavity, with the mode profile superimposed (E_y-field). The r/a ratio is 0.32, while the modified central hole has $r/a = 0.22$ and the half ellipses have ellipticity of 0.2. (b) Transmission spectrum of the empty and infilled PhC, showing the air-band edge and the cavity resonance, the latter normalized to unity. The blue and red stripes denote simulated positions of the band edge (BE) and the cavity resonance (CR). The green stripes denote these positions for an index n_{eff}.

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The elastomer has a temperature dependent index $n_{elast}(T) = 1.478 - 3.32 \times 10^{-4} \times (T - T_0)$ in the range 293-323 K ($T_0 = 293$ K), as deduced from refractometry measurements at 1550 nm. Further, the elastomer is highly transparent in the wavelength range of the measurements, which follows from absorbance measurements on a control sample. In particular, we find $\alpha = 0.4$ cm^{-1} and $\mathrm{Im}(\varepsilon) = \frac{\lambda}{2\pi}\alpha = 10^{-5}$ at 1550 nm, as upper bounds for the absorption coefficient and the imaginary part of the dielectric constant, respectively. These values imply, also in view of the inferred quality factor due to absorption (see below), that absorption can be neglected in our devices.

The cavity, centered between the waveguides, is the modified point-defect cavity of Loncar *et al.*,[12] i.e., the four holes closest to a smaller central defect hole are reshaped into half ellipses. The cavity is very sensitive to an index change of the infill since an appreciable part of the mode energy is localized in the holes. The inset of Fig. 1(a) shows a SEM image of the cavity, with the mode superimposed.

Transmission measurements are performed with the end-fire-technique, using a white light source (Fianium SC 400) combined with a prism based spectral selection unit, giving a wavelength range 1300–1700 nm. The polarization is selected in-plane to excite transverse electric PhC modes. Transmitted light is measured with an optical spectrum analyzer (ANDO-AQ6315A). The temperature of the chip is regulated with a temperature controller, using a heating resistor and a Pt100 sensor mounted on the sample holder. The resulting accuracy of the sample-holder temperature is better than 0.2 °C in the temperature range 20–60 °C.

Figure 1(b) shows the room-temperature transmission of one of the PhCs, in a range covering the air band and part of the bandgap, both for the empty and infilled PhC. For the empty case, the steep side at 1365 nm is the air-band edge, while the strong peak at 1436 nm is the cavity resonance occurring at the shorter wavelength (this cavity has two resonances; the other one is at longer wavelength). These positions agree well with the positions in the transmission spectrum calculated with the finite-difference time-domain (FDTD) simulator CrystalWave,[13] as indicated in Fig. 1(b) with the blue vertical stripes. After infilling, in spite of the decreased index contrast ($n_{elast}(T_0) = 1.478$), we still clearly observe the main features of the spectrum, which exhibits a pronounced red shift. The air-band edge and the cavity peak now are at about 1500 and 1570 nm, respectively, implying a 135 nm shift. The simulations predict a stronger shift, as indicated by the red vertical stripes. This difference will be discussed below.

In Fig. 2(a) we zoom in on the cavity peak, for nine temperatures. In addition to the data in the right panel of Fig. 2(a), taken after infilling, we also present in the left panel the data for the empty case, for reference. In the right panel we clearly observe the elastomer-induced thermal tuning effect sought for. With increasing temperature the peak shows a steady blue shift. Further, we observe a broadening of the resonance, i.e., a reduction of the quality factor. From a comparison with the T-dependence shown for the empty case, which shows a red shift due to the positive TOC of silicon, we conclude that the negative TOC of the elastomer indeed overcompensates the positive TOC of the silicon. Fig. 2(b) shows

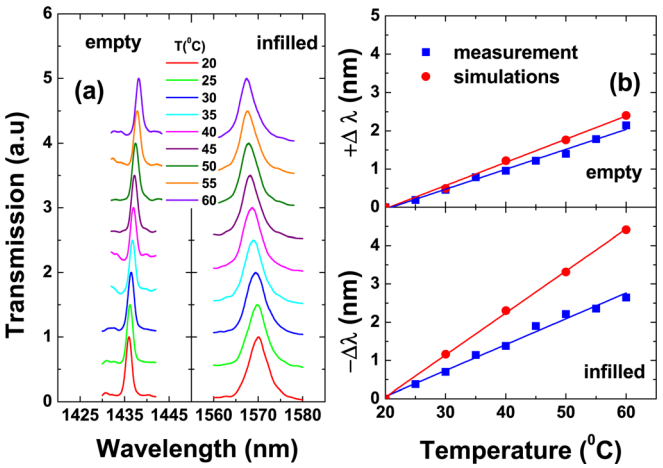

FIG. 2. (Color online) (a) Cavity resonance as a function of temperature, for temperatures as indicated, and for the empty and infilled PhC. The curves were normalized to unity and offset for clarity. (b) Temperature dependence of the measured and simulated shift of the cavity resonance, for the empty and infilled PhC. The lines are fits to the data points.

the peak shift as a function of temperature, as derived from the measurements and simulations, for the latter using the above $n_{elast}(T)$ and $n_{Si}(T) = 3.48 + 1.85 \times 10^{-4} \times (T - T_0)$.[14] For the empty case the linear fits to the data points yield experimental and simulated peak shifts of 2.1 and 2.4 nm, respectively, for the total temperature change. We consider this a good agreement. For the infilled case, however, the experimental and simulation data show a discrepancy. Thermal tuning for the total temperature change amounts to shifts of −2.7 and −4.4 nm, for the measurements and the simulations, respectively, as again deduced from the fits.

The thermal tuning behaviour can be further discussed using the perturbation expression for the relative shift of the resonance wavelength[1]

$$\frac{\Delta\lambda(T)}{\lambda(T_0)} \approx \sum_i \frac{\Delta n_i(T)}{n_i(T_0)} \times fr(i). \qquad (1)$$

Here the summation index denotes silicon or elastomer, and $fr(i)$ is the fraction of the electric energy of the cavity mode in the region where the index perturbation occurs ($fr(\mathrm{Si}) + fr(\mathrm{elast}) = 1$). From the measured total tuning of −2.7 nm and using $n_{elast}(T)$ and $n_{Si}(T)$, we obtain $fr(\mathrm{Si}) = 0.66$ and $fr(\mathrm{elast}) = 0.34$. So, 34% of the total energy of the cavity mode, in combination with the negative TOC of the elastomer, induces the thermal tuning effect we observe.

The aforementioned discrepancies for the position of the band edge and the resonance, and for the resonance shift with temperature, suggests that the experiment probes effective values of the index and the TOC of the elastomer that are systematically some lower than the regular values. By performing further simulations we find that for the band edge and resonance position the discrepancy is to a large extent removed by using $n_{eff} = 0.92 \times n_{elast}$ (green stripes in Fig. 1(b); stripe positions fitted to experimental positions, with emphasis on the resonance position). Since the cavity mode is more sensitive to the infilled holes than to the claddings, we interpret this reduced index as an indication of partially filled cavity holes. Contrary to holes in non-membrane PhCs, however, where partial filling may arise from air

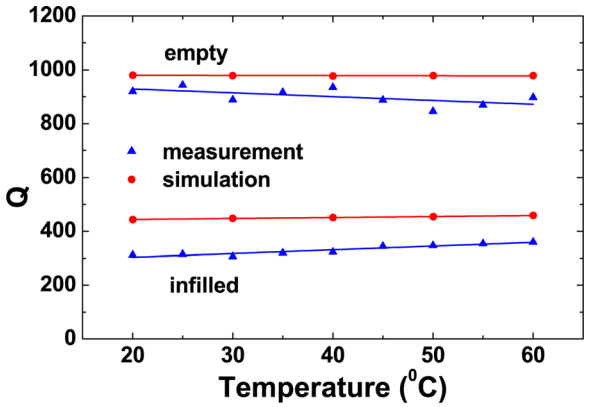

FIG. 3. (Color online) *T*-dependence of the measured and simulated quality factor of the resonance, for the empty and the infilled PhC.

inclusions in the lower part of the holes,[15] we suggest that here partial infilling has a different origin. Evaporation of the solvent out of the solution goes along with a density increase, leading to the regular density of the elastomer. In Ref. 16, that treats solvent evaporation from large area polymer films, the density increase results from film-thickness reduction. In our case the elastomer solution in the holes is a three-dimensional system with an aspect ratio close to unity, so that size reduction in the lateral direction may be expected as well, a process in which the cohesion forces of the compacting elastomer exceed the adhesion forces to the wall of a hole. Modelling the partial filling of cavity holes with an empty shell ($n=1$) surrounding a cylindrical elastomeric core, we find $f_{shell}=0.28$ and $f_{core}=0.72$ for the filling fractions. In view of the roughness of the model, these fractions show fair agreement with the ratio of the slopes of the lines in Fig. 2(b) for the infilled case, which amounts to 0.61 and should be compared to $f_{core}=0.72$.

From the resonances in Fig. 2(a) we determine the quality factor Q, using fits to the measured line shapes. Fig. 3 shows the resulting T-dependence of Q, along with simulated Q values, for which in this case we use the Harminv tool of MEEP,[17] which can directly output Q values. As a result of infilling Q is reduced from about 900 to about 330, while both for the empty and infilled case Q is only weakly T-dependent. The reduction of Q is understood from the property that the PhC mirrors surrounding the cavity have a shallower bandgap and thus a lower reflectivity after infilling.[15] Looking in more detail, it is seen that the infilled cavity shows a slight but steady increase of Q with temperature. This arises from the index decrease of the elastomer. The simulated Q is systematically higher than the measured Q, which we attribute to fabrication imperfections. Treating $\mathrm{Im}(\varepsilon)=10^{-5}$ as a perturbation[1] and using $fr(\mathrm{elast})=0.34$, we estimate the quality factor due to absorption in the elastomer and find $Q_{abs}=6.4\times10^5$. This is much larger than the Q-values in Fig. 3, so that the absorption channel does not limit the quality factor in our devices. It follows that the Q of an infilled cavity (lossless elastomer) that is reduced to 90% of its value by "turning on" Q_{abs} amounts to $Q=7.1\times10^4$.

In conclusion, we have performed global infilling of silicon photonic crystals with the elastomer Kraton SEBS G 1657 and measured thermal tuning of the cavity transmission. The transmission shows a pronounced blue shift with temperature, which originates from the strong thermal expansion of the elastomer and the resulting negative thermal optical coefficient. This interpretation is supported by simulations, which also suggest fractional infilling of the holes with elastomer, the filling fraction being 72%. These results call for local thermal tuning, for example using dye or quantum dot doping of the elastomer, which enables conversion of locally applied optical energy into heat.

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