Liquid crystal-infiltrated nanocavity and waveguide in deeply etched InP-based photonic crystals

I. Barbu[1], H.H.J.E. Kicken[1], P.A.M. Nouwens[1], R.W. van der Heijden[1], F. Karouta[1],
R. Nötzel[1], and H.W.M. Salemink[1,2]

[1]COBRA Inter-University Research Institute and Centre for NanoMaterials, Eindhoven University of Technology, POBox 513, NL 5600MB Eindhoven, The Netherlands
i.barbu@student.tue.nl
[2]Kavli Institute of Nanoscience, Delft University of Technology, POBox 5053, NL 2600 GB Delft, The Netherlands

Abstract. *Deeply etched InP-based planar photonic crystals incorporating point and line defect structures were fabricated and experimentally investigated. Tuning of the H1 cavity mode and the W3 waveguide mini-stopband by infiltration with the liquid crystal K15 is experimentally demonstrated.*

Introduction

Much research effort has been devoted to the study of photonic crystals (PC) [1] due to their unique optical properties. A practical realization of 2D planar PCs consists of a periodic arrangement of air cylinders deeply etched in a semiconductor heterostructure slab waveguide of the type InP-InGaAsP-InP [2,3], which is an important system for photonic integrated circuits, operating at telecom wavelengths. PCs incorporating defects can then serve as building blocks for circuit components.

In this contribution we report the smallest possible cavity in this 2D PC, created by omitting the etching of a single hole, known as H1 cavity. Small cavities are of interest for components as a low-threshold laser [4,5] or drop filter [6]. Also the W3 waveguide, consisting of a line defect with three missing rows of holes is investigated. It displays a Mini Stopband (MSB), which can be employed as a wavelength division demultiplexer [7]. Both devices were studied in combination with infiltration of the air holes with Liquid Crystal (LC) [8,9] to create the possibility of tuning or trimming the PC-based devices.

Experimental details

2D PCs consisting of a triangular array of air holes were deeply etched in an InP/InGaAsP/InP slab waveguide with the lattice constant a varying from 309 to 522 nm (Δa = 20 nm) (“lithographic tuning”) and hole radii r designed to be r/a~0.3. The structures were defined by 30 keV electron-beam lithography and etched using Cl_2-based Inductively Coupled Plasma (ICP) etching [3]. The etched holes show almost vertical sidewalls in their upper part [3]. The 500 nm-thick quaternary layer was sandwiched between an upper 500-nm thick InP cladding layer and a bottom InP buffer layer. Transmission measurements based on the end-fire approach used as light source a tunable external cavity diode laser (1470-1570 nm tunable range). Tapered ridge waveguides were used to couple the light into and out of the PC waveguide or cavity. The nematic liquid crystal K15 (5CB) used for infiltration has a crystalline to nematic phase transition temperature T_{cn} = 23°C and a nematic to isotropic transition temperature (clearing temperature) T_{ni} = 35.4°C [9]. In the nematic state the LC-K15 is a birefringent material with n_o = 1.516 and n_e = 1.682 as the ordinary and extraordinary refractive indices, respectively at a wavelength of 1.5 μm. In the isotropic state the refractive index at $T = 40^{o}C$ is $n_i = 1.575$.

Experimental results and discussion

In order to assess the LC infiltration efficiency of our InP-based PCs, transmission measurements were first performed at room temperature (RT) (approximately 23°C). A comparison between the RT transmission spectra in the frequency region near the H1-cavity resonance peak is shown in Fig. 1(a) both for the LC-K15 infiltrated and uninfiltrated sample. The cavity is shown in the inset to Fig. 1(a) and has 4 PC rows between its center and the access waveguides. All data are disturbed by strong modulations, resulting from Fabry Perot interferences in the cavities formed by the entrance and exit access ridge waveguides. Both waveguides are approximately one mm long, and are terminated by the highly reflective cleaved facet at one side and the photonic crystal mirror at the other side. Mostly, a data sampling period of typically $d\lambda = 1$ nm is chosen that does not resolve the FP-fringes, so that the data as in Fig. 1(a) appear noisy. For accurate measurements, or quantitative estimates, the sampling period is decreased to $d\lambda = 10$ pm, which fully resolves the FP fringes as in Fig. 1(b). The two access ridge waveguides have slightly different lengths l_1 and l_2, leading to a low-frequency beat in the FP-modulation, which is also clearly present in Fig. 1(b). From the convolution of the high-frequency FP fringes in Fig.1(b) the cavity quality factor Q can be reliably estimated as Q ≈ 63. This Q-factor value compares favorably to that typically reported for the much larger FP-type cavity in similar InP-based PC's, which are in the order 20 to 30 [2]. Optimized chemically assisted ion beam etching (CAIBE) processes, however, have yielded single row Fabry-Perot cavities with Q up to ~300 [10].

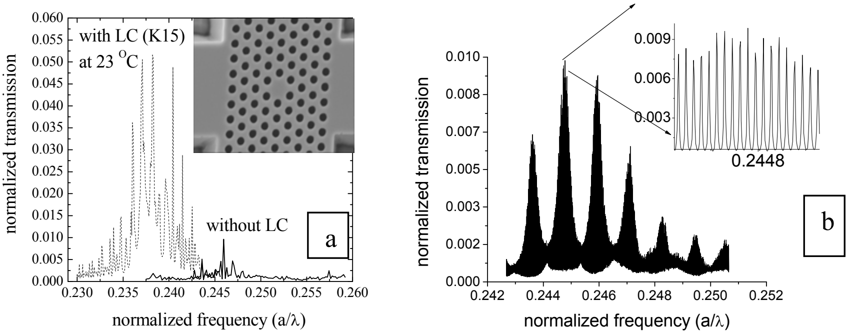

Figure 1: (a) H1-cavity resonance peak with (dashed line) and without (solid line) LC-K15 infiltration. The peak energy position redshifts, clearly indicating an increase in the average refractive index of the holes n_{hole}. A top-view scanning electron microscopy image (SEM) illustrating the H1 cavity is given in the inset. (b) High resolution measurement of the H1 cavity resonance for the uninfiltrated case. Both the low and the high frequency modulation (inset) are illustrated. The inset is a zoom-in on the peak centered at $a/\lambda = 0.2448$.

Infiltration has a strong effect on the H1 cavity resonance as shown in Fig 1(a). The cavity peak redshifts by approximately $\Delta(a/\lambda)=0.8\times10^{-2}$. The redshift corresponds to an increase in the average refractive index n_{hole} of the holes, as expected. Martz *et al.* [9] have observed the redshift of a ~1-row FP cavity resonance upon infiltration with the same LC of $\Delta(a/\lambda)=1.38\times10^{-2}$. Simulations suggest that our lower value for the H1 cavity results from a lower effective index of the holes, or incomplete infiltration. Although the H1 cavity mode peak transmission T_{peak} is enhanced by 5 times after infiltration, its quality factor decreases to only Q~36. Both the transmission enhancement and peak broadening were also observed for the FP-cavity with an empty-hole Q-factor of ~300 [9]. This behavior may be explained by a modification of the PC mirror optical properties and the H1 intracavity losses [9] which are likely to influence both the cavity mode excitation efficiency and the mode profile. It is believed that higher excitation efficiency might account for larger T_{peak} whereas weaker confinement of the mode inside the cavity (greater penetration into the PC mirrors) could result into lower cavity quality factors. However, further experimental and theoretical investigations should be performed in order to verify these assumptions.

The second defect structure whose spectral properties were investigated was the PC W3 waveguide. It is now a well-known fact [7,11] that in such a 2D PC multimode channel waveguide an anticrossing phenomenon takes place when the guided fundamental mode (FM) couples to a counterpropagating higher order mode (HOM). Then part of the FM energy is transferred to the HOM and thus a dip T_{min} called a “mini-stopband” (MSB) [11] appears in the transmission spectrum. The HOM corresponds to light bouncing between the PC boundaries, thus slowly propagating and resembling the FP resonator.

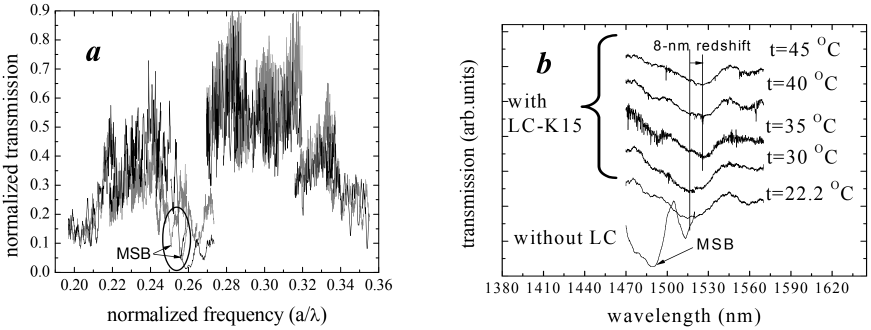

Figure 2: (a) wide frequency, low resolution transmission spectrum versus *a/λ* (“lithotuned”) before (black) and after infiltration (grey) (b) transmission versus wavelength scan for a single PC for the sharp MSB dip before and after infiltration and in the latter case at several temperatures. All spectra are vertically shifted for clarity.

We observe the MSB in a W3 waveguide easily and consistently in several W3 guides investigated, as shown in the wide frequency scan in Fig. 2(a) for a 10 μm long guide. This wide scan, which is necessarily obtained from several PCs with different lattice constants (lithotuning) and low resolution, is not necessarily continuous as the properties may differ somewhat from crystal to crystal. For accurate measurements, one particular PC is picked that contains a sharp dip due to the MSB. The MSB is shown in Fig. 2(b) for the crystal with interhole spacing a = 381 nm before and after the infiltration. Data are taken in high resolution, but Fabry-Perot fringes are numerically averaged out. Near the dip, the FP fringe amplitude decreases strongly as the W3 waveguide becomes lossy. RT transmission measurements (22.2±0.2°C) of the infiltrated sample revealed a redshift of 30.3 nm from 1487 nm to 1517.3 nm of the MSB wavelength location. When the temperature was raised up to 30±0.2°C with the LC still deep in the nematic state, no measurable shift of the MSB was noticed. Only when the PC device reached the LC K15 clearing temperature of 35 ^{0}C, an additional redshift of 8 nm of T_{min} was noticed. A similar redshift upon temperature tuning was observed for the FP resonance peak [12]. The LC is now in the isotropic state and in this regime the refractive index is constant n_i = 1.575. Therefore, a variation of the MSB position is not expected when the temperature is increased above T_{ni}. The spectra in Fig. 2 corresponding to 35, 40 and 45^{o}C illustrate the expected zero shift of the MSB.

Conclusions

We have demonstrated the possibility of tuning the spectral properties of a H1 cavity mode formed in a deeply etched InP-based 2D PC by infiltration with the liquid crystal K15. A redshift of the H1 cavity resonance was observed simultaneously with enhanced peak transmission and decreased cavity quality factor. Furthermore, a similar PC containing a W3 waveguide was filled with the same LC. We successfully demonstrated the temperature tuning of the waveguide MSB by thermally modifying the LC refractive index.

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