

# Wavelength tuning of planar photonic crystals by local processing of individual holes

**Citation for published version (APA):**

Kicken, H. H. J. E., Alkemade, P. F. A., Heijden, van der, R. W., Karouta, F., Nötzel, R., Drift, van der, E. W. J. M., & Salemink, H. W. M. (2009). Wavelength tuning of planar photonic crystals by local processing of individual holes. *Optics Express*, 17(24), 22005-22011. <https://doi.org/10.1364/OE.17.022005>

**DOI:**

[10.1364/OE.17.022005](https://doi.org/10.1364/OE.17.022005)

**Document status and date:**

Published: 01/01/2009

**Document Version:**

Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

**Please check the document version of this publication:**

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
- The final author version and the galley proof are versions of the publication after peer review.
- The final published version features the final layout of the paper including the volume, issue and page numbers.

[Link to publication](#)

**General rights**

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license above, please follow below link for the End User Agreement:

[www.tue.nl/taverne](http://www.tue.nl/taverne)

**Take down policy**

If you believe that this document breaches copyright please contact us at:

[openaccess@tue.nl](mailto:openaccess@tue.nl)

providing details and we will investigate your claim.

# Wavelength tuning of planar photonic crystals by local processing of individual holes

H. H. J. E. Kicken<sup>1,\*</sup> and P. F. A. Alkemade<sup>2</sup> and R. W. van der Heijden<sup>1</sup> and F. Karouta<sup>1</sup> and R. Nötzel<sup>1</sup> and E. van der Drift<sup>2</sup> and H. W. M. Salemink<sup>2</sup>

<sup>1</sup>COBRA Research Institute and Center for NanoMaterials, Eindhoven University of Technology, P.O. Box 513, NL-5600 MB Eindhoven, The Netherlands

<sup>2</sup>Kavli Institute of Nanoscience, Delft University of Technology, P.O. Box 5053, NL-2600 GB Delft, The Netherlands

\*Corresponding author: [h.h.j.e.kicken@tue.nl](mailto:h.h.j.e.kicken@tue.nl)

**Abstract:** Tuning of the resonant wavelength of a single hole defect cavity in planar photonic crystals was demonstrated using transmission spectroscopy. Local post-production processing of single holes in a planar photonic crystal is carried out after selectively opening a masking layer by focused ion beam milling. The resonance was blue-shifted by enlargement of selected holes using local wet chemical etching and red-shifted by infiltration with liquid crystals. This method can be applied to precisely control the resonant frequency, and can also be used for mode selective tuning.

© 2009 Optical Society of America

OCIS codes: (000.0000) General.

---

## References and links

1. J. D. Joannopoulos, S. G. Johnson, R. D. Meade and J. N. Winn, *Photonic crystals: molding the flow of light*, Princeton, NJ: Princeton Univ. Press, 2008.
2. S. F. Mingaleev, M. Schillinger, D. Hermann, and K. Busch, *Tunable photonic crystal circuits: concepts and designs based on single-pore infiltration*, *Opt. Lett.* **29**, 2858 (2004).
3. S. W. Leonard, J. P. Mondia, H. M. van Driel, O. Toader, S. John, K. Busch, A. Birner, U. Gösele, and V. Lehmann, *Tunable two-dimensional photonic crystals using liquid crystal infiltration*, *Phys. Rev. B* **61**, R2389 (2003).
4. Ch. Schuller, F. Klopff, J. P. Reithmaier, M. Kamp, and A. Forchel, *Tunable photonic crystals fabricated in III-V semiconductor slab waveguides using infiltrated liquid crystals*, *Appl. Phys. Lett.* **82**, 2767 (2003).
5. G. Mertens, T. Röder, H. Matthias, H. Marsmann, H.-S. R. Kitzerow, S. L. Schweizer, C. Jamois, R. B. Wehrspohn, and M. Neubert, *Two- and three-dimensional photonic crystals made of macroporous silicon and liquid crystals*, *Appl. Phys. Lett.* **83** (2003).
6. M. Lončar, A. Scherer, and Y. Qiu, *Photonic crystal laser sources for chemical detection*, *Appl. Phys. Lett.* **82**, 4648 (2003).
7. B. Maune, J. Witzens, T. Baehr-Jones, M. Kolodrubetz, H. Atwater, A. Scherer, R. Hagen, and Y. Qiu, *Optically triggered Q-switched photonic crystal laser* *Opt. Express* **13**, 4699 (2005).
8. J. Martz, R. Ferrini, F. Nesch, L. Zuppiroli, B. Wild, L. A. Dunbar, R. Houdré, M. Mulot, and S. Anand, *Liquid crystal infiltration of InP-based planar photonic crystals*, *J. Appl. Phys.* **99**, 103105 (2006).
9. R. Ferrini, J. Martz, L. Zuppiroli, B. Wild, V. Zabelin, L. A. Dunbar, R. Houdré, M. Mulot and S. Anand, *Planar photonic crystals infiltrated with liquid crystals: optical characterization of molecule orientation*, *Opt. Lett.* **31**, 1238 (2006).

10. R. van der Heijden, C. F. Carlström, J. A. P. Sniijders, R. W. van der Heijden, F. Karouta, R. Nötzel, H. W. M. Salemink, B. K. C. Kjellander, C. W. M. Bastiaansen, D. J. Broer, and E. van der Drift, *InP-based two-dimensional photonic crystals filled with polymers*, Appl. Phys. Lett. **88**, 161112 (2006).
11. P. El-Kallassi, R. Ferrini, L. Zuppiroli, N. Le Thomas, R. Houdré, A. Berrier, S. Anand, and A. Talneau, *Optical tuning of planar photonic crystals infiltrated with organic molecules*, J. Opt. Soc. Am. B **24**, 2165 (2007).
12. S. Tay, J. Thomas, B. Momeni, M. Askari, A. Adibi, P. J. Hotchkiss, S. C. Jones, S. R. Marder, R. A. Norwood, and N. Peyghambarian, *Planar photonic crystals infiltrated with nanoparticle/polymer composites*, Appl. Phys. Lett. **91**, 221109 (2007).
13. A. Faraon, D. Englund, D. Bulla, B. Luther-Davies, B. J. Eggleton, N. Stoltz, P. Petroff, and J. Vučković, *Local tuning of photonic crystal cavities using chalcogenide glasses*, Appl. Phys. Lett. **92**, 043123 (2008).
14. D. Dalacu, S. Frédéric, P. J. Poole, G. C. Aers, and R. L. Williams, *Postfabrication fine-tuning of photonic crystal microcavities in InAs/InP quantum dot membranes*, Appl. Phys. Lett., **87**, 151107 (2005).
15. K. Hennessy, A. Badolato, A. Tamboli, P.M. Petroff, E. Hu, M. Atatüre, J. Dreiser, and A. Imamoğlu, *Tuning photonic crystal nanocavity modes by wet chemical digital etching*, Appl. Phys. Lett. **87**, 021108 (2005).
16. T. Sünner, R. Herrmann, A. Löffler, M. Kamp, and A. Forchel, *Fine-tuning of GaAs photonic crystal cavities by digital etching*, MicroElec. Eng. **84**, 1405 (2007).
17. F. Intonti, S. Vignolini, V. Türrck, M. Colocci, P. Benotti, L. Pavesi, S. L. Schweizer, R. Wehrspohn, and D. Wiersma, *Rewritable photonic circuits*, Appl. Phys. Lett. **89**, 211117 (2006).
18. C. L. C. Smith, D. K. C. Wu, M. W. Lee, C. Monat, S. Tomljenovic-Hanic, C. Grillet, B. J. Eggleton, D. Freeman, Y. Ruan, S. Madden, B. Luther-Davies, H. Giessen, and Y.-H. Lee, *Microfluidic photonic crystal double heterostructures*, Appl. Phys. Lett., **91**, 121103, (2007).
19. C. L. C. Smith, U. Bog, S. Tomljenovic-Hanic, M. W. Lee, D. K. C. Wu, L. O'Faolain, C. Monat, C. Grillet, T. F. Krauss, C. Karnutsch, R. C. McPhedran, and B. J. Eggleton, *Reconfigurable microfluidic photonic crystal slab cavities*, Opt. Express **16**, 15887 (2008).
20. P. El-Kallassi, S. Balog, R. Houdré, L. Balet, L. Li, M. Francardi, A. Gerardino, A. Fiore, R. Ferrini, and L. Zuppiroli, *Local infiltration of planar photonic crystals with UV-curable polymers*, J. Opt. Soc. Am. B **25**, 1562 (2008).
21. K. Hennessy, C. Högerle, E. Hu, A. Badolato, and A. Imamoğlu, *Tuning photonic nanocavities by atomic force microscope nano-oxidation*, Appl. Phys. Lett. **89**, 041118 (2006).
22. M.-K. Seo, H.-G. Park, J.-K. Yang, J.-Y. Kim, S.-H. Kim, and Y.-H. Lee, *Controlled sub-nanometer tuning of photonic crystal resonator by carbonaceous nano-dots*, Opt. Express **16**, 9829 (2008).
23. R. Ferrini, D. Leuenberger, M. Mulot, M. Qiu, J. Moosburger, M. Kamp, A. Forchel, S. Anand and R. Houdré, *Optical study of two-dimensional InP-based photonic crystals by internal light source technique*, J. Quantum Elec. **38**, 786 (2002).
24. C. F. Carlström, R. van der Heijden, F. Karouta, R. W. van der Heijden and H. W. M. Salemink, and E van der Drift, *Cl2/O2-inductively coupled plasma etching of deep hole-type photonic crystals in InP*, J. Vac. Sci. Technol. B **24**, L6 (2006).
25. J. Topol'ančik, P. Bhattacharya, J. Sabarinathan, and P.-C. Yu, *Fluid detection with photonic crystal-based multichannel waveguides*, Appl. Phys. Lett. **82**, 1143 (2003).
26. R. W. Tjerkstra, F. B. Segerink, J. J. Kelly, W. L. Vos, *Fabrication of three-dimensional nanostructures by focused ion beam milling*, J. Vac. Sci. Technol. B **26**, 973 (2008).
27. W. C. L. Hopman, F. Ay, W. Hu, V. J. Gadgil, L. Kuipers, M. Pollnau, and R. M. de Ridder, *Focused ion beam scan routine, dwell time and dose optimizations for submicrometre period planar photonic crystal components and stamps in silicon*, Nanotechnol. **18**, 195305 (2007).
28. M. J. Cryan, M. Hill, D. Cortaberria Sanz, P. S. Ivanov, P. J. Heard, L. Tian, S. Yu, and J. M. Rorison, *Focused ion beam-based fabrication of nanostructured photonic devices*, IEEE J. Sel. Top. Quantum. Electron **11**, 1266 (2005)
29. D. Freeman, S. Madden, and B. Luther-Davies, *Fabrication of planar photonic crystals in a chalcogenide glass using a focused ion beam*, Opt. Express **13**, 3079 (2005).
30. T. Stomeo, G. Visimberga, M. T. Todaro, A. Passaseo, R. Cingolani, M. De Vittorio, S. Cabrini, A. Carpentiero, and E. Di Fabrizio, *Rapid prototyping of two-dimensional photonic crystal devices by a dual beam focused ion beam system*, Microelec. Eng. **78-79**, 417 (2005).
31. P. M. Nellen, P. Strasser, V. Callegari, R. Wüest, D. Erni, and F. Robin, *Focused ion beam modifications of indium phosphide photonic crystals*, Microelec. Eng. **84**, 1244 (2007).
32. P. M. Nellen, V. Callegari, and R. Brönnimann, *FIB-milling of photonic structures and sputtering simulation*, Microelectron. Eng. **83**, 1805 (2006).
33. E. Graugnard, D. P. Gaillot, S. N. Dunham, C. W. Neff, T. Yamashita, and C. J. Summersa, *Photonic band tuning in two-dimensional photonic crystal slab waveguides by atomic layer deposition*, Appl. Phys. Lett. **89**, 181108 (2006).

## 1. Introduction

Photonic crystals (PCs) influence the flow of light on the wavelength scale, and will enable the ultimate miniaturization of photonic integrated circuits (PIC) [1]. Post-production tuning is of importance for PIC as a means of correcting fabrication deviations, active device control and realization of additional functionality [2]. In particular, the precise control of resonant wavelengths of cavities is of importance. PC cavities are essential components in PIC. The spectral features of cavities are generally narrow, thus, large tuning effects can be realized when the effective refractive index of the cavity is varied.

Recently, significant progress has been made on post-production tuning of photonic crystals and cavities. As a means of trimming or tuning, complete infiltration of the PC was carried out with materials such as liquid crystals (LC) [3, 4, 5, 6, 7, 8, 9], polymers [10, 11, 12] and chalcogenide glass [13]. With these methods, it is possible to red-shift the spectral features of the original PC device, since the air inside the holes is replaced with a material with a higher refractive index. In contrast, a digital etching approach [14, 15, 16], i.e. cyclic oxidation and oxide removal, results in blue-shifting of spectral features as high index material is removed.

A more attractive method of post-processing is to address a small area of a device. In this way, e.g. one cavity or one of its resonant modes can be modified, without affecting the overall properties of the PC. Recently, several of such methods were reported. These include infiltration of several holes by micro-pipetting [17, 18, 19], photo-darkening of chalcogenide glass [13], local in-situ polymerization of globally infiltrated monomers [20], nano-oxidation by atomic force microscope [21] and controlled deposition of carbonaceous nano-dots [22].

Here, we present a novel lithographic technique of tuning PC devices, based on local mask opening for individual holes. This enables the use of any post production method on the exposed area of the PC, while not affecting other holes in the PC. None of the other techniques is capable of being both local on the single hole level and free, regarding the choice of postprocessing technique. The process is demonstrated by application of both local digital etching and local LC infiltration of the nearest-neighbor-holes of a point defect (H1) cavity in the technologically important InP system [23].

## 2. Experimental

The PCs were fabricated by etching a triangular lattice of air holes of  $< 250$  nanometer (nm) diameter, through a 500 nm InP/500 nm InGaAsP layerstack on an InP substrate using  $\text{Cl}_2/\text{O}_2$  chemistry [24]. The hole depth is at least  $2.5 \mu\text{m}$ , i.e. aspect ratio of  $>10$ . A so-called H1-cavity is created by eliminating one hole in the PC. The cavities were probed through access ridge waveguides (RWG) on the chip. The airfilling fraction was determined from Scanning Electron Microscope (SEM) images to be 0.27. Transmission spectroscopy was carried out using an end-fire technique using a tunable laser in the range of  $1.47 \mu\text{m}$  to  $1.57 \mu\text{m}$  in TE polarization.

After PC and waveguides are made, the transmission spectrum of the device was measured. Next, a  $\text{SiN}_x$  masking layer with a thickness of several hundred nm is deposited by plasma enhanced chemical vapor deposition (PECVD). This  $\text{SiN}_x$  masking layer covers, but does not significantly fill the holes, see figure 1a). After the holes are covered by the mask the device is remeasured to verify that deposition of the mask layer does not affect the spectrum. For the infiltration experiments, the nematic liquid crystal 4-n-pentyl-4'-cyanobiphenyl (5CB, Merck) is used.

Holes in the PC lattice can be targeted by focussed ion beam (FIB) milling in a dual beam FIB system. First, shallow markers are created in the masking layer in the vicinity of the area of interest. Next, using SEM (at 20 kV energy) it is possible to detect the holes of the PC lattice through the masking layer. Thus, the PC lattice can be related to the markers. In the final step

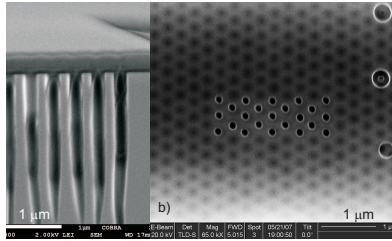


Fig. 1. a) SEM picture of a cross-section of a PC covered by a  $\text{SiN}_x$  masking layer. b) SEM picture of an array of individually targeted holes by FIB milling. SEM allows detection of the PC holes through the masking layer. On the right side the alignment markers are visible. The scale in both figures is indicated by the white bar, which has a length of  $1 \mu\text{m}$  in both cases.

individual holes can be targeted for FIB milling on the basis of the markers, see figure 1b). The precision, both in x- and in y-direction, of the FIB milling is 30 - 40 nm (standard deviation).

Post-processing of a single hole will only yield a small shift of the resonant frequency for the H1 cavity. Since the Q-factors of small cavities fabricated in the deeply etched InP/InGaAsP/InP system are low, this would result in shifts within the linewidth. Therefore, to optically demonstrate the selective mask opening mechanism, local post-processing of the six holes adjacent to an H1 cavity was performed.

To open the selected holes, a hexagonal pattern encompassing the six holes next to the H1 cavity was fabricated by FIB milling (see figure 2a), leaving a  $\text{SiN}_x$  layer of some tens of nm at the target position. It is necessary not to open the masking layer completely as the FIB etchrate on the underlying InP is high. Attempting to fully open the masking layer in a single step effectively destroys the PC. The final step consists of thinning down the remaining  $\text{SiN}_x$  layer by wet chemical etching using a diluted solution of HF in water (1:200), opening the holes adjacent to the defect completely (see figure 2b). The wet chemical etching step can be controlled to only open the pre-thinned region, while the rest of the mask remains sufficiently thick to protect the holes. The wet etching does not affect the InP.

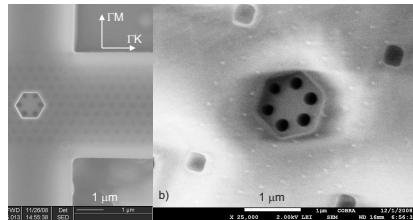


Fig. 2. a) 20 kV SEM picture after FIB opening of a hexagonal shape covering the holes adjacent to the H1-defect. The vertical arm of the cross-like structure is the access RWGs used for transmission spectroscopy. b) SEM picture of the hexagonal opening after the wet chemical etching process, showing the six opened PC holes. The four dark squares are the markers used for the alignment procedure. The holes situated below the thicker part of the mask remain closed. The scale in both figures is indicated by the white bar, which has a length of  $1 \mu\text{m}$  in both cases.

The work of Topol'ančik *et al.* [25] describes the opening of large areas of PC masked by  $\text{SiO}_x$  using electron beam lithography (EBL) for subsequent infiltration. However, since we use

high aspect-ratio RWGs we avoid planarization required for EBL, due to the use of the FIB. FIB milling is also used as a method of fabrication of PCs in diverse materials [26, 27, 28, 29, 30] by direct milling, i.e. without masking layer. Also, FIB modification of conventionally fabricated PC devices by direct milling is reported [31]. However, direct FIB milling of InP is severely challenging because of increased surface roughness due to InGa deposition [31], material redeposition inside the holes and self-focusing [32]. Although these direct writing methods by FIB are a viable route for post fabrication modification, they are neither precise, with respect to the impact on the spectral features, nor reversible.

### 3. Results & Discussion

Figure 3a shows a wide-band spectrum of the H1 cavity, measured in transmission for three conditions: as fabricated ("after fabrication"), after local digital etching ("after etching") and after local LC infiltration ("LC filled"). The resonance after fabrication is clearly visible at  $a/\lambda = 0.24$ . The spectrum is modulated by a complex pattern of Fabry-Perot (FP) fringes arising from reflections at the end-facets of the access RWGs and the PC boundaries. Since only the envelope of the signal is relevant, these were not analyzed in detail. Some discrete jumps are visible in the spectrum which are due to minor deviations between structures of the lithographically tuned series. Three dimensional Finite Difference Time Domain (3D-FDTD) calculations simulate the resonances, under the same three conditions as in the experiment, see figure 3b. In figure 3b an additional spectrum is given for the case that all the holes would be infiltrated, i.e. a failed experiment. The Q-factor of the cavity for these deeply etched structures is known to be low due to the low vertical index contrast. Comparison with the 3D-FDTD calculations shows that extra losses are incurred due to fabrication imperfections. The Q-factor of the experimental cavity was determined from the envelope to be approximately 50, by a factor of 3 smaller than expected from the simulations.

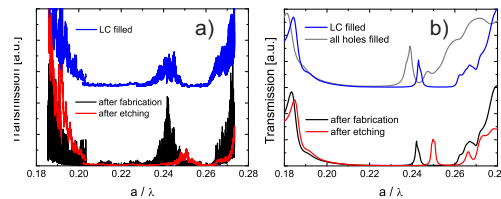


Fig. 3. a) Transmission spectrum of the H1 defect resonance. The spectra are shown stacked for clarity. The "after fabrication" line represents the measurement after fabrication. The "after etching" line displays the resonance after 15 steps of digital etching increasing the hole diameter from 190 nm to 210 nm, giving rise to a blue-shift of 40 nm ( $\Delta a/\lambda \sim 0.01$ ). After filling ("LC filled" line) the opened and enlarged holes with LC, the resonance displays a red-shift of 40 nm, approximately returning the resonance frequency to its original position. The change of the shape of the resonance for both "after etching" and "LC filled" with respect to the reference is due to the presence of the  $\text{SiN}_x$  layer, which also covers the end-facets and acts as an anti-reflection coating. b) 3D-FDTD calculations of all the steps in the post-processing scheme. A "completely filled" line was added to indicate the result of a failed experiment, i.e. all the holes of the PC are infiltrated. The calculations use the following parameters:  $a = 380$  nm, reference diameter = 203 nm, after etch diameter = 226 nm, LC filled effective refractive index of the holes = 1.41, corresponding to a LC filling efficiency of  $\sim 75\%$ .

After every step in the opening process (mask deposition, FIB etching) the spectrum was re-measured and remained unchanged. Thus the spectrum "after fabrication" in figure 3a also

represents the cavity spectrum after the holes are opened. By repeatedly subjecting the selectively opened holes to alternating an oxygen plasma and an etchant, which removes the oxide formed by the plasma, the diameter of the selected holes is enlarged. As a result of the larger holes the resonance is blueshifted (figure 3a, after etching line) by 40 nm. This process of "digital etching" is a precise and effective method of tuning, since both the thickness of the oxide layer and the number of etching steps can be accurately controlled [14, 15, 16]. In this case, 15 successive oxidizing and etching steps were applied to achieve the 40 nm shift. The increased hole size could be directly verified from SEM inspection, yielding an increased hole diameter from 190 nm to 210 nm. For the 3D-FDTD calculations an increase of  $20\pm 5$  nm of the hole diameter was needed to obtain the measured shift. The uncertainty is quite high for this determination, due to the large linewidth. Since the main part of the PC is unexposed to the digital etching treatment, due to the protective masking layer, see figure 2b, the bulk properties of the PC away from the cavity under modification, remain unchanged, apart from some possible influence of the masking layer.

In the last step the selectively opened and enlarged holes are filled with LC (figure 3a, LC filled line) by deposition of a droplet on the sample surface. The introduction of the LC into the opened holes gives rise to a large redshift of 40 nm, consistent with the increased refractive index of holes directly surrounding the defect. 3D-FDTD calculations yield a infiltration efficiency of 70-80% to match the resonance frequency. Filling factors of the same magnitude were also found in other LC infiltration experiments [8]. As only the six holes adjacent to the defect are filled, the PC retains its bulk properties, thus the band edges of the PC remain unaffected. The Q-factor remains approximately constant. In contrast, results from global infiltration techniques consistently yield a decrease of the Q-factor [6]. Apart from the linewidth, the calculations are in very good agreement with the experimental data. The high frequency transmission band onset occurs near  $a/\lambda \sim 0.26$  in all three experimental conditions. If all the holes of the PC were infiltrated, the high frequency band edge would show a considerable shift as well, see figure 3b, bringing the resonance and high frequency band edge closer together [8, 10]. This is not observed experimentally, showing that only the six holes are infiltrated indeed. It independently confirms optically what is already evident from the SEM-data in figure 2b.

Since the LC is easily dissolved in common solvents, the LC may be removed from the holes to continue the digital etching process after which the LC can be re-introduced into the holes. In this way, the resonance may be positioned close to the desired location by post-processing. The resonance frequency can subsequently be actively tuned, exploiting the relatively large dependence of the LC refractive index on an external electric field or temperature. Better precision of the blue-shift of the resonance may be achieved by using an infiltration method with more control over the refractive index of the infill, such as Atomic Layer Deposition (ALD) [33]. Since different resonant modes have spatially distinct electromagnetic field distributions, local post-processing can address specific modes for tuning.

#### 4. Conclusion

In conclusion, we have demonstrated for the first time tuning of resonant modes by local post-processing of individual holes in photonic bandgap structures. The six holes adjacent to an H1-defect cavity were selectively opened using FIB milling. Using digital etching the H1 cavity resonance was blue-shifted by 40nm, and subsequently 40 nm red-shifted by local infilling with liquid crystal. This method can be applied to precisely control the resonant frequency by both blue- and red-shift, and can also be used for mode selective tuning of resonant states by targeting the appropriate holes.

## **Acknowledgement**

The authors gratefully acknowledge useful discussions with C. W. M. Bastiaansen and D. J. Broer concerning LC aspects and thank P. Nouwens and T. de Vries for contributions to the experimental work. This work is part of the research programme of the 'Stichting voor Fundamenteel Onderzoek der Materie (FOM)', which is financially supported by the 'Nederlandse Organisatie voor Wetenschappelijk Onderzoek (NWO)'. Part of this research is supported by NanoNed, a technology programme of the Dutch ministry of Economic Affairs via the foundation STW.