

# Liquid crystal tuning of InGaAsP photonic crystal membrane type nanocavities

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

Dündar, M. A., Kicken, H. H. J. E., Silov, A. Y., Nötzel, R., Karouta, F., & Heijden, van der, R. W. (2009). Liquid crystal tuning of InGaAsP photonic crystal membrane type nanocavities. In S. Beri, P. Tassin, G. Craggs, X. Leijtens, & J. Danckaert (Eds.), *Proceedings 14th Annual Symposium of the IEEE Photonics Benelux Chapter, 5-6 November 2009, Brussels, Belgium* (pp. 101-104). Brussels University Press.

**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.

## Liquid crystal tuning of InGaAsP photonic crystal membrane type nanocavities

M. A. Dündar, H. H. J. E. Kicken, A. Yu. Silov, R. Nötzel, F. Karouta, and R. W. van der Heijden

COBRA Research Institute, Eindhoven University of Technology, P.O. Box 513  
NL-5600 MB Eindhoven, The Netherlands

*We demonstrate mode-dependent tuning of liquid crystal (4-pentyl-4'-cyanobiphenyl, 5CB, Merck) infiltrated into InGaAsP photonic crystal (PhC) membranes with embedded InAs quantum dots when the temperature or the power of an incident laser is varied. The cavity modes can be tuned in opposite directions and exhibit a sudden change at the clearing temperature. The mechanism relies on the existence of both ordinary and extraordinary refractive indices of the liquid crystal arising from specific molecular alignment inside the PhC holes. For high laser powers, large and reversible tuning of cavity modes is observed which is tentatively attributed to temperature induced liquid transport.*

### Introduction

Photonic crystal (PhC) membrane type nanocavities have attracted much attention during last decade because they are able to confine the light in a small modal volume (V) with a high quality factor (Q). A high Q/V ratio and the ability to tune the resonant frequencies make nanocavities attractive both for fundamental research and for applications. So far, they have been widely used to realise different devices such as ultra-low threshold lasers [1]. Lack of active tuning of the cavity modes over large spectral ranges is the main obstacle for applications. Changing the cavity's average refractive index by changing the molecular orientations of infiltrated liquid crystal (LC) in the PhC holes is a promising way to achieve a large spectral range of active and reversible tuning. In this work, we demonstrate thermal and thermo-optic tuning of LC infiltrated InGaAsP PhC membrane type of nanocavities. A mode dependent tuning, which may yield either a redshift or a blueshift of the nanocavity modes, is observed when the temperature is increased across the ordering temperature of the liquid crystals (LCs) that are infiltrated in the PhC airholes.

### The sample preparation and the experimental set-up

A 220 nm thick InGaAsP quaternary layer, which contains 1 monolayer of self-assembled InAs Quantum Dots (density  $3 \times 10^{10} \text{ cm}^{-2}$ ), is grown on an InP buffer layer by Metal-Organic Chemical Vapour Deposition. A hexagonal photonic crystal pattern with cavities is defined in a 350 nm thick ZEP 520 resist by 30 keV electron beam lithography. This pattern is transferred to an underlying 400 nm thick SiNx mask layer, deposited by Plasma Enhanced Chemical Vapor Deposition and opened through CHF<sub>3</sub> Reactive Ion Etching. In the next step, the pattern is created in the semiconductor layer stack by Inductively Coupled Plasma etching using Cl<sub>2</sub>:Ar:H<sub>2</sub> chemistry. The final step consists of a wet chemical etching to undercut the InGaAsP layer using a HCl:H<sub>2</sub>O=4:1 solution at 2 °C. The cavities consist of a single missing air hole surrounded by six holes with modified size and/or position in order to achieve high-Q modes [2]. Figure 1

shows the scanning electron microscope image of a fabricated InGaAsP nanocavity having a lattice spacing ( $a$ ) of 480 nm and radius-to-lattice spacing ratio ( $r/a$ ) of 0.3. The radius of the six modified holes is reduced by 33 nm and the center positions are shifted radially outwards by 13 nm.

The LC 4-pentyl-4'-cyanobiphenyl (5CB, Merck), which has the nematic-isotropic phase transition temperature, or clearing temperature,  $T_c$  at 35 °C, is infiltrated under ambient pressure. This is carried out by putting a drop of LC on the sample, while the sample and the LC are heated above  $T_c$ . The excess liquid is blown off the sample by dry nitrogen. To investigate the temperature tuning, the infiltrated sample is placed on a current controlled heating stage. A CW He-Ne laser ( $\lambda = 632$  nm) or a power tunable CW diode laser ( $\lambda = 660$  nm) is focused on the sample through a high numerical aperture microscope objective (for the thermal tuning 100x, N.A = 0.55 and for the thermo-optic tuning 50x, N.A=0.5). Excitation of the cavities and the collection of PL emission are done by the same objective. The collected PL is then dispersed in a monochromator and detected by a liquid nitrogen cooled InGaAs array.

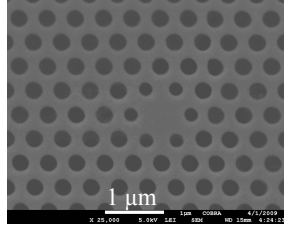


Figure 1: Scanning electron microscope (SEM) image of the modified InGaAsP nanocavity.

### Thermal tuning of the liquid crystal infiltrated PhC membranes

The LC is a birefringent material having two different refractive indices, ordinary and extraordinary, in the nematic state depending on the incident optical polarization. Figure 2(a) represents the temperature dependence of the ordinary ( $n_o$ ) and the extraordinary ( $n_e$ ) refractive index of the LC 5CB for the wavelength of 1.5  $\mu\text{m}$ , calculated from the parameters given in Ref. [3]. The  $n_o$  and the  $n_e$  have an opposite temperature dependence, which varies slightly with temperature below  $T_c$  and shows an abrupt change at  $T_c = 35$  °C, when both  $n_e$  and  $n_o$  become equal to the isotropic refractive index  $n_i$ . The isotropic refractive index does not change with the temperature. Figure 2(b) shows the PL spectrum collected from the nanocavity, before infiltration. The modes are identified by a systematic investigation of PhC-cavities for varying lattice spacings and by comparison with known spectra of this type of cavities [4]. The peaks occurring at 1461 nm and 1468 nm are quadrupole modes, referred to as the  $Q_1$ -mode and the  $Q_2$ -mode respectively. The  $Q_1$ -mode and the  $Q_2$ -mode are degenerate in ideal cavities, but in practice are split due to fabrication tolerances. The peak occurring at 1479 nm is the hexapole mode, referred to as the H-mode. Figure 2(c) shows the spectrum of the same cavity after the infiltration of the LC, which is done with the LC in the nematic state. All resonant modes are redshifted by more than 70 nm due to the change in the ambient refractive index. Figure 2(d) shows the temperature dependent wavelength shift of the three modes. As the temperature is increased from 22°C to 44°C, the  $Q_1$ -mode and the H-mode redshift by more than 9 nm and 6 nm respectively, with an abrupt jump of 4 nm and 2 nm at the phase transition temperature. On the other hand, the  $Q_2$ -mode blueshifts by more than 3 nm, with a jump of around 1.5 nm at the transition point. The redshift

and the blueshift are attributed to the increase in the ordinary and the decrease in the extraordinary branch of the LCs refractive index. It implies that the electric field distribution of  $Q_2$ -mode has a substantial component parallel to the LC director. The average electric field orientation with respect to the LC orientation can be mode dependent, so that different modes can be dominated by either branch of the LCs refractive index.

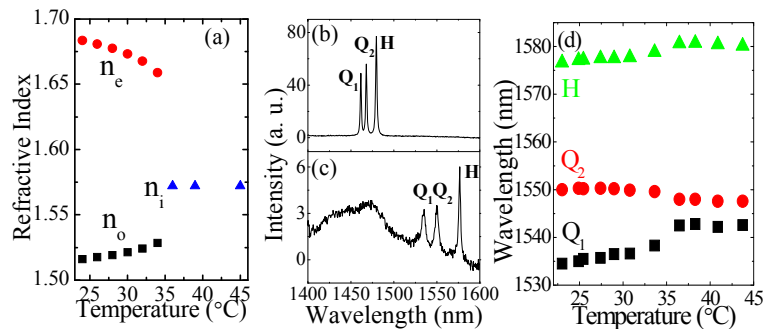


Figure 2: a) Temperature dependence refractive index change of the LC. b) PL spectrum of the nanocavity before the infiltration c) after the infiltration of the LC. d) The resonant wavelength shift of the modes with the increase of the temperature from 22 °C to 44 °C.

## Origin of the birefringence

The LC orientation is determined by sidewall anchoring, surface energy and molecular elasticity. Depending on these effects, three LC molecular orientations inside small diameter voids are theoretically proposed: uniform axial, planar, and escaped radial, as sketched in Fig. 3 [5]. For the uniform axial orientation, Fig. 4(a), only  $n_o$  would be relevant for the TE-polarized cavity modes. Our experimental data can be explained if a substantial part of LC molecules are aligned perpendicular to the hole axis. This type of configuration can be either planar or escaped radial type of alignment.

## Thermo-optic tuning of liquid crystal infiltrated PhC membranes

Preliminary experiments have been conducted to investigate the tuning of LC infiltrated PhC nanocavities by thermo-optic effects. Figure 4 shows the mode tuning of another modified H1 cavity having the same lattice spacing as previous one but different surrounding hole modifications. The holes are reduced by 34 nm and shifted radially outward by 24 nm. As the applied laser power is increased from 40  $\mu$ W to 460  $\mu$ W, all modes are blueshifted by more than 10 nm including an abrupt shift around 170  $\mu$ W. On the other hand, the experiments on the thermo-optic tuning of unfilled cavities have demonstrated strong redshift of the cavity modes as the incident laser power increases [6, 7]. From Fig. 2(d), the  $n_e$  only has a small contribution to the refractive index. Therefore, the large blueshift must be attributed to a different mechanism. The mechanism is likely related to the laser induced large temperature gradient around the cavity. As the laser power increases, the LC will be moved away from the cavity due to the large temperature gradient, the precise mechanism being unknown at present. The changes in Fig. 4 are reversible. As the power decreases, the LC flows back into the cavity due to the wetting of the LC on the sample. Note also an abrupt change near 170  $\mu$ W, which could correspond to the clearing temperature of the LC.

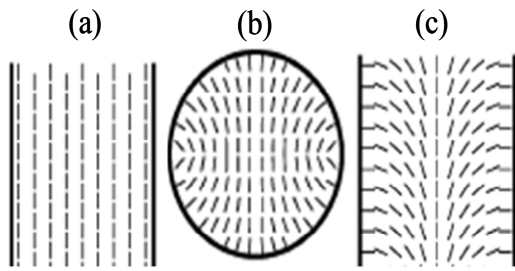


Figure 3: Schematic of a) axial uniform, b) planar, and c) escaped radial type of the LC alignment in the holes.

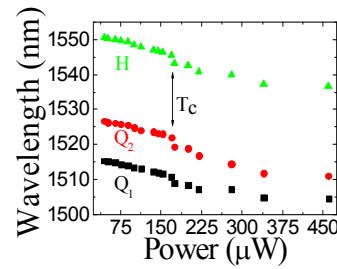


Figure 4: Thermo-optic tuning of a LC infiltrated modified H1 cavity.

## Conclusion

In this work, we have demonstrated the thermal and thermo-optic effects on the tuning of LC infiltrated InGaAsP nanocavity modes. The modes can be tuned in opposite direction which is attributed to the birefringent properties of the LC. The modes exhibit either a blueshift or a redshift at the LC clearing temperature, depending on the LC orientation. For an intense laser power, the possible fluid transport could be the origin of the unexpected large blueshift of the cavity modes. The results are consistent with both the planar, and the more likely escaped radial type of the LC configuration inside the PhC holes.

## References

- [1] O. Painter, R. K. Lee, A. Scherer, A. Yariv, J. D. O'Brien, P. D. Dapkus, I. Kim, "Two-dimensional photonic band-gap defect mode laser," *Science*, vol. 284, 1819-1821 1999.
- [2] H.-G. Park, J.-K. Hwang, J. Huh, H.-Y. Ryu, S.-H. Kim, J.-S. Kim, and Y.-H. Lee, "Characteristics of modified single-defect two-dimensional photonic crystal lasers," *IEEE J. Quantum Electron.*, vol. 38, 1353-1365, 2002.
- [3] J. Li and S.T. Wu, "Extended Cauchy equations for the refractive indices of liquid crystals," *J. Appl. Phys.*, Vol. 95, 896-901, 2004.
- [4] M. Shirane, S. Kono, J. Ushida, S. Ohkouchi, N. Ikeda, Y. Sugimoto, and A. Tomita, "Mode identification of high-quality-factor single-defect nanocavities in quantum dot-embedded photonic crystals," *J. Appl. Phys.*, vol. 101, 073107, 2007.
- [5] S. V. Burylov, "Equilibrium configuration of a nematic liquid crystal confined to a cylindrical cavity," *JETP*, vol. 85, 873-886, 1997.
- [6] A. Faraon, D. Englund, I. Fushman, J. Vučković, N. Stoltz and P. Petroff, "Local quantum dot tuning on photonic crystal chips," *Appl. Phys. Lett.* Vol., 90, 213110, 2007.
- [7] M. A. Dündar, F. Bordas, T. J. Eijkemans, N. Chauvin, A.Y. Silov, R. Nötzel, F. Karouta, and R. W. Van der Heijden, "Lithographic and optical tuning of InGaAsP membrane photonic crystal nanocavities with embedded InAs quantum dots," *J. Nanophoton.*, vol. 3, 031765, 2009.