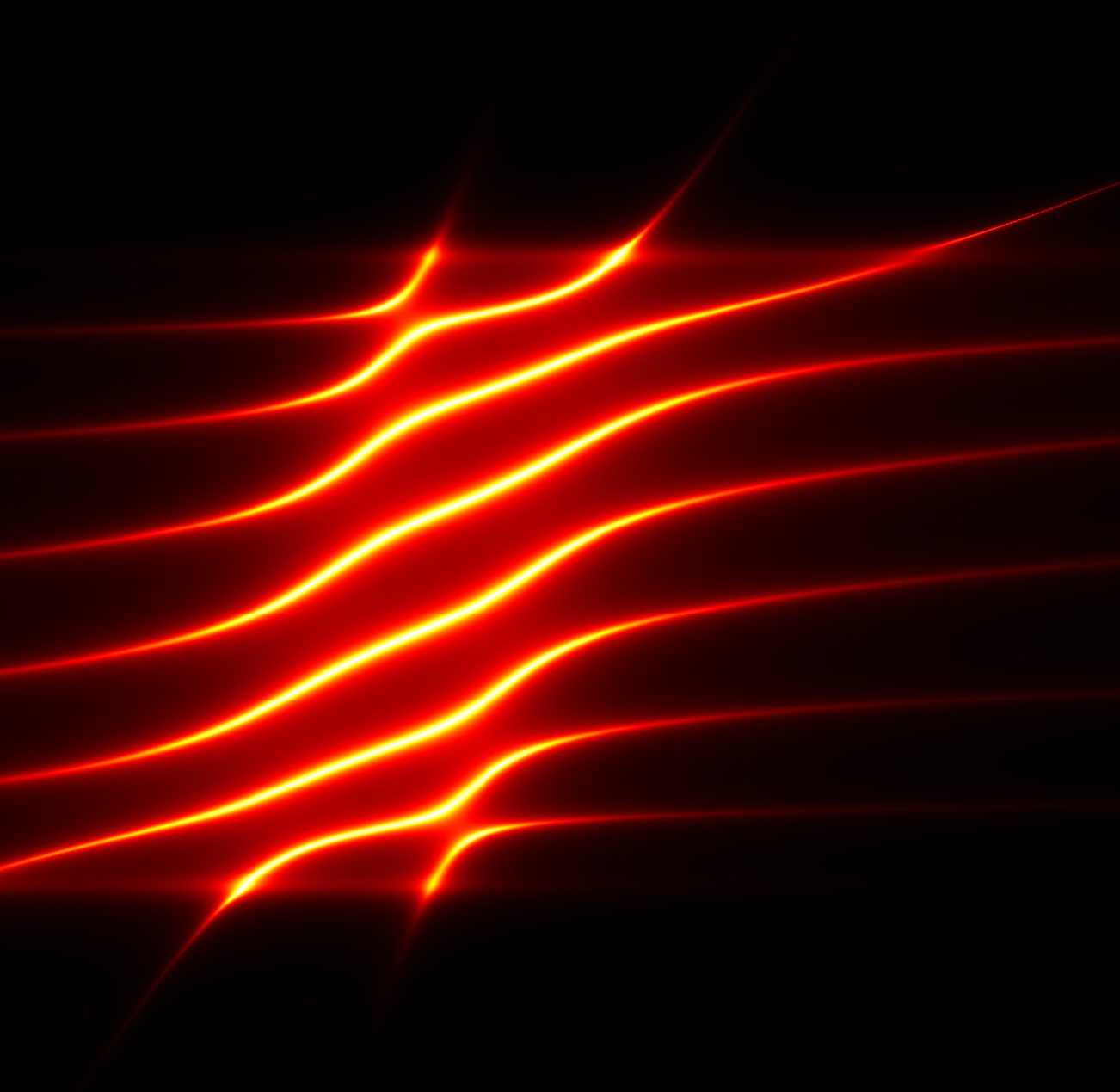


Dynamic tuning of photonic crystal nanocavities



Sergei Sokolov

DYNAMIC TUNING OF PHOTONIC CRYSTAL NANOCAVITIES

Dynamische verstemming van
nanoresonatoren in fotonische kristallen

Promotiecommissie

Promotor prof. dr. A.P. Mosk

Voorzitter en secretaris prof. dr. ir. J.W.M. Hilgenkamp

Overige leden prof. dr. C. Lienau
 dr. A. De Rossi
 dr. I. M. Vellekoop
 prof. dr. W.L. Vos
 prof. dr. C. van der Wal

The work described in this thesis is financially supported by the
‘European Research Council’ (ERC) grant 279248.

It was carried out at the
Complex Photonic Systems Group,
Department of Science and Technology
and MESA+ Institute for Nanotechnology,
University of Twente, P.O. Box 217,
7500 AE Enschede, The Netherlands

and in part at
Nanophotonics, Debye Institute for Nanomaterials Science,
Center for Extreme Matter and Emergent Phenomena,
Utrecht University, P.O. Box 80.000,
3508 TA Utrecht, The Netherlands.

Cover: antircrossing of 10 nanocavities

DYNAMIC TUNING OF PHOTONIC CRYSTAL NANOCAVITIES

PROEFSCHRIFT

ter verkrijging van
de graad van doctor aan de Universiteit Twente,
op gezag van de rector magnificus,
prof. dr. T.T.M. Palstra,
volgens besluit van het College voor Promoties
in het openbaar te verdedigen
op vrijdag 27 januari 2017 om 16.45 uur

door

Sergei Sokolov

geboren op 28 mei 1990
te Severomorsk, Russia

Dit proefschrift is goedgekeurd door:

Prof. Dr. A. P. Mosk

Contents

1	Introduction	1
1.1	Photonic crystal nanocavity	2
1.2	Influence of intrinsic disorder on nanocavities	3
1.3	Thermal tuning	3
1.4	Overview of this thesis	4
2	Apparatus for probing and controlling photonic nanostructures	11
2.1	Probe system	11
2.1.1	General description	11
2.1.2	Available measurement methods	12
2.1.3	Coupling IR probe light from out-of-plane	14
2.1.4	High-speed data acquisition	15
2.2	Pump system	17
2.2.1	General description	17
2.2.2	Pump during high-speed data acquisition	17
2.3	Conclusion	18
3	Local thermal resonance control of GaInP photonic crystal membrane cavities using ambient gas cooling	21
3.1	Introduction	21
3.2	Experiment and sample description	22
3.3	Experimental results	23
3.4	Modelling of the experiment	25
3.5	Conclusions	28
4	Tuning out disorder-induced localization in nanophotonic cavity arrays	31
4.1	Introduction	31
4.2	Sample and experimental setup	32
4.3	Thermal response matrix approach	34
4.4	Alignment of the array	35
4.5	Conclusion	38
4.6	Methods	38
5	Dynamic tuning of the coupling constant between photonic crystal nanocavities	43
5.1	Introduction	43
5.2	Description of the experiment	44
5.3	Experimental results	45

5.4	Numerical simulation of the experiment	47
5.5	Semi-analytic model	49
5.5.1	First-order perturbation theory	49
5.5.2	Field-overlap integral approach	50
5.5.3	Pump-induced mode effect	51
5.6	Conclusion	52
5.7	Outlook	52
6	Field programmable nanophotonic arrays with ancillary cavities	57
6.1	Introduction	57
6.2	Tuning of the coupling rate between nanocavity and waveguide . .	58
6.2.1	Mechanism of coupling rate tuning	58
6.2.2	Experimental observation	59
6.3	Tuning of the coupling constant between two nanocavities	61
6.3.1	Mechanism of coupling constant tuning	61
6.3.2	Experimental observation	62
6.3.3	Numerical simulation of the experiment	64
6.4	Proposed tunable CROW structures	66
6.4.1	Band structure properties	66
6.4.1.1	2-frequency structure	67
6.4.1.2	3-frequency structure	70
6.4.2	Transmission properties of finite crows with tunable coupling strength	71
6.4.2.1	2-frequency structure	71
6.4.2.2	3-frequency structure	72
6.5	Conclusion	73
6.A	Appendix	74
6.A.1	Analytic description of tuning of the coupling rate between a nanocavity and a waveguide	74
6.A.2	Determination of parameters for the system with tunable load to the waveguide	76
6.A.3	Analytic description of tuning of the coupling constant between two nanocavities	76
6.A.4	Determination of parameters for the system with tunable coupling constant between two nanocavities	78
7	Non-thermal effects of local thermal tuning with laser light	83
7.1	Introduction	83
7.2	Reversible, slow laser-induced changes	84
7.2.1	Steady-state experiments	84
7.2.2	Reversibility of the wavelength change	85
7.2.3	FDTD evaluation of water effects	87
7.3	Irreversible effects	88
7.3.1	Optical darkening of the surface	88
7.3.2	Non-reversible changes of resonance frequency and Q-factor . .	89
7.4	Data analysis procedure to correct for post-pump effects	90

7.5	Immersion of samples in liquids	92
7.6	Conclusion	94
8	Measurement of the linear thermo-optical coefficient of $\text{Ga}_{0.51}\text{In}_{0.49}\text{P}$ using photonic crystal nanocavities	97
8.1	Introduction	97
8.2	Sample and experimental setup	97
8.3	Experiment description	99
8.4	Conclusion	101
9	Summary	105
	Nederlandse samenvatting	107
	List of publications related to this thesis	109
	Acknowledgments	111

CHAPTER 1

Introduction

Light is the only data carrier that can satisfy the constantly increasing demand for speed and bandwidth of data transfer as well as the requirement of low power consumption. Modern telecommunications was revolutionized by optical fibers [1]. For instance, the fast internet speed which is nowadays taken for granted is provided by optical fibers. On a large scale they successfully replaced kilometers of electric cables, but on the small scale of on chip data transfer optical technology is not yet widespread [2, 3].

Several different ways and technologies have been proposed and demonstrated to control light propagation at the micro- and nanoscale such as ridge waveguides together with ring and racetrack resonators [4], photonic crystals [5], quasicrystals [6], hyperuniform structures [7] and pattern-optimized structures [8, 9]. In particular, a lot of attention is focused on photonic crystal structures which became extremely popular in the last couple of decades. Photonic crystals are 3D, 2D and 1D periodical structures where the dielectric function of a material is periodically varied on the scale of the wavelength of light. Interestingly, such complex structures can be found in nature, e.g. bright colored wings of beetles and butterflies are biological photonic crystals [10, 11]. The most striking property of photonic crystals is that light propagation is forbidden in certain directions. Specifically, in the 3D case, if the dielectric constants of materials are different enough, then the propagation of light can be stopped in all directions, in a certain light frequency range [12–14].

3D photonic crystals are arguably the best candidates for the future of optical integrated circuits, as they allow the control of light in three dimensions. However, the fabrication of these structures is difficult, so only a few research groups have succeeded in achieving this feat [15–17]. Essential elements like waveguides and nanocavities in 3D photonic crystals have been proposed, but are yet to be materialized [18–20]. On the other hand, 2D photonic crystal structures can be fabricated using advanced lithography methods and they forbid light propagation in the plane of the structure for a certain wavelength range of light. One of the most studied examples are thin 2D membranes where the photonic crystal structure is achieved by creating a periodical 2D pattern of air holes. By implementing a certain air hole pattern one is able to make crucial elements such as waveguides and nanocavities. Combination of these elements have been experimentally used to achieve impressive functionalities and observe fascinating physical phenomena, such as all-optical switches [21], on-chip lasers [22] and spectrometers [23], slow light [24], wavelength demultiplexers [25], single photon

generation [26] and other nonlinear devices [27].

Photonic crystal nanocavities are local lattice defects in photonic crystals and photonic crystal waveguides. In the 2D case the optical confinement of cavity modes is achieved by the surrounding crystal structure, where a leak channel is formed by out-of-plane radiation losses. For membrane structures, nanocavities can be created by removing, shifting or deforming certain airholes [28, 29]. Two parameters that are important for applications are the quality factor (Q-factor) which describes the ability of a cavity to confine light temporally and the mode-volume which defines the spatial confinement of the mode. As a rule of thumb, one can say that a high Q-factor correlates with a large mode volume [12].

To change properties of a system composed of photonic nanocavities after the fabrication, e.g. to compensate disorder-induced effects [30], and achieve dynamic control of the system, e.g. to experimentally measure circuit parameters [31] or implement all-optical memory [32], one requires a tool which can locally perturb the refractive index thereby changing properties of the system.

In this thesis we develop light induced thermal tuning to control resonance frequencies and coupling rates in arrays of photonic crystal nanocavities. Thermal tuning gives local and reversible refractive index change which in addition to great flexibility given by wavefront shaping [33] and holography techniques [34] makes it one of the best candidates to control systems made of many photonic crystal nanocavities.

In this chapter we describe the nanocavities which are used in this thesis, the role of intrinsic disorder in the system as well as the thermal tuning process. At the end of the chapter, we give an overview of this thesis.

1.1 Photonic crystal nanocavity

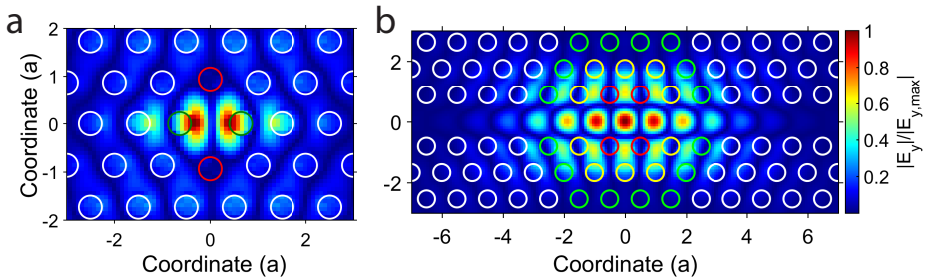


Figure 1.1: Nanocavities used in this thesis. **a** - Normalized E_y field for a H0 cavity. **b** - Normalized E_y field for a mode-gap cavity. One row of holes is removed to create a line defect. Circles represent hole contours. Colored circles represent shifted holes, with different colors corresponding to different shifts. a is a period of the photonic crystal lattice.

In this work two types of membrane photonic crystal nanocavities have been used. Their structure as well as their mode profiles are presented in Figure 1.1. The first defect cavity is H0 cavity [35, 36] which is created in a bulk 2D photonic crystal by shifting 4 holes away from the center as it is shown in the Figure 1.1a. The mode is concentrated in between the shifted holes. This cavity has a small mode volume about 3 cubic half wavelengths and a Q-factor on the order of 10^3 . The second cavity is mode-gap cavity [37, 38] made in a photonic crystal waveguide by local width modulation of that waveguide as shown in Figure 1.1b. This cavity has a large Q-factor of about 10^6 and a larger mode volume than the H0 cavity ($\sim 10 \cdot (\lambda/2n)^3$). The mode of this cavity is mainly concentrated in the waveguide region. When such photonic crystal nanocavities are placed physically close to each other they become optically coupled. In an array of optically coupled cavities light propagates at an extremely low group velocity [24, 39].

1.2 Influence of intrinsic disorder on nanocavities

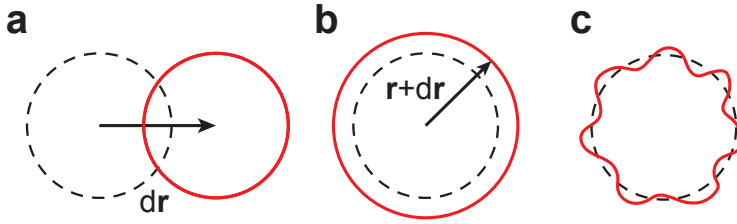


Figure 1.2: Types of intrinsic disorder in the system. a - hole position shift, b - hole radius change, c - hole shape variations.

Resonance properties of nanocavities described above are affected by inherent disorder in a photonic crystal. This disorder includes hole position shifts and radius changes [30, 40] as well as hole shape variations [41, 42] as shown in Figure 1.2. Disorder plays an important role in the field of nanophotonics as every sample is affected by it. Disorder perturbs the mode profile of every cavity which induces a random resonance wavelength change. Surprisingly, shape irregularities on the order of 1 nm can induce resonance wavelength change by more than 1 nm [40, 42]. Disorder can even affect the coupling constant between nanocavities.

1.3 Thermal tuning

The main tool to control resonance properties of nanocavities in this thesis is local heating with a focused laser beam. When the surface of the membrane is illuminated with the laser beam, the laser light gets absorbed in the membrane material which eventually results in a local temperature rise assuming the photon energy is larger than the bandgap of the semiconductor material of the

membrane. This is schematically shown in Figure 1.3. The local temperature increase results in a local change of the refractive index which in turn induces changes in resonance frequency and coupling constant as reported in this thesis.

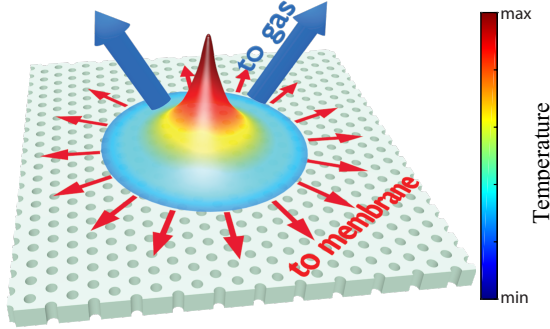


Figure 1.3: Temperature distribution in the membrane. Heat diffuses inside the membrane as well as into the ambient gas medium as indicated by red and blue arrows, respectively. These two effects determine the width of the temperature profile. Colored cone represents a temperature distribution in the membrane.

The temperature distribution inside the membrane is not confined within the focused spot, but is defined by the heat diffusion in the system [43]. This diffusion induces unwanted effects like thermal crosstalk between different structures on the nanophotonic chip.

1.4 Overview of this thesis

In this thesis we investigate and control photonic crystal nanocavities as well as the interaction between them. The principal tool of this control is local laser-induced heating. We study how heat propagates in photonic crystal membranes and we use local heating to counteract the disorder in coupled cavity systems. We also investigate the coupling constant change between nanocavities with various approaches. This thesis has the following structure:

In **Chapter 2**, the apparatus which was specifically built for research in this thesis is presented. We describe the pump and probe paths used in the setup, and introduce and compare different ways of probing photonic crystal nanostructures. We also show a high-speed data acquisition and pump gating scheme designed to suppress degradation effects of semiconductor samples.

In **Chapter 3**, the experimental and numerical investigation of heat propagation in photonic crystal membranes is described. The tuning response of a single H0 type nanocavity [35, 44] on pump position was measured experimentally with nitrogen and helium gases as ambient medium. The experiment was modeled using first-order perturbation theory [12] and finite element method (COMSOL). We show that the thermal profile inside the membrane is more confined in case of He than of N₂.

In **Chapter 4**, we present a new method to eliminate the disorder in systems of coupled mode-gap resonators [37, 38]. We use a spatial light modulator and digital holography [33, 34] to simultaneously control the resonance wavelengths of several nanocavities and introduce a response matrix approach to deal with thermal crosstalk between nanocavities. We tune disordered cavities into resonance and accurately model the behavior of the system with coupled mode theory [45].

In **Chapter 5**, we introduce a novel way to control the coupling constant between two directly coupled nanocavities by thermally perturbing the area between them. We experimentally show that this effect depends on the pump position. To get insight into the mechanism of the coupling constant change, we present finite difference time domain (FDTD) simulations [46] as well as a semi-analytical explanation of the effect.

In **Chapter 6**, we use ancillary cavities to control the coupling rate between the nanocavity and the waveguide as well as the coupling constant between two nanocavities. This method to control coupling is explained by the adiabatic elimination process, well known in atomic physics [47]. We experimentally achieve a large variation of the coupling rates and describe them analytically with coupled mode theory. In the case where we modulate the coupling constant between two nanocavities a surprising difference is observed between experiment and analytic theory. To understand this difference, numerical simulations were performed. We also propose two new types of coupled resonator optical waveguides whose bandwidth can be tuned using ancillary cavities. We theoretically investigate their dispersion and transmission properties.

In **Chapter 7**, non-thermal pump induced effects observed during experiments are reported. We study time-dependent as well as permanent resonance frequency and Q-factor changes. We perform numerical simulations to study the influence of surface water on the resonance frequency of nanocavities. Finally, we describe the procedure to remove the frequency shift effects from datasets and report initial experiments on the immersion of nanophotonic samples in liquids that may reduce the nonthermal effects.

In **Chapter 8**, we determine the precise value of the thermal-optical coefficient of $\text{Ga}_{0.51}\text{In}_{0.49}\text{P}$ material used for all the nanocavities in this thesis. This is achieved by heating the sample with mode-gap nanocavities with a heating stage. To get the precise value of the coefficient we take into account material expansion effects as well as surface water effects.

Finally, in **Chapter 9**, we provide a summary of the thesis.

Bibliography

- [1] G. P. Agrawal, *Fiber-optic communication systems* (Wiley-Interscience, 2002). — p.1.
- [2] C. Sun *et al.*, *Single-chip microprocessor that communicates directly using light*, *Nature* **528**, 534 (2015). — p.1.
- [3] Y. A. Vlasov, *CMOS integrated silicon nanophotonics: Enabling technology for exascale computational systems*, SEMICON 2010 (unpublished). — p.1.
- [4] W. Bogaerts, P. De Heyn, T. Van Vaerenbergh, K. De Vos, S. Kumar Selvaraja, T. Claes, P. Dumon, P. Bienstman, D. Van Thourhout, and R. Baets, *Silicon microring resonators*, *Laser Photon. Rev.* **6**, 47 (2012). — p.1.
- [5] Y. A. Vlasov, M. O'Boyle, H. F. Hamann, and S. J. McNab, *Active control of slow light on a chip with photonic crystal waveguides*, *Nature* **438**, 65 (2005). — p.1.
- [6] Z. Vardeny, A. Nahata, and A. Agrawal, *Optics of photonic quasicrystals*, *Nat. Photon.* **7**, 177 (2013). — p.1.
- [7] J. Haberkorn and F. Scheffold, *Fabrication of mesoscale polymeric templates for three-dimensional disordered photonic materials*, *Opt. Express* **21**, 1057 (2013). — p.1.
- [8] B. Shen, P. Wang, R. Polson, and R. Menon, *An integrated-nanophotonics polarization beamsplitter with $2.4 \times 2.4 \mu\text{m}^2$ footprint*, *Nat. Photon.* **9**, 378 (2015). — p.1.
- [9] A. Y. Piggott, J. Lu, K. G. Lagoudakis, J. Petykiewicz, T. M. Babinec, and J. Vučković, *Inverse design and demonstration of a compact and broadband on-chip wavelength demultiplexer*, *Nat. Photon.* **9**, 374 (2015). — p.1.
- [10] K. Michielsen and D. G. Stavenga, *Gyroid cuticular structures in butterfly wing scales: Biological photonic crystals*, *J. R. Soc. Interface* **5**, 85 (2008). — p.1.
- [11] A. R. Parker, D. R. McKenzie, and M. C. J. Large, *Multilayer reflectors in animals using green and gold beetles as contrasting examples*, *J. Exp. Biol.* **201**, 1307 (1998). — p.1.
- [12] J. Joannopoulos, S. G. Johnson, J. N. Winn, and R. D. Meade, *Photonic crystals: Molding the flow of light* (Princeton University Press, Princeton, 2008). — p.1, 2, 4.
- [13] E. Yablonovitch, *Inhibited spontaneous emission in solid-state physics and electronics*, *Phys. Rev. Lett.* **58**, 2059 (1987). — p.1.
- [14] S. John, *Strong localization of photons in certain disordered dielectric superlattices*, *Phys. Rev. Lett.* **58**, 2486 (1987). — p.1.
- [15] M. D. Leistikow, A. P. Mosk, E. Yeganeh, S. R. Huisman, A. Lagendijk,

- and W. L. Vos, *Inhibited spontaneous emission of quantum dots observed in a 3D photonic band gap*, Phys. Rev. Lett. **107**, 1 (2011). — p.1.
- [16] S. Takahashi, K. Suzuki, M. Okano, M. Imada, T. Nakamori, Y. Ota, K. Ishizaki, and S. Noda, *Direct creation of three-dimensional photonic crystals by a top-down approach*, Nat. Mater. **8**, 721 (2009). — p.1.
- [17] C. Marichy, N. Muller, L. S. Froufe-Pérez, and F. Scheffold, *High-quality photonic crystals with a nearly complete band gap obtained by direct inversion of woodpile templates with titanium dioxide*, Sci. Rep. **6**, 21818 (2016). — p.1.
- [18] L. A. Woldering, A. P. Mosk, and W. L. Vos, *Design of a three-dimensional photonic band gap cavity in a diamondlike inverse woodpile photonic crystal*, Phys. Rev. B **90**, 1 (2014). — p.1.
- [19] E. Lidorikis, M. L. Povinelli, S. G. Johnson, and J. D. Joannopoulos, *Polarization-independent linear waveguides in 3D photonic crystals.*, Phys. Rev. Lett. **91**, 023902 (2003). — p.1.
- [20] K. Gondaira, K. Ishizaki, K. Kitano, T. Asano, and S. Noda, *Control of radiation angle by introducing symmetric end structure to oblique waveguide in three-dimensional photonic crystal*, Opt. Express **24**, 13518 (2016). — p.1.
- [21] T. Tanabe, M. Notomi, S. Mitsugi, A. Shinya, and E. Kuramochi, *All-optical switches on a silicon chip realized using photonic crystal nanocavities*, Appl. Phys. Lett. **87**, 1 (2005). — p.1.
- [22] H. Altug, D. Englund, and J. Vučković, *Ultrafast photonic crystal nanocavity laser*, Nature Phys. **2**, 484 (2006). — p.1.
- [23] A. C. Liapis, B. Gao, M. R. Siddiqui, Z. Shi, and R. W. Boyd, *On-chip spectroscopy with thermally-tuned high-Q photonic crystal cavities*, Appl. Phys. Lett. **108**, 021105 (2016). — p.1.
- [24] M. Notomi, E. Kuramochi, and T. Tanabe, *Large-scale arrays of ultrahigh-Q coupled nanocavities*, Nat. Photon. **2**, 741 (2008). — p.1, 3.
- [25] K. Nozaki, E. Kuramochi, A. Shinya, and M. Notomi, *25-channel all-optical gate switches realized by integrating silicon photonic crystal nanocavities*, Opt. Express **22**, 3491 (2014). — p.1.
- [26] A. S. Clark, C. Husko, M. J. Collins, G. Lehoucq, S. Xavier, A. D. De Rossi, S. Combrié, C. Xiong, and B. J. Eggleton, *Heralded single-photon source in a III-V photonic crystal*, Opt. Lett. **38**, 649 (2013). — p.2.
- [27] A. Martin, G. Moille, S. Combrié, G. Lehoucq, T. Debuisschert, J. Lian, S. Sokolov, A. P. Mosk, and A. De Rossi, *Triply-resonant Continuous Wave Parametric Source with a Microwatt Pump*, ArXiv:1602.04833 [physics.optics] (2016). — p.2.
- [28] Y. Akahane, T. Asano, B. Song, and S. Noda, *High-Q photonic nanocavity in a two-dimensional photonic crystal*, Nature **425**, 944 (2003). — p.2.
- [29] M. Minkov and V. Savona, *Automated optimization of photonic crystal slab cavities.*, Sci. Rep. **4**, 5124 (2014). — p.2.
- [30] H. Hagino, Y. Takahashi, Y. Tanaka, T. Asano, and S. Noda, *Effects of fluctuation in air hole radii and positions on optical characteristics in photonic crystal heterostructure nanocavities*, Phys. Rev. B **79**, 085112 (2009).

-
- p.2, 3.
- [31] T. Cai, R. Bose, G. S. Solomon, and E. Waks, *Controlled coupling of photonic crystal cavities using photochromic tuning*, Appl. Phys. Lett. **102**, (2013). — p.2.
 - [32] R. S. Tucker, P. Ku, and C. C. J. Chang-Hasnain, *Slow-Light Optical Buffers: Capabilities and Fundamental Limitations*, J. Lightwave Technol. **23**, 4046 (2005). — p.2.
 - [33] I. M. Vellekoop and A. P. Mosk, *Focusing coherent light through opaque strongly scattering media.*, Opt. Lett. **32**, 2309 (2007). — p.2, 5.
 - [34] M. Pasienski and B. Demarco, *A high-accuracy algorithm for designing arbitrary holographic atom traps*, Opt. Express **16**, 2176 (2008). — p.2, 5.
 - [35] Z. Zhang and M. Qiu, *Small-volume waveguide-section high Q microcavities in 2D photonic crystal slabs*, Opt. Express **12**, 3988 (2004). — p.3, 4.
 - [36] K. Nozaki, T. Tanabe, A. Shinya, S. Matsuo, T. Sato, H. Taniyama, and M. Notomi, *Sub-femtojoule all-optical switching using a photonic-crystal nanocavity*, Nat. Photon. **4**, 477 (2010). — p.3.
 - [37] E. Kuramochi, M. Notomi, S. Mitsugi, A. Shinya, T. Tanabe, and T. Watanabe, *Ultrahigh- Q photonic crystal nanocavities realized by the local width modulation of a line defect*, Appl. Phys. Lett. **88**, 041112 (2006). — p.3, 5.
 - [38] S. Combrié, A. De Rossi, Q. V. Tran, and H. Benisty, *GaAs photonic crystal cavity with ultrahigh Q : microwatt nonlinearity at 1.55 μm* , Opt. Lett. **33**, 1908 (2008). — p.3, 5.
 - [39] A. Yariv, Y. Xu, R. K. Lee, and A. Scherer, *Coupled-resonator optical waveguide: a proposal and analysis*, Opt. Lett. **24**, 711 (1999). — p.3.
 - [40] Y. Taguchi, Y. Takahashi, Y. Sato, T. Asano, and S. Noda, *Statistical studies of photonic heterostructure nanocavities with an average Q factor of three million*, Opt. Express **19**, 11916 (2011). — p.3.
 - [41] D. Gerace and L. C. Andreani, *Effects of disorder on propagation losses and cavity Q -factors in photonic crystal slabs*, Phot. Nano. Fund. Appl. **3**, 120 (2005). — p.3.
 - [42] L. Ramunno and S. Hughes, *Disorder-induced resonance shifts in photonic crystal nanocavities*, Phys. Rev. B **79**, 161303 (2009). — p.3.
 - [43] H. S. Carslaw and J. C. Jaeger, *Couduction of heat in solids* (Oxford University Press, 1959). — p.4.
 - [44] N. Tran, S. Combrié, P. Colman, A. De Rossi, and T. Mei, *Vertical high emission in photonic crystal nanocavities by band-folding design*, Phys. Rev. B **82**, 075120 (2010). — p.4.
 - [45] H. A. Haus and W. Huang, *Coupled-mode theory*, Proc. IEEE **79**, 1505 (1991). — p.5.
 - [46] A. F. Oskooi, D. Roundy, M. Ibanescu, P. Bermel, J. D. Joannopoulos, and S. G. Johnson, *Meep: A flexible free-software package for electromagnetic simulations by the FDTD method*, Comp. Phys. Comm. **181**, 687 (2010). — p.5.
 - [47] E. Brion, L. H. Pedersen, and K. Mølmer, *Adiabatic Elimination in a Lambda System*, J. Phys. A **40**, 14 (2006). — p.5.

CHAPTER 2

Apparatus for probing and controlling photonic nanostructures

In this chapter we describe the details of apparatus that was used to perform all experiments reported in this thesis. The apparatus consists of a probe system that measures reflection, transmission and scattering spectra, and a pump system that illuminates the sample with structured light out of the photonic crystal plane.

2.1 Probe system

2.1.1 General description

Here we describe the infrared spectroscopy setup which is used to probe the samples. A continuous-wave tunable IR laser (Santec TSL-710) is the main light source. This laser offers a combination of narrow linewidth, precise tunability and broad tuning range. A fiber system was built to distribute the laser power between different ports. The scheme of the fiber setup is presented in Figure 2.1. Light from the IR laser is distributed between a fiber Fabry-Pérot interferometer (FFPI), acetylene and cyanide reference cells and the main signal branch. These frequency references are discussed in Section 2.1.4. The main signal branch is attenuated to the desired level by a free-space power attenuation ND filter set. After the ND filter set IR light can be directed either to the polarization maintaining lensed fiber L1 through the fiber circulator or to the free-space fiber collimator. When light is directed to the lensed fiber L1 then the reflection from the system is collected on amplified photodiode PD4 and transmission is collected on amplified photodiode PD5 through lensed fiber L2. The lensed fibers have $NA=0.55$.

The free-space part of the setup is presented in Figure 2.2. When IR light is coupled into the sample using lensed fiber L1 the out-of-plane scattered light can be collected using objective with $NA=0.4$ and imaged on the amplified photodiode PD6. At the same time the surface of the sample is imaged on the IR camera, which allows to image and select the region of interest which will be focused on PD6 through the aperture A1. Any possible pump light reflections are cut with long pass filter LP.

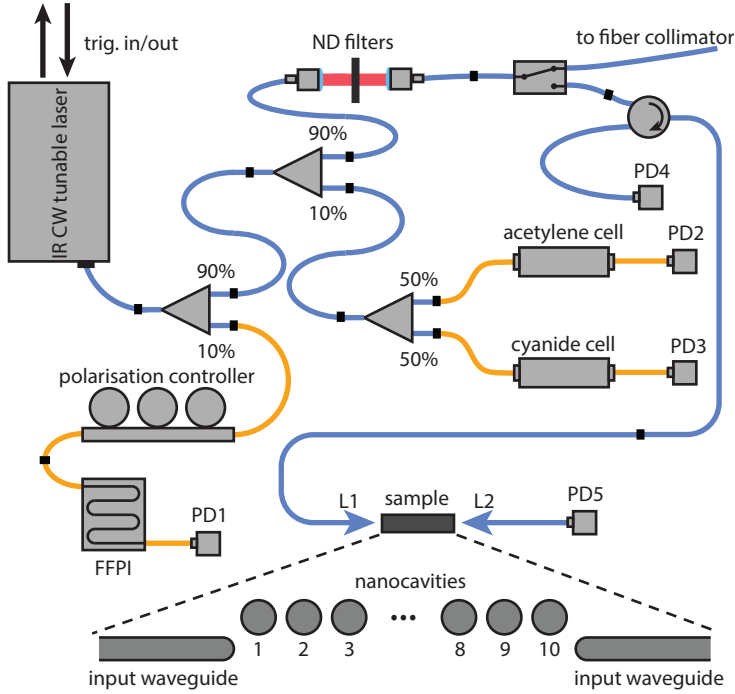


Figure 2.1: Fiber-based probe part of the setup. Blue lines represent polarization-maintaining fibers, yellow lines - single mode fibers. Black rectangles on fiber path are mating sleeves. Blue arrows are lensed fibers. After the ND filter set the light can be switched between two channels: to the fiber collimator and to the lensed fiber. The inset shows a sample with 10 optically coupled nanocavities.

2.1.2 Available measurement methods

The comparison between reflection, transmission and out-of-plane signals measured for a sample containing 10 coupled photonic crystal nanocavities is presented in Figure 2.3. The scheme of the sample is presented in the inset of the Figure 2.1. Cavities are made in a photonic crystal membrane with thickness $h = 180 \text{ nm}$ and lattice period $a = 485 \text{ nm}$. The lattice is triangular. The membrane is made of $\text{Ga}_{0.51}\text{In}_{0.49}\text{P}$. Cavities are placed in the barrier waveguide with width $W_0 = 0.98\sqrt{3}a$. The distance between cavities is $10a$, except cavities 1-2 and 9-10 where distance is $9a$. Cavities 1 and 10 are coupled in turn to input and output photonic crystal waveguides with width $W_1 = 1.1\sqrt{3}a$. To achieve a good coupling efficiency from free-space with lensed fiber into the photonic crystal waveguide special mode-converters were fabricated [1].

Unfortunately, the radiation pattern of high-Q nanocavities has most part of their emission at grazing angles outside the acceptance of our objective. As a result, the signal-to-noise ratio (SNR) is low. One cannot just increase the power of an input signal because this causes bistability [2] due to the nonlinearity of

the material and the high Q-factor of the cavities. The SNR of the out-of-plane signal can be increased by using a cooled low-noise photodiode or by creating a grating structure to change the angular distribution of the cavity emission [3]. The signal can be also measured on the IR camera which improves SNR, but increases the measurement time dramatically.

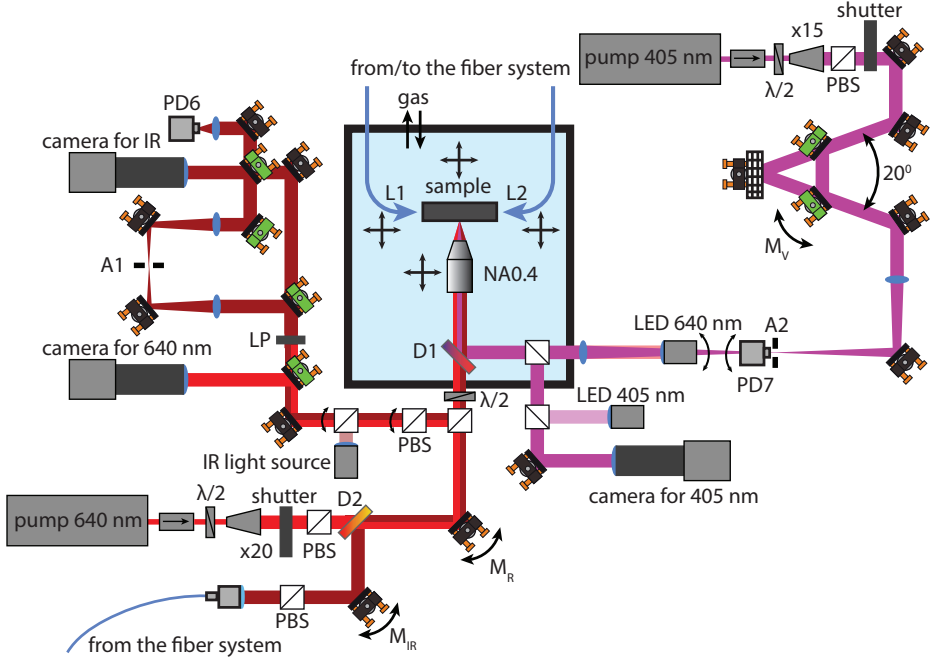


Figure 2.2: Free-space part of the setup. Key elements of the setup are presented on the scheme. Green mirrors are flip mirrors. Blue lines represent PM fibers used to guide light in and out of the system. Lensed fibers L1 and L2 as well as sample are mounted on XYZ stages. Objective is mounted on XY stage. Black contour represents the flow box used to create gas atmosphere around the sample. The box has windows for light with IR and violet AR coatings. Windows are not shown on the picture.

Each spectrum has 3 characteristic regions: the region below the bandgap, colored red in Fig. 2.3, where mode-gap cavity resonances are located (see chapter 4, 5, 6 and 8), the green region where random modes [4] are found and the blue region where the barrier photonic crystal waveguide is open and Fabry-Pérot resonances occur. It is hard to define the clear boundary between these 3 regions because of the intrinsic disorder in the system which smears out the bandedge [5], creates random modes for all the frequencies below the band edge of the waveguide with width W_0 and perturbs resonance frequencies of mode-gap cavities. In the reflection all the resonance lines have Fano lineshapes as a result of interference between signal reflected from the system and from the end of the lensed fiber L1 [6]. The same happens in transmission due to the interference

with TM light [7]. The Fano lineshape together with interference fringes observed in reflection significantly complicates the data analysis. To avoid Fano lineshape one can collect out-of-plane light where all the lines have a Lorentzian line shape which is easy to analyze and interpret.

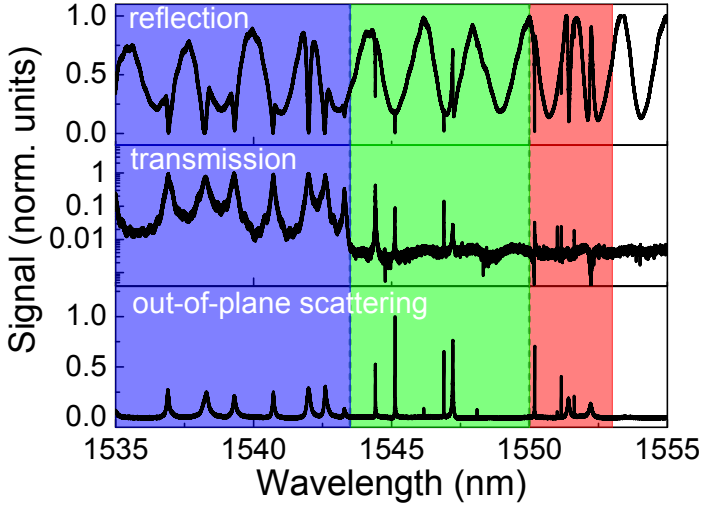


Figure 2.3: Spectra comparison. Comparison between reflection, transmission and out-of-plane scattering spectra for nanophotonic sample. The red region depicts the wavelength range where mode-gap cavity resonances are found. The green region is attributed to the wavelength range where random modes are present. The blue region represents the transmission band of the barrier waveguide. Borders between regions are not strictly defined due to the disorder.

2.1.3 Coupling IR probe light from out-of-plane

Every cavity emits IR light which can be collected and measured as described in previous section. This implies that one can reverse the light path by focusing IR light on the cavity, couple light into it and measure the transmission through the lensed fiber L1 which was previously used to launch light into the system. This reciprocal approach has advantage of a great signal to noise ratio and allows to selectively couple to particular resonances. In Figure 2.4 we show example spectra, where light is coupled to either cavity 1, 2 or 3. When light is coupled to cavity 1 the resonance of cavity 1 has the highest intensity, then when it is coupled to cavity 2 the peak of cavity 2 becomes bright and the same happens to cavity 3. The position of the probe spot is selected with mirror M_{IR} from Figure 2.2. The full width at half maximum (FWHM) of the focused spot is $2.2 \mu\text{m}$. The results measured by this technique are easy to interpret as all lines have Lorentzian lineshape and SNR can be $> 10^4$.

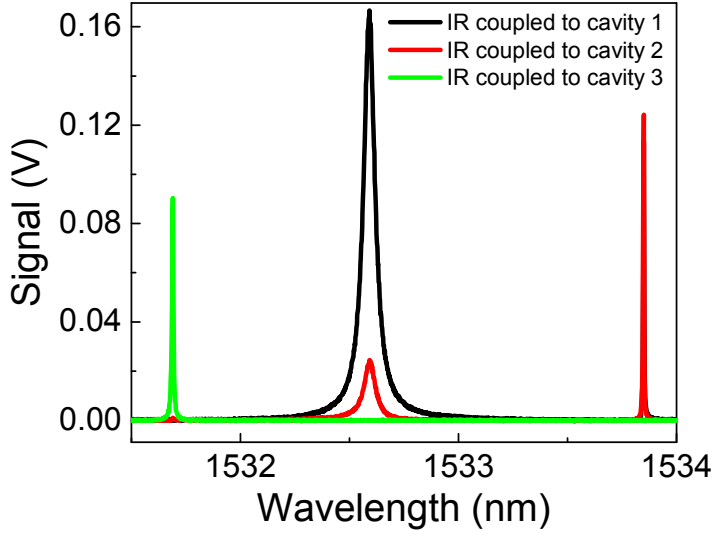


Figure 2.4: Transmission spectra. IR probe light is coupled either into cavity 1, 2 or 3. The transmission is measured through the lensed fiber L1 and collected on photodiode PD4.

2.1.4 High-speed data acquisition

When the wavelength of the IR laser is scanned slowly it can output a TTL trigger signal indicating a certain wavelength step. The required wavelength step for most of our measurements is around 1 pm. Most of the measurements in this thesis involved local heating with a laser. As described in Chapter 7 this way of tuning comes with non-thermal effects which build up with exposure. To minimize these effects we scan the wavelength of the IR laser and measure the spectra at the highest possible scanning speed which is 100 nm/s. Unfortunately at this speed our IR laser cannot output triggers fast enough resulting in an imprecise measurement.

To be able to perform fast laser scans with 1-pm resolution an external wavelength reference scheme was developed (see Figure 2.1) based on the system at Thales [8]. The absolute wavelength during the measurement is determined from acetylene and cyanide wavelength reference cells. The spectra of these cells are precisely known [9, 10] and are very stable under environmental condition changes, such as temperature and pressure fluctuations. Spectra of the cells used in our setup are shown in Figure 2.5. These cells can be used for wavelength reference between 1511 and 1656 nm.

To get the relative wavelength during the scan the fiber Fabry-Pérot interferometer [11] is used. A compact fiber-based Fabry-Pérot interferometer can have a small free spectral range (FSR). The experimentally measured FSR of interferometer used in the setup is 125.1 MHz, corresponding to 1 pm increment at 1550 nm. The transmission through FFPI measured with a scanning speed

of 100 nm/s is presented in Figure 2.6. The spectrum mainly consists of large sharp fringes, with small peaks on a side. Large and small peaks were found to correspond to different polarizations of light, their relative intensity can be adjusted with a paddle polarization controller (see Figure 2.1).

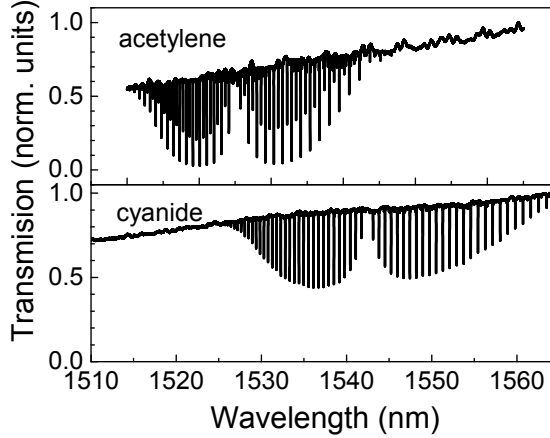


Figure 2.5: Spectra of acetylene and cyanide cells. High resolution spectra are measured with the slow scanning speed of the laser without external wavelength reference system.

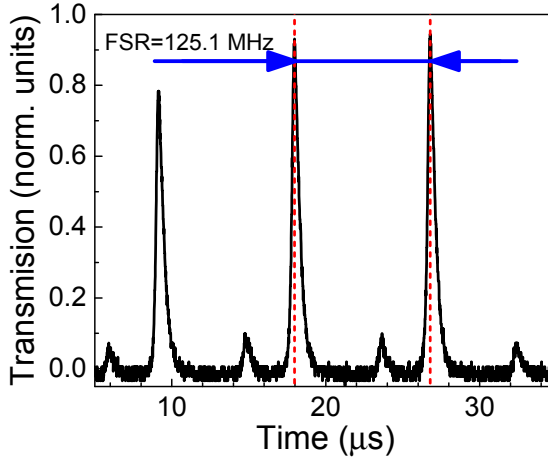


Figure 2.6: Transmission through fiber Fabry-Pérot interferometer. A short part of the transmission between 1530 and 1545 nm is shown. Large and small peaks correspond to different polarizations of the light.

When fast measurement is performed the analog trigger of the data acquisition board (DAQ) is set to a level to catch large Fabry-Pérot peaks and sample

the data flow. At the same time the transmission of cyanide and acetylene cells is measured for absolute wavelength reference. Knowing the absolute wavelength of absorption peaks of acetylene and cyanide and the frequency step of the FFPI one can easily reconstruct the spectra. In some cases when the intensity of the small Fabry-Pérot peak becomes comparable to the large peak accidental double triggering might happen. To avoid that an effective trigger hold-off scheme was implemented where data acquisition was repeated, taking blank datapoints until the second FFPI peak has passed. It is based on the fact that during acquisition the data acquisition board [NI USB-6356] is blind to any input triggers.

2.2 Pump system

2.2.1 General description

Two pump CW lasers were used in the setup to thermally tune nanostructures. The optical paths for these lasers are presented on Figure 2.2. The first laser is the red pump laser with the wavelength 640 nm. The position of the laser focus on the sample is manually controlled with the mirror M_R , where the size of the focused spot is $1.5 \mu\text{m}$. The power of the laser is controlled using the combination of a $\lambda/2$ waveplate and polarisation beamsplitter (PBS). The sample is imaged at this wavelength on a separate camera which can be accessed with a flip mirror. The second laser is a violet laser with a wavelength of 405 nm. The power of this laser can be also controlled by the combination of a $\lambda/2$ and PBS. The surface of the sample is also imaged on a separate camera, as the focal distance of the objective is different for IR, red and violet light. There is a reflective phase-only LCOS SLM device in the optical path of the violet laser. The SLM is imaged with a 4f lens system on the back aperture of the objective. This SLM is used for single pump spot positioning, pump linescans [4, 12] and digital holography [13] (see Chapter 4). When a single violet laser spot on the surface of the sample with relatively high power is required, using the SLM is not favorable due to significant fluctuations in the pump power induced by SLM refresh noise. To avoid this noise problem two flip mirrors are placed to bypass SLM. The position of the focus is then controlled by the mirror M_V . The FWHM of the focus spot is then equal to $0.8 \mu\text{m}$. A box is built covering the long optical path of the violet laser to suppress the influence of airflow.

2.2.2 Pump during high-speed data acquisition

It is important to limit the time during which pump lasers illuminate the surface to reduce accumulative laser-induced changes. To achieve that, two mechanical shutters were placed in the beginning of the optical paths for the red and violet lasers. These shutters are synchronized with the start of the laser scan such that first shutter opens before the IR laser starts a wavelength sweep. The time-sequence of a typical measurement is presented in Figure 2.7.

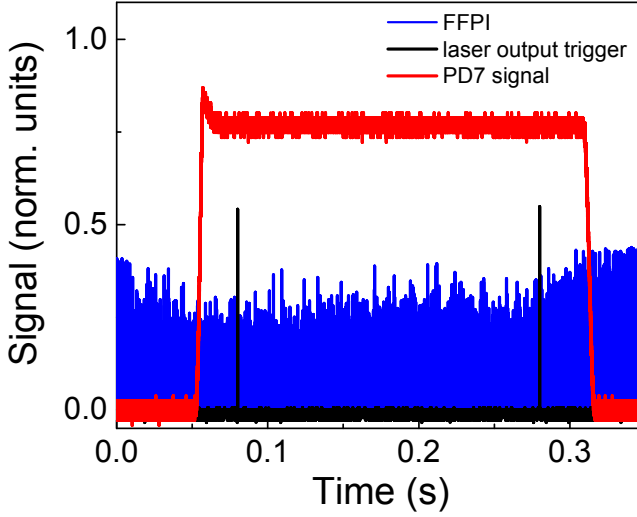


Figure 2.7: Pump-probe synchronization. The laser is scanned over 20 nm, start and end triggers are shown. The shutter is open for 250 μ s to account for the jitter of the IR laser scanning start edge.

The IR laser is scanned between 1530 and 1550 nm, the beginning and the end of the scan are indicated with laser output trigger. The start of the IR laser sweep and the shutter opening are controlled with the TTL trigger pulse generated from the DAQ board. The shutter state is measured using the photodiode PD7, with violet laser focused on it. The IR laser should be prearmed before the scan, but even then it takes about 100 ms to start the scan. This delay time jitters, so to account for that the time-window when the surface is illuminated is slightly expanded to 250 ms.

2.3 Conclusion

In this chapter we described several details of the apparatus which was built to perform pump-probe experiments involving IR probing of the structure and thermal tuning with two lasers of 450 and 640 nm. The coupling of IR light from the out-of-plane into cavities is presented as an effective way to obtain Lorentzian line shapes with high SNR. To suppress surface effects resulting in resonance wavelength changes a high-speed data acquisition scheme together with pump light gating is developed.

Bibliography

- [1] Q. Tran, S. Combrié, P. Colman, and A. De Rossi, *Photonic crystal membrane waveguides with low insertion losses*, Appl. Phys. Lett. **95**, 061105 (2009). — p.12.
- [2] M. Brunstein, R. Braive, R. Hostein, a. Beveratos, I. Rober-Philip, I. Sagnes, T. J. Karle, a. M. Yacomotti, J. a. Levenson, V. Moreau, G. Tessier, and Y. De Wilde, *Thermo-optical dynamics in an optically pumped Photonic Crystal nano-cavity*, Opt. Express **17**, 17118 (2009). — p.12.
- [3] N. Tran, S. Combrié, P. Colman, A. De Rossi, and T. Mei, *Vertical high emission in photonic crystal nanocavities by band-folding design*, Phys. Rev. B **82**, 075120 (2010). — p.13.
- [4] J. Lian, S. Sokolov, E. Yüce, S. Combrié, A. De Rossi, and A. P. Mosk, *Measurement of the profiles of disorder-induced localized resonances by local tuning*, Opt. Express **24**, 21939 (2016). — p.13, 17.
- [5] V. Savona, *Electromagnetic modes of a disordered photonic crystal*, Phys. Rev. B **83**, 085301 (2011). — p.13.
- [6] J. Lian, S. Sokolov, E. Yüce, S. Combrié, A. De Rossi, and A. P. Mosk, *Fano lines in the reflection spectrum of directly coupled systems of waveguides and cavities: measurements, modeling and manipulation of the Fano asymmetry*, arXiv:1610.08351 [physics.optics] (2016). — p.13.
- [7] J. Lian, *Control of resonances in photonic crystal waveguides* (Ph.D. thesis, Enschede, 2016). — p.14.
- [8] Private communication with A. De Rossi and S. Combrié. — p.15.
- [9] S. L. Gilbert and W. C. Swann, *Acetylene $^{12}\text{C}_2\text{H}_2$ Absorption Reference for 1510 nm to 1540 nm Wavelength Calibration - SRM 2517a*, NIST Special Publication 512 (2001). — p.15.
- [10] S. L. Gilbert, W. C. Swann, and C.-M. Wang, *Hydrogen Cyanide $\text{H}_{13}\text{C}_{14}\text{N}$ Absorption Reference for 1530 nm to 1565 nm Wavelength Calibration - SRM 2519a*, NIST Special Publication 512 (2005). — p.15.
- [11] A. Yariv and Y. Pochi, *Photonics: Optical electronics in modern communications* (Oxford University Press, 2007). — p.15.
- [12] S. Sokolov, J. Lian, E. Yüce, S. Combrié, G. Lehoucq, A. De Rossi, and A. P. Mosk, *Local thermal resonance control of GaInP photonic crystal membrane cavities using ambient gas cooling*, Appl. Phys. Lett. **106**, 171113 (2015). — p.17.
- [13] M. Pasienski and B. Demarco, *A high-accuracy algorithm for designing arbitrary holographic atom traps*, Opt. Express **16**, 2176 (2008). — p.17.

CHAPTER 3

Local thermal resonance control of GaInP photonic crystal membrane cavities using ambient gas cooling

We perform spatially dependent tuning of a GaInP photonic crystal cavity using a continuous wave violet laser. Local tuning is obtained by laser heating of the photonic crystal membrane. The cavity resonance shift is measured for different pump positions and for two ambient gases: He and N₂. We find that the width of the temperature profile induced in the membrane depends strongly on the thermal conductivity of the ambient gas. For He gas a narrow spatial width of the temperature profile of 2.8 μm is predicted and verified in experiment.

3.1 Introduction

Photonic crystal (PhC) cavities are widely studied because of their fascinating applications [1–3]. Arrays of PhC cavities can form coupled resonator optical waveguides (CROW), which are very promising for slow light applications [4] and the study of light localization [5]. Various fabrication imperfections can cause a disorder in a CROW structure which leads to a detuning of cavities from the intended resonance and reduces the waveguide throughput and bandwidth. Tuning each cavity independently can restore cavities in resonance and counteract the disorder. There is a variety of methods to change the refractive index of a PhC cavity, including free-carrier injection [6], the nonlinear Kerr effect [7], thermal effects [8, 9], oxidation [10–12] and chemical processes[13]. Of these methods, thermal tuning through local laser heating is easy, reversible and can give a steady-state control of the resonance properties of the system. However due to the diffusion of heat in the PhC membrane thermal control of one cavity will affect the neighbor cavities. The width of the temperature profile is determined by the sample material and the surrounding media. Therefore one can expect that by carefully selecting the sample material and ambient medium one can control the width of the temperature profile.

This chapter has been published as: S. Sokolov, J. Lian, E. Yüce, S. Combr  , A. De Rossi, A. P. Mosk, *Appl. Phys. Lett.* **106**, 171113 (2015).

3.2 Experiment and sample description

In this work we use the semiconductor alloy $\text{Ga}_{0.51}\text{In}_{0.49}\text{P}$ as a sample material and two gases, nitrogen and helium, as a surrounding media. $\text{Ga}_{0.51}\text{In}_{0.49}\text{P}$ has a thermal conductivity [14] of $4.9 \text{ W}/(\text{m}\cdot\text{K})$ which is quite small in comparison to other semiconductor materials [15]. The thermal conductivity of gases is often assumed to be negligible compared to semiconductors, such as Si. However, the effect of the gas on the width of the thermal profile depends strongly on the ratio of the thermal conductivity of the gas and the semiconductor. Helium has a high thermal conductivity [16] of $0.153 \text{ W}/(\text{m}\cdot\text{K})$, which is more than 6 times higher than of nitrogen [16] ($0.024 \text{ W}/(\text{m}\cdot\text{K})$) and only 32 times smaller than that of $\text{Ga}_{0.51}\text{In}_{0.49}\text{P}$. Therefore the combination of $\text{Ga}_{0.51}\text{In}_{0.49}\text{P}$ and He should have a high thermal exchange efficiency and small width of the temperature profile in comparison with other materials. To investigate the width of the temperature profile in PhC membranes we measured the response of the resonance of a H0-type cavity to a spatially scanned continuous wave (CW) heating laser focused on the membrane.

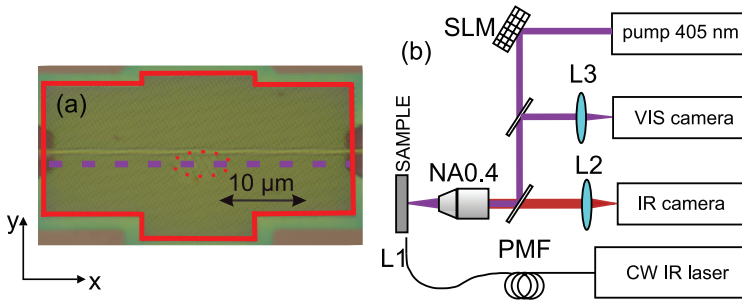


Figure 3.1: (a) Optical microscope image of a GaInP PhC (red line) with an H0 cavity (red dotted ellipse) in the center. (b) The pump-probe setup.

The PhC H0 nanocavity is implemented in a triangular lattice of air holes with a period $a=505 \text{ nm}$ and a hole radius $0.24 a$. The hole shift for the H0 cavity is $0.16 a$. A subharmonic hole structure is induced to enhance the radiation from the cavity in a vertical direction [17]. The cavity is made of a suspended membrane of $\text{Ga}_{0.51}\text{In}_{0.49}\text{P}$ with a thickness of 180 nm . The membrane is covered with 30 nm of Si_3N_4 on the top using a PECVD technique to tune the cavity resonance. The detailed description of the fabrication method can be found in Ref.18. A microscope picture of the cavity with the surrounding PhC is presented in Fig. 3.1a. The cavity is close to the center of the membrane and the IR light is evanescently coupled through a PhC waveguide. Mode converters at the end of the waveguide decrease the Fabry-Pérot interference in the waveguide and increase the coupling efficiency [19].

The setup is shown in Fig. 3.1b. The CW IR laser probe light was coupled to the PhC waveguide using a polarization maintaining lensed fiber with NA of 0.55. The out-of-plane scattered light was collected using a 0.4 NA objective and

imaged on an IR CCD camera using tube lens L2. The total magnification of the system is 50x. We recorded spectra by sweeping the wavelength of the IR laser and taking IR camera snapshots for each wavelength. The oxygen concentration was reduced to less than 0.025% to suppress oxidation effects [10–12]. The chamber was kept at a slight overpressure (less than 2 mbar above atmospheric pressure). Thermal tuning was performed using a 405 nm CW diode laser, which was focused onto the surface of the sample into a spot with a FWHM of $0.96\ \mu\text{m}$ using the same objective. The surface of the sample with the pump spot was also imaged with a visible range camera using tube lens L3 with a system magnification of 27x. The position of the pump spot was controlled using a spatial light modulator. The pump spot was moved along a line through the center of the cavity (see Fig. 3.1a) and the resonance spectrum of the cavity was measured for a sequence of pump positions. Any effects of slow oxidation or water coverage are eliminated by alternating between reference spectra (without pump laser) and signal spectra (with pump).

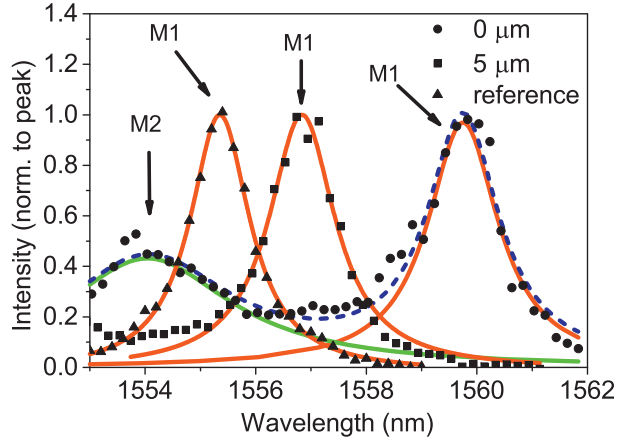


Figure 3.2: Spectra obtained from the out-of-plane scattered light for no-pump reference and for pump positions on top of the cavity and $5\ \mu\text{m}$ away from the center of the cavity in N_2 atmosphere. Color lines are Lorentzian fits.

3.3 Experimental results

Resonance spectra for the reference and for pump positions of 0 and $5\ \mu\text{m}$ relative to the center of the cavity in N_2 are presented in Fig. 3.2. The closer the pump spot is placed to the cavity, the stronger the redshift is due to the better overlap of the temperature profile and the cavity mode. We observe two resonance modes: the high- Q low-frequency mode (M1) and the low- Q high-frequency M2. Both resonances have a distinct Lorentzian shape and quality factors of about 1000 and 300 are estimated for modes M1 and M2 respectively. The calculated loaded Q -factor of the mode M1 is about 2500, because the cavity is designed to be overcoupled. The resonance M2 corresponds to a higher order mode which is

predicted from calculations. The mode M1 is much brighter than M2. The two modes have slightly different spatial positions, and the reference position is the center of mode M1. We use the wavelength shift of mode M1 to determine the spatially dependent cavity response to the pump. Apart from the redshift we observed a reduction of the intensity of the out-of-plane scattered light when the pump was positioned close to the cavity. We attribute this reduction to the fact that the cavity resonance was tuned farther away from the PhC band, thereby reducing the evanescent coupling to the waveguide.

The pump power incident on the sample was $110 \mu\text{W}$ in N_2 atmosphere. The spatial response curve for N_2 atmosphere is presented in Fig. 3.3a. The maximum redshift is 4.5 nm and the FWHM spatial width (Δx_{eff}) of the tuning curve is $5.1 \mu\text{m}$.

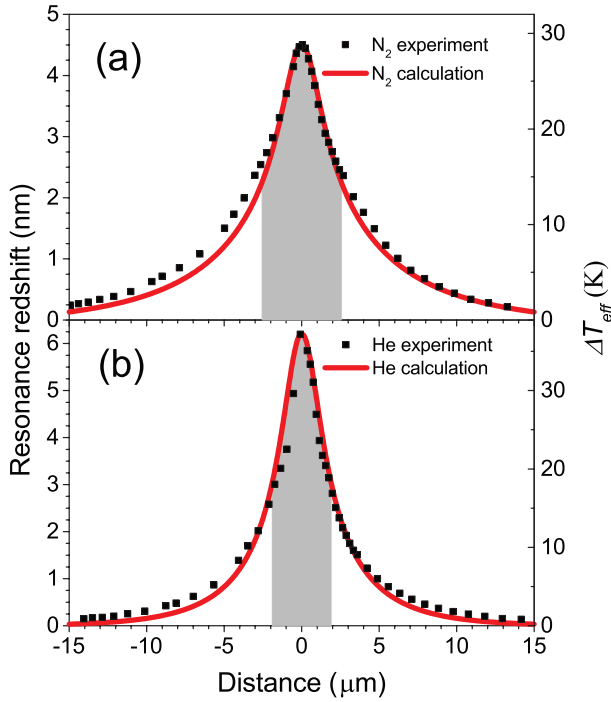


Figure 3.3: Redshift of the cavity resonance and ΔT_{eff} for different pump positions with nitrogen (a) and helium (b) as an ambient gas. Red curves represent the redshift calculated according to the model. From one measurement to another we observed an error less than 3% of the shift for N_2 , and less than 1% for He.

In He atmosphere a larger pump power of $220 \mu\text{W}$ was used (see Fig. 3.3b). The maximum observed redshift is 6.2 nm and Δx_{eff} is only $3.7 \mu\text{m}$. As a result of the high thermal conductivity of the He, both the redshift (normalized to power) and Δx_{eff} are smaller by 30% compared to N_2 . This thermal profile can be used to predict thermal crosstalk in structures with multiple cavities such as

CROWs. Compensation of crosstalk is typically possible when the crosstalk is below about 50%, i.e. for elements spaced more than $\Delta x_{\text{eff}}/2$. A reduction of Δx_{eff} therefore directly translates into a higher possible integration density of independently tuned cavities.

3.4 Modelling of the experiment

We have performed numerical calculations to model the resonance wavelength change of the cavity for different pump positions taking into account material and pump properties. For small perturbations of the refractive index the wavelength change can be expressed as [20]

$$\Delta\lambda = \frac{\lambda}{\langle n \rangle} \frac{dn}{dT} \Delta T_{\text{eff}}, \text{ with} \quad (3.1)$$

$$\Delta T_{\text{eff}} = \frac{\int \Delta T(\mathbf{r} - \mathbf{r}_0) \epsilon(\mathbf{r}) |\mathbf{E}(\mathbf{r})|^2 d^3r}{\int \epsilon(\mathbf{r}) |\mathbf{E}(\mathbf{r})|^2 d^3r}, \quad (3.2)$$

where ΔT_{eff} is temperature averaged over the mode profile $\epsilon(\mathbf{r})|\mathbf{E}(\mathbf{r})|^2$ of the cavity, $\epsilon(\mathbf{r})$ is the dielectric constant of the membrane material, $\Delta T = T - T_0$ is the local temperature change in the PhC averaged over the membrane thickness, $\frac{dn}{dT}$ is the linear coefficient of the refractive index temperature response, $\langle n \rangle$ is the averaged refractive index of the membrane material and $\mathbf{r}_0$ is the position of the pump. $T_0 = 293.15 \text{ K}$ is the ambient temperature. The mode profile was calculated using a finite difference time domain method [21]. Temperature profiles were calculated in COMSOL using a steady state heat diffusion model with a constant source term assuming that thermal conductivities are not temperature dependent within the relevant temperature range:

$$\kappa(x, y, z) \nabla^2 T(x, y, z) + W(x, y, z) = 0, \quad (3.3)$$

where $\kappa(x, y, z)$ is the thermal conductivity and W is a source term inside the membrane written as a sum of two terms $W = W_E + W_R$, due to the excess energy of the carriers and their recombination respectively.

We observe photoluminescence (PL) of $\text{Ga}_{0.51}\text{In}_{0.49}\text{P}$ at 670 nm caused by the pump light. The bandgap of $\text{Ga}_{0.51}\text{In}_{0.49}\text{P}$ is 1.85 eV and the energy of a 405 nm photon is 3.06 eV. The excess energy term (W_E) is released within about a picosecond upon optical excitation and therefore has the spatial profile of the pump spot (a Gaussian width $\sigma_E = 0.41 \mu\text{m}$) and corresponds to a fraction $f_E = 0.4$ of the initial power. The recombination term (W_R) has the profile of the PL spot, a Gaussian width $\sigma_R = 0.50 \mu\text{m}$, and it takes a fraction $f_R = 0.6$ of the photon energy. We assume that all absorbed light is converted into heat, because the estimated radiative carrier recombination efficiency is less than 1%. The excess energy term is expressed as

$$W_E(x, y, z) = f_E \frac{P(1 - R)}{2\pi\sigma_E^2} \alpha e^{-(x^2 + y^2)/2\sigma_E^2} e^{-\alpha z}. \quad (3.4)$$

Here R is the reflection coefficient of the membrane estimated to be 9.5%, α is the absorption coefficient of $\text{Ga}_{0.51}\text{In}_{0.49}\text{P}$, and P is the total power of the pump beam. The recombination heating term has the same Gaussian shape with the appropriate fraction and width inserted. The size of the air gap between the membrane and GaAs substrate for our samples is equal to $1.5\text{ }\mu\text{m}$, the size of the air layer above the membrane was taken to be $10\text{ }\mu\text{m}$. All external boundaries are Dirichlet type with temperature T_0 . The photonic crystal is assumed to be a rectangle of $40 \times 20\text{ }\mu\text{m}$. Dirichlet boundaries are considered because the membrane is surrounded from four sides by the bulk material, which acts like a perfect heat sink. Thermal conductivities for gases were taken from Ref.16. The coating layer made of Si_3N_4 has a thermal conductivity [22] of $24.5\text{ W}/(\text{m}\cdot\text{K})$. The thermal conductivity of the membrane was taken as volume averaged between holes of the PhC lattice and two layers of Si_3N_4 and $\text{Ga}_{0.51}\text{In}_{0.49}\text{P}$. The absorption coefficient [23] of $\text{Ga}_{0.51}\text{In}_{0.49}\text{P}$ at 405 nm is $24.5\text{ }(\mu\text{m})^{-1}$ and the absorption coefficient [24] of Si_3N_4 is less than $0.006\text{ }(\mu\text{m})^{-1}$. As a result nearly all pump light is absorbed by the $\text{Ga}_{0.51}\text{In}_{0.49}\text{P}$ membrane. The temperature profile can be calculated without any free parameters. The only parameter which is unknown for the redshift calculation is $\frac{dn}{dT}$ for $\text{Ga}_{0.51}\text{In}_{0.49}\text{P}$.

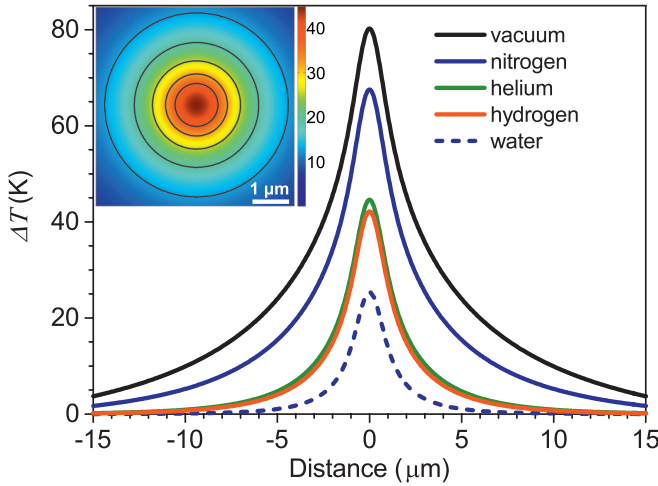


Figure 3.4: X-axis crosssection of the calculated temperature profile (ΔT) for different ambient media. The pump focus is placed in the center of the cavity. The power of the pump light is $220\text{ }\mu\text{W}$. The inset shows the 2D averaged temperature profile for helium. The isotherms have a step of 6.3 K .

The resulting effective temperature profiles are presented in Fig. 3.3a,b, and are in excellent agreement with the experiment for both nitrogen and helium. The maximum temperature rise in case of nitrogen atmosphere is 29 K , and in case of He it is 37 K , so the ratio of these two values normalized to the incident power is equal to 0.63 . The experimental ratio of redshifts is 0.69 . From Fig. 3.3 we also estimate the so far unknown $\frac{dn}{dT}$ for $\text{Ga}_{0.51}\text{In}_{0.49}\text{P}$. We obtain the value

of $3.1 \pm 0.5 \times 10^{-4} \text{K}^{-1}$.

Instead of helium one could use media with a higher thermal conductivity. In Fig. 3.4 calculated temperature profiles along the central line of the PhC membrane (see Fig. 3.1) are presented for different surrounding media. These are bare temperature profiles, not convolved with the cavity mode. The widest temperature profile is found in case of vacuum. Water has a thermal conductivity 4 times higher than He, which results in a significantly narrower temperature profile. We note that low-refractive-index liquids such as acetone and isopropanol have thermal conductivities comparable to that of He. Using liquids for heat exchange completely changes the optical properties of the sample, therefore using a high-thermal-conductivity gas is a more appropriate option in many cases.

The general tendency of the width Δx_{th} and the peak value (ΔT_{max}) of the bare temperature profile is presented in Fig. 3.5.

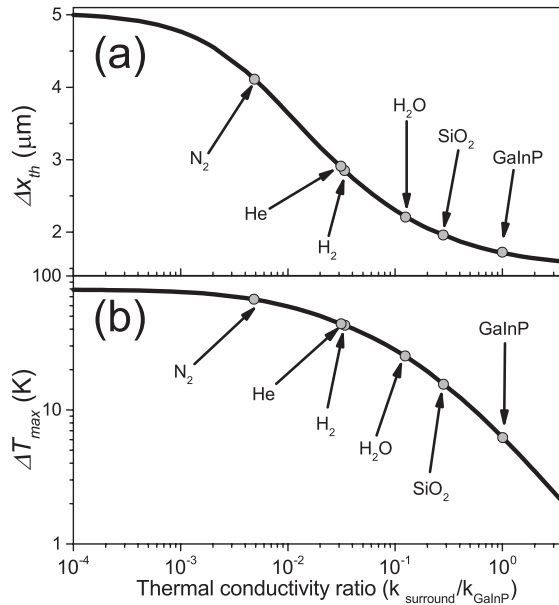


Figure 3.5: Calculated Δx_{th} (a) and ΔT_{max} (b) vs thermal conductivity ratio of surrounding media and $\text{Ga}_{0.51}\text{In}_{0.49}\text{P}$. Some well-known materials are marked. The power of the pump light is $220 \mu\text{W}$.

In case of low ambient thermal conductivity heat tends to diffuse inside the membrane, therefore Δx_{th} and the peak temperature reach constant values of $5 \mu\text{m}$ and 79K , respectively. For large thermal conductivities of the surrounding media all heat diffuses rapidly into the ambient media reducing Δx_{th} and the peak temperature.

Gas cooling is most relevant for thermal tuning of resonances in membranes made of materials with small thermal conductivities such as $\text{Ga}_{0.51}\text{In}_{0.49}\text{P}$. In highly conducting materials like Si the thermal profile is significantly larger [9]

and is typically determined by the material boundaries rather than by heat exchange with the gas.

For time-dependent tuning applications such as a switch or a tracking filter the time response is of importance. From time-dependent simulations we estimate that the 10% to 90% temperature rise time in a nitrogen atmosphere is about 6 μs , but in helium it reduces to 2 μs . Therefore, helium not only helps to improve the spatial resolution of thermal tuning but also makes the tuning response about three times faster. Similarly, it should reduce thermal optical nonlinearities that result from absorption of cavity-enhanced probe light.

3.5 Conclusions

In conclusion, we measured the spectral tuning curve of a thermally tuned cavity for different surrounding media and found an excellent agreement between experiment and our numerical calculations. Our results and our calculations are of importance for applications such as thermal control of CROWs where the width of the temperature profile should be minimized. Also our calculations offer insight in the role of ambient materials for any applications that involve local laser heating.

Bibliography

- [1] A. Yariv, Y. Xu, R. K. Lee, and A. Scherer, *Coupled-resonator optical waveguide: a proposal and analysis*, Opt. Lett. **24**, 711 (1999). — p.21.
- [2] Y. Akahane, T. Asano, B. Song, and S. Noda, *High-Q photonic nanocavity in a two-dimensional photonic crystal*, Nature **425**, 944 (2003). — p.21.
- [3] A. B. Matsko, *Practical applications of microresonators in optics and photonics* (CRC Press, 2009). — p.21.
- [4] N. Matsuda, E. Kuramochi, H. Takesue, and M. Notomi, *Dispersion and light transport characteristics of large-scale photonic-crystal coupled nanocavity arrays*, Opt. Lett. **39**, 2290 (2014). — p.21.
- [5] S. Mookherjee, J. S. Park, S. Yang, and P. R. Bandaru, *Localisation in silicon nanophotonic slow-light waveguides*, Nat. Photon. **2**, 90 (2008). — p.21.
- [6] C. Husko, A. De Rossi, S. Combri , Q. V. Tran, F. Raineri, and C. W. Wong, *Ultrafast all-optical modulation in GaAs photonic crystal cavities*, Appl. Phys. Lett. **94**, 021111 (2009). — p.21.
- [7] E. Y ce, G. Ctistis, J. Claudon, E. Dupuy, R. D. Buijs, B. de Ronde, A. P. Mosk, J.-M. Gerard, and W. L. Vos, *All-optical switching of a microcavity repeated at terahertz rates*, Opt. Lett. **38**, 374 (2013). — p.21.
- [8] M. Notomi, A. Shinya, S. Mitsugi, G. Kira, E. Kuramochi, and T. Tanabe, *Optical bistable switching action of Si high-Q photonic-crystal nanocavities*, Opt. Express **13**, 2678 (2005). — p.21.
- [9] J. Pan, Y. Huo, K. Yamanaka, S. Sandhu, L. S. R. Timp, M. L. Povinelli, S. Fan, M. M. Fejer, and J. S. Harris, *Aligning microcavity resonances in silicon photonic-crystal slabs using laser-pumped thermal tuning*, Appl. Phys. Lett. **92**, 103114 (2008). — p.21, 27.
- [10] C. J. Chen, J. Zheng, T. Gu, J. F. McMillan, M. Yu, G. Lo, D. Kwong, and C. W. Wong, *Selective tuning of high-Q silicon photonic crystal nanocavities via laser-assisted local oxydation*, Opt. Express **19**, 12480 (2011). — p.21, 23.
- [11] H. S. Lee, S. Kiravittaya, S. Kumar, J. D. Plumhof, L. Balet, L. H. Li, M. Francardi, A. Gerardino, A. Fiore, A. Rastelli, and O. G. Schmidt, *Local tuning of photonic crystal nanocavity modes by laser-assisted oxidation*, Appl. Phys. Lett. **95**, 191109 (2009). — p.21, 23.
- [12] F. Riboli, N. Caselli, S. Vignolini, F. Intonti, K. Vynck, P. Barthelemy, A. Gerardino, L. Balet, L. Li, A. Fiore, M. Gurioli, and D. Wiersma, *Engineering of light confinement in strongly scattering disordered media*, Nat. Mater. **13**, 720 (2014). — p.21, 23.
- [13] K. Hennessy, A. Badolato, A. Tamboli, P. M. Petroff, E. Hu, M. Atatüre,

- J. Dreiser, and A. Imamoglu, *Tuning photonic crystal nanocavity modes by wet chemical digital etching*, Appl. Phys. Lett. **87**, 021108 (2005). — p.21.
- [14] S. Adachi, *Lattice thermal conductivity of group-IV and III-V semiconductor alloys*, J. Appl. Phys. **102**, 063502 (2007). — p.22.
- [15] M. Levinshstein, S. Rumyantsev, and M. Shur, *Handbook series on semiconductor parameters* (World Scientific, 1996), Vol. 1. — p.22.
- [16] H. Anderson, *A physicist's desk reference* (American institute of physics, NY, 1989). — p.22, 26.
- [17] N. Tran, S. Combrié, P. Colman, A. De Rossi, and T. Mei, *Vertical high emission in photonic crystal nanocavities by band-folding design*, Phys. Rev. B **82**, 075120 (2010). — p.22.
- [18] S. Combrié, S. Bansropun, M. Lecomte, O. Parillaud, S. Cassette, H. Benisty, and J. Nagle, *Optimization of an inductively coupled plasma etching process of GaInP/GaAs based material for photonic band gap applications*, J. Vac. Sci. Technol. B **23**, 1521 (2005). — p.22.
- [19] Q. Tran, S. Combrié, P. Colman, and A. De Rossi, *Photonic crystal membrane waveguides with low insertion losses*, Appl. Phys. Lett. **95**, 061105 (2009). — p.22.
- [20] J. Joannopoulos, S. G. Johnson, J. N. Winn, and R. D. Meade, *Photonic crystals: Molding the flow of light* (Princeton University Press, Princeton, 2008). — p.25.
- [21] A. F. Oskooi, D. Roundy, M. Ibanescu, P. Bermel, J. D. Joannopoulos, and S. G. Johnson, *Meep: A flexible free-software package for electromagnetic simulations by the FDTD method*, Comp. Phys. Comm. **181**, 687 (2010). — p.25.
- [22] MIT material property database, <http://www.mit.edu/~6.777/matprops/matprops.htm>. — p.26.
- [23] M. Schubert, V. Gottschalch, C. M. Herzinger, H. Yao, and P. G. Snyder, *Optical constants of $Ga_xIn_{1-x}P$ lattice matched to GaAs*, J. Appl. Phys. **77**, 3416 (1995). — p.26.
- [24] E. Palik, *Handbook of optical constants of solids* (Academic Press, 1985). — p.26.

CHAPTER 4

Tuning out disorder-induced localization in nanophotonic cavity arrays

Weakly coupled high- Q nanophotonic cavities are building blocks of slow-light waveguides and other nanophotonic devices. Their functionality critically depends on tuning as resonance frequencies should stay within the bandwidth of the device. Unavoidable disorder leads to random frequency shifts which cause localization of the light in single cavities. We present a new method to finely tune individual resonances of light in a system of coupled nanocavities. We use holographic laser-induced heating and address thermal crosstalk between nanocavities using a response matrix approach. As a main result we observe a simultaneous anticrossing of 3 nanophotonic resonances, which were initially split by disorder.

4.1 Introduction

Optical circuits containing high- Q photonic crystal nanocavities have been proposed for delay lines, optical memory storage, optomechanics and quantum communication [1–8]. However, unavoidable fabrication disorder in nanophotonic structures causes scattering which leads to frequency detuning, signal attenuation, and eventually localizes optical modes which ruins the transmission properties of the whole system [9, 10]. Even state-of-the-art nanofabrication with random spatial variations of only $\Delta x = 1$ nm can lead to resonance wavelength detunings of more than $\Delta \lambda = 1$ nm [11, 12].

Several methods have been proposed to tune nanocavities. Methods based on local refractive index change, such as photodarkening, photoactivation and photo-oxidation [13–15], have limited tuning range and irreversibility as well as introduction of optical loss. Other methods which involve free-carriers or heat suffer from diffusion, namely free-carriers and heat diffuse far beyond the physical size of the cavity [16–18]. Since in a system with a useful optical coupling between nanocavities elements should be placed physically close to each other, this results in unavoidable crosstalk in the tuning process. In addition, in high- Q systems

This chapter has been published as: S. Sokolov, J. Lian, E. Yüce, S. Combrié, A. De Rossi, A. P. Mosk, arXiv:1608.01257 [physics.optics]

carriers dissipate on a time scale comparable to or shorter than the resonance lifetime.

In this work, we demonstrate a new approach for realignment of resonances of closely-spaced cavities based on holographic thermal tuning. By accurately measuring the thermal response of resonance wavelength in the system and obtaining the power settings required to hybridize cavities, we experimentally align an array of three nanocavities, which were initially misaligned by more than 200 unloaded resonator linewidths. Our method is scalable to large arrays and enables programmable photonic devices where circuit functionalities can be dynamically switched on and off.

4.2 Sample and experimental setup

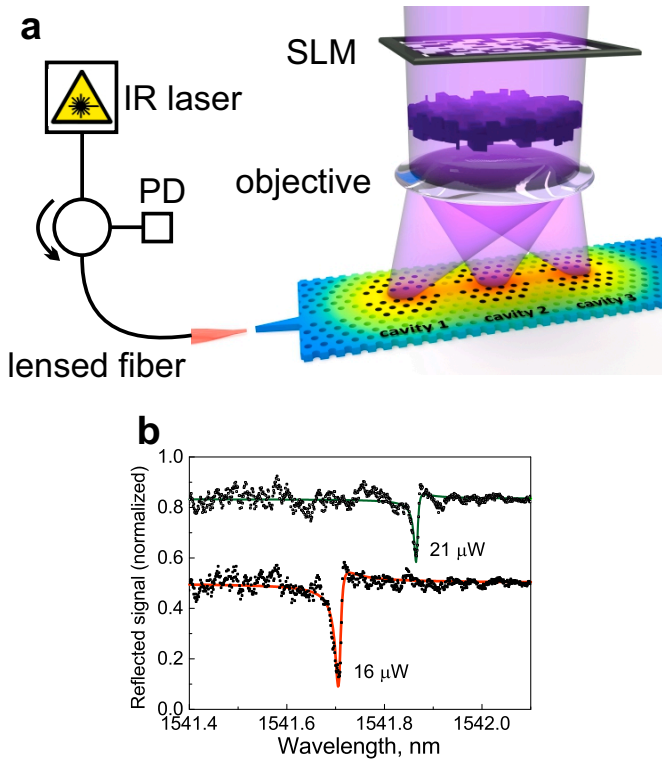


Figure 4.1: Schematic of the experiment. **a** Pump light is modulated by the SLM to holographically create several focused spots on the sample. The SLM is imaged to the pupil of the objective. Continuous wave IR probe light from a tunable laser with TE polarization is coupled to the sample through a polarization maintaining lensed fiber and the reflected signal is collected on a photodiode using a fiber circulator. **b** Reflection spectra showing the resonance of cavity 3 for pump powers 16 μW and 21 μW . Power applied to cavity 1 is 9 μW . Solid lines represent Fano fits.

The sample under investigation is $\text{Ga}_{0.51}\text{In}_{0.49}\text{P}$ air-suspended photonic crystal membrane with thickness $d = 180\text{nm}$. Three nanocavities are defined in a photonic crystal waveguide with width of $0.98\sqrt{3}a$ made in a hexagonal lattice with period $a = 485\text{ nm}$ and hole radius $r = 0.28a$. They are defined by local width modulation [19] of the waveguide with a maximum hole shift of $0.0124a$. An out-of-line waveguide with a width $1.1\sqrt{3}a$ is used to couple light in and out of the system. The distance between cavity 1 and cavity 2 is $4.4\text{ }\mu\text{m}$, and the distance between cavity 2 and 3 is $4.9\text{ }\mu\text{m}$. Numerically calculated coupling rates are $\Gamma_{12} = 0.00022\omega_0$ and $\Gamma_{23} = 0.00015\omega_0$, where ω_0 is the resonance wavelength of the cavity, Γ_{jk} is a coupling rate between cavity j and k .

The setup for the thermal control is shown in Fig. 4.1a. CW pump light ($\lambda = 405\text{ nm}$) is used to thermally tune nanocavities. A liquid crystal spatial light phase modulator (SLM) was placed in the Fourier plane of the objective to holographically [20] create several focused spots on the sample. Light was focused into tight spots with FWHM $0.8\text{ }\mu\text{m}$. The absolute intensity of all pump spots was measured using a CCD camera placed in the reflection configuration and calibrated with a power meter. To attribute a particular resonance to a particular cavity we performed pump line-scans of the pump spot along the cavity array [18, 21]. The resulting linescan of our sample is presented in Figure 4.2. The closer the pump spot to the center of a particular mode-gap cavity the bigger the overlap of the temperature profile created by the pump laser and mode profile of the cavity. This allows to easily identify resonances, as indicated in Figure 4.2. To extract resonance wavelengths and widths the reflection spectra were fitted with appropriate Fano line-shape of the resonances [22], as it is shown in Figure 4.1b.

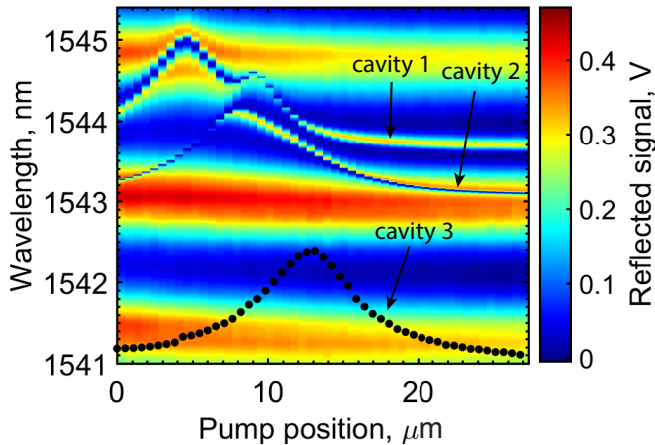


Figure 4.2: Pump line-scan. Response of cavity resonances for pump placed at different positions. The power on the surface of the sample is $32\text{ }\mu\text{W}$. Black dots indicate resonance of the cavity 3 for better visibility.

4.3 Thermal response matrix approach

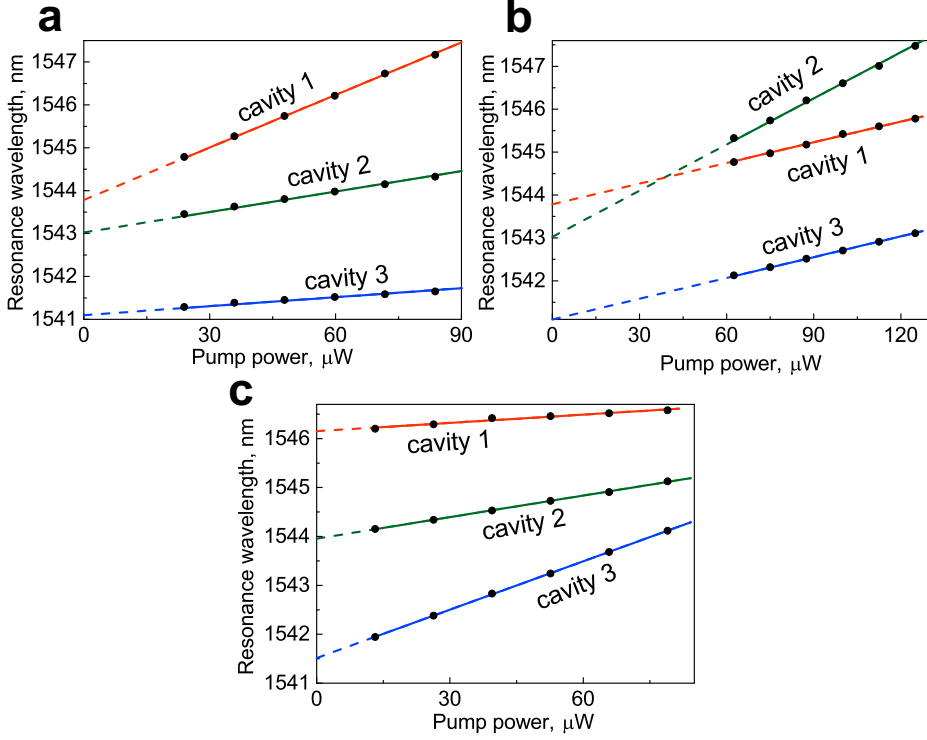


Figure 4.3: Determination of the thermal response matrix. a,b,c Response curves of cavity resonances to pump spots placed on top of cavity 1 (a), 2 (b), 3 (c). Solid lines are line fits to experimental data and dashed lines are extrapolation of fitting curves to the zero power. In c cavity 1 was biased with 60 μW pump power to separate the resonances.

When a photonic crystal membrane is heated with focused CW laser light the width of the temperature profile is more than 4 times larger than the diffraction-limited laser focus [14, 18]. Although this width can be tailored by properly selecting the material of the membrane and the ambient media [18], significant crosstalk remains for any choice of material. To account for that crosstalk we employ a response matrix approach. In the linear tuning regime, where the resonance shift is proportional to the applied power, we construct a matrix (M_{ij}) which expresses the response of the resonance wavelength ($\Delta\lambda_i$) to the applied pump powers P_i :

$$\Delta\lambda_i = \sum_j M_{ij} \cdot P_j \quad (4.1)$$

Diagonal elements of the response matrix determine the response of the addressed cavity and off-diagonal elements determine crosstalk to the neighbors. Ideally the response matrix values can be calculated [18], however they are sensitive to experimental details, therefore we use measured values.

We place a single pump spot on top of each cavity at a time and measure resonance redshift versus applied pump power. The result is presented in Figure 4.3a,b,c for cavity 1, 2 and 3 respectively. In some cases when cavity resonances occur too close together, a second pump spot is placed to bias the resonance, as in Fig. 4.3c. Resonance shifts are then fitted with linear dependencies, where slopes give thermal crosstalk values. The cavity directly under the pump spot displays the steepest slope whereas resonances of neighbor cavities have smaller slopes. The measured response matrix is

$$M = \begin{pmatrix} 4.1 & 1.6 & 0.6 \\ 1.6 & 3.6 & 1.5 \\ 0.7 & 1.6 & 3.3 \end{pmatrix} \cdot 10^{-2} \frac{\text{nm}}{\mu\text{W}} \quad (4.2)$$

Response values differ slightly from cavity to cavity as a consequence of positioning accuracy of pump spots and the difference in physical separation between cavities. On average first-neighbor crosstalk is 44%, whereas second-neighbor crosstalk is 17%. Such levels of thermal crosstalk cannot be neglected. We find bare wavelengths of nanocavity resonances to be 1543.78 ± 0.11 nm for cavity 1, 1543.02 ± 0.04 nm for cavity 2 and 1541.1 ± 0.04 nm for cavity 3, which matches with reference measurements. Due to the disorder cavity 3 is detuned from cavities 1 and 2 by about $\Delta\lambda = 2$ nm. The observed detunings can be explained by disorder, taking into account our fabrication accuracy of $\Delta x \approx 4$ nm.

4.4 Alignment of the array

To find the required powers and the target wavelength at which all the resonances anticross we solve the resulting linear programming problem. The condition for this problem is that all applied powers are positive. We find that the target wavelength is 1544.79 nm and corresponding powers are $P_1 = 9 \mu\text{W}$, $P_2 = 0 \mu\text{W}$ and $P_3 = 108 \mu\text{W}$. As a result of the procedure the lowest pump power is always zero, therefore to align three resonances 2 pump spots are sufficient. In general to align N cavities one needs to place at least $N - 1$ pump spots on the surface of the sample.

In Fig. 4.4a we show the hybridization of the three resonances which is the main result of this paper. We set P_1 to the calculated value and gradually increase P_3 and plot resonance wavelengths. The resonances anticross and become fully hybridized at around $108 \mu\text{W}$. The reflection spectra for this power is shown in Figure 4.4c. In the region where resonances are hybridized they cannot be attributed to a particular cavity, hence we label them as resonance I, II and III. At low pump powers resonances I, II and III represent cavities 1,2 and 3 correspondingly. At high powers after the resonances anticross, resonance I localizes on cavity 3 and resonance III localizes on cavity 1. For pump powers higher than $140 \mu\text{W}$, resonance I becomes very weak and its wavelength cannot be extracted.

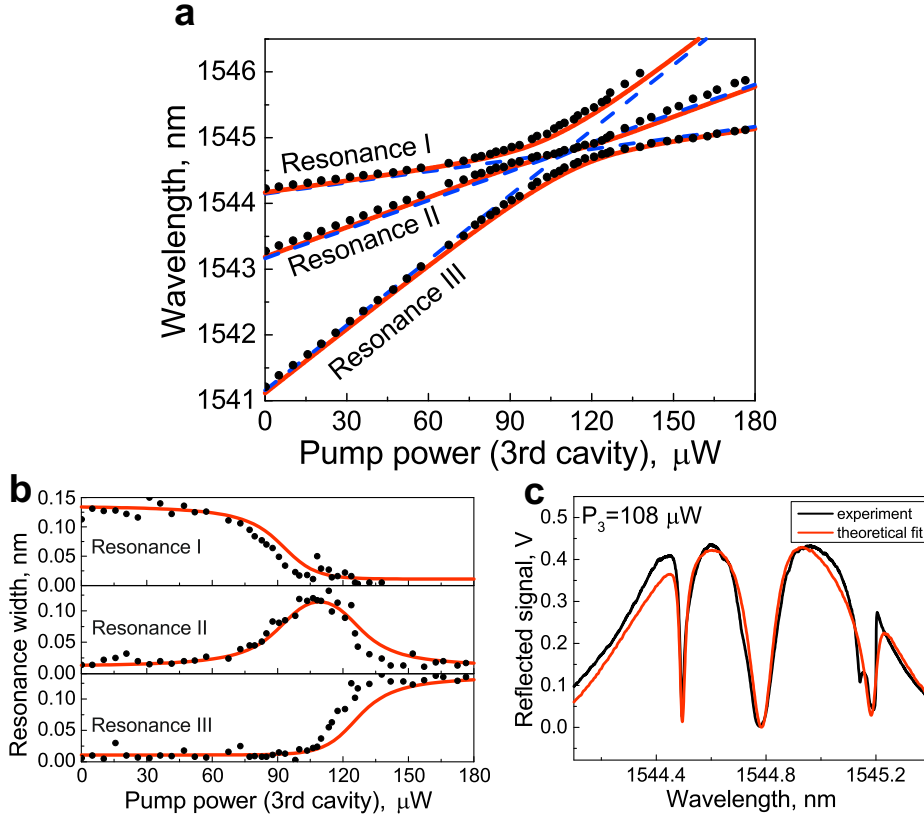


Figure 4.4: Alignment of cavity resonances. Resonance positions **a** and widths **b** are obtained from reflection spectra by fitting Fano lineshapes. The pump power for cavity 1 was fixed to 9 μW , while the power for cavity 3 was increased from 0 to 180 μW . Red solid line is a fit by coupled-mode theory. Blue dashed lines represent uncoupled resonance wavelengths. **c** - Spectra of the sample for $P_3 = 108 \mu\text{W}$. Red solid line represents Fano line fit with 3 resonance lines and 5th order polynomial as a background.

In case of weak optical coupling between cavities the behavior of the resonances can be described by coupled-mode theory [23] assuming only nearest-neighbor coupling. The result is presented in Fig 4.4a. To find coupling rates for our cavities the parameters of the coupled-mode model were adjusted in the region where cavities are coupled, i.e. for powers between 70 and 140 μW . We find good agreement between theory and experiment and obtain coupling rates which are equal to $\Gamma_{12} = (0.90 \pm 0.29) \cdot 10^{-4} \cdot \omega_0$, $\Gamma_{23} = (1.92 \pm 0.27) \cdot 10^{-4} \cdot \omega_0$, or equivalently $\Gamma_{12} = 0.14 \pm 0.05 \text{ nm}$ and $\Gamma_{23} = 0.30 \pm 0.04 \text{ nm}$.

The experimentally determined values of the coupling rates are different from the numerically calculated ones. This suggests that disorder affects not only the resonance wavelength and Q-factor, but also the mode profile of a cavity, which

determines the coupling constant [23].

The widths of all three resonances are expected to change while the cavities anticross. Cavity 1 is the closest cavity to the input waveguide which suggests that it should have the largest width due to the leak to the waveguide. At the same time when cavities are coupled the leakage from second and third cavity to the waveguide should increase, and resonances II and III should broaden. In Fig. 4.4b the experimental dependence of the widths of the resonances on applied power P_3 is presented. The width of the resonance I slowly decreases with pump power P_3 and becomes very narrow at high pump powers confirming that it has become localized on cavity 3. The inverse dependence is pronounced for resonance III which starts localized on cavity 3 and ends on cavity 1. At the point of anticrossing resonance II becomes the broadest.

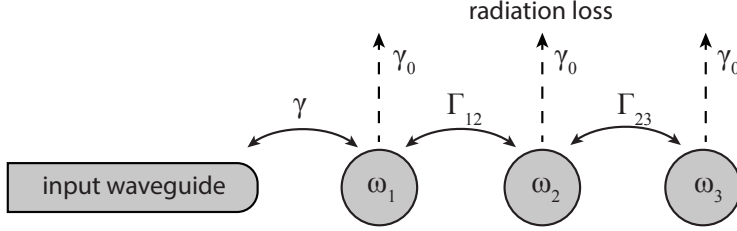


Figure 4.5: Model of the sample. The light is coupled to the first cavity in the system with coupling rate γ , then each cavity in the array is coupled to the nearest neighbor by coupling constants Γ_{12} and Γ_{23} .

The width of the resonances can be predicted using temporal coupled-mode theory [24] where we take into account the influence of the input waveguide and radiation loss. The model is presented in Figure 4.5. Cavities 2 and 3 are placed physically away from the input waveguide and therefore the coupling rates between them and the waveguide can be neglected. These resonances are visible in reflection only due to the light which leaks via the cavity 1. Only nearest neighbor coupling is taken into account. This result in the following system of equations:

$$\begin{cases} S_- = -1 + \sqrt{2\gamma}a_1, \\ \frac{da_1}{dt} = -i\omega_1a_1 - i\Gamma_{12}a_2 - a_1\gamma - a_1\gamma_0 + \sqrt{2\gamma}, \\ \frac{da_2}{dt} = -i\omega_2a_2 - i\Gamma_{12}a_1 - i\Gamma_{23}a_3 - a_2\gamma_0, \\ \frac{da_3}{dt} = -i\omega_3a_3 - i\Gamma_{23}a_2 - a_3\gamma_0 \end{cases} \quad (4.3)$$

Here γ is a coupling rate to the input waveguide, S_- is a complex amplitude of the outgoing waveguide mode, a_1 , a_2 and a_3 are complex amplitude of the field inside cavities, ω_1 , ω_2 and ω_3 are bare frequencies of nanocavities and γ_0 determines intrinsic cavity decay rate. We define two free parameters which are the loaded Q-factor of the first cavity (Q_L) and the intrinsic Q-factor (Q_0) of cavities assuming that it is the same for all cavities. We fit these free parameters

outside the hybridization region, i.e. for power less than $70 \mu\text{W}$ and more than $140 \mu\text{W}$ and obtain a good agreement with experiment (see Fig. 4.4b). The value for intrinsic Q-factor is found to be $Q_0 = (1.42 \pm 0.45) \cdot 10^5$, while the value of loaded Q-factor for the first cavity is $Q_L = (1.12 \pm 0.05) \cdot 10^4$. The numerically calculated value of the loaded Q-factor is 11000 which matches the value obtained from the experiment.

4.5 Conclusion

In conclusion, we have proposed and implemented a new method to program individual resonance wavelengths of coupled cavities. We corrected for thermal tuning crosstalk in the system to obtain independent tuning of resonances by measuring the thermal response matrix. We coupled three nanocavities and hybridized their local resonances into spatially extended modes. This shows that our method is capable of counteracting disorder in arrays of coupled cavities. The resonance wavelengths and widths were very well reproduced by a coupled-mode model. Our method can be easily extended to a larger number of nanocavities by adding more pump spots to the system. Resonance tuning with crosstalk compensation is likely to become a valuable method for any type of systems where disorder influences resonance states is required such as optomechanical systems [7, 25], many resonator systems [26–29], disordered necklace states [10, 30] and complex boson sampling networks [31, 32].

4.6 Methods

The experiment was performed in dry nitrogen atmosphere to minimize oxidation and surface water effects [14]. The sample temperature was locked at $41.85 \pm 0.001 \text{ }^\circ\text{C}$. To further minimize these effects the illumination time of the surface with pump light was minimized to 270 ms during which the pumped measurement was taken. Nonetheless, minor surface effects were present in the data, resulting in resonance blueshifts and redshifts. To correct for that we performed reference measurement with no pump light immediately after each pumped measurement. Then surface effects for crosstalk matrix coefficients were eliminated by subtracting reference resonance values from pumped ones. As there is significant coupling between resonances 1 and 2 in the unpumped sample, to extract the bare resonance frequencies we used only data taken at pump powers $> 10 \mu\text{W}$. During the final measurement resonance shifts due to above mentioned effects were less than 80 pm for all presented datapoints.

Bibliography

- [1] A. Yariv, Y. Xu, R. K. Lee, and A. Scherer, *Coupled-resonator optical waveguide: a proposal and analysis*, Opt. Lett. **24**, 711 (1999). — p.31.
- [2] E. Parra and J. R. Lowell, *Toward Applications of Slow Light Technology*, Opt. Photonics News **18**, 40 (2007). — p.31.
- [3] F. Morichetti, C. Ferrari, A. Canciamilla, and A. Melloni, *The first decade of coupled resonator optical waveguides: Bringing slow light to applications*, Laser Photon. Rev. **6**, 74 (2012). — p.31.
- [4] H. Takesue, N. Matsuda, E. Kuramochi, W.J. Munro, and M. Notomi, *An on-chip coupled resonator optical waveguide single-photon buffer*, Nat. Commun. **4**, 2725 (2013). — p.31.
- [5] E. Kuramochi, K. Nozaki, A. Shinya, K. Takeda, T. Sato, S. Matsuo, H. Taniyama, H. Sumikura, and M. Notomi, *Large-scale integration of wavelength-addressable all-optical memories on a photonic crystal chip*, Nat. Photon. **8**, 474 (2014). — p.31.
- [6] M. Notomi, E. Kuramochi, and T. Tanabe, *Large-scale arrays of ultrahigh- Q coupled nanocavities*, Nat. Photon. **2**, 741 (2008). — p.31.
- [7] K. Fang, M. H. Matheny, X. Luan, and O. Painter, *Optical transduction and routing of microwavephonons in cavity-optomechanical circuits*, Nat. Photon. **10**, 489 (2016). — p.31, 38.
- [8] M. Tillmann, B. Dakić, R. Heilmann, S. Nolte, A. Szameit, and P. Walther, *Experimental boson sampling*, Nat. Photon. **7**, 540 (2013). — p.31.
- [9] M. L. Cooper, G. Gupta, M. a. Schneider, W. M. J. Green, S. Assefa, F. Xia, Y. a. Vlasov, and S. Mookherjea, *Statistics of light transport in 235-ring silicon coupled-resonator optical waveguides*, Opt. Express **18**, 26505 (2010). — p.31.
- [10] F. Sgrignuoli, G. Mazzamuto, F. Intonti, F. S. Cataliotti, M. Gurioli, and C. Toninelli, *Necklace State Hallmark in Disordered 2D Photonic Systems*, ACS Photonics **2**, 1636 (2015). — p.31, 38.
- [11] Y. Taguchi, Y. Takahashi, Y. Sato, T. Asano, and S. Noda, *Statistical studies of photonic heterostructure nanocavities with an average Q factor of three million*, Opt. Express **19**, 11916 (2011). — p.31.
- [12] L. Ramunno and S. Hughes, *Disorder-induced resonance shifts in photonic crystal nanocavities*, Phys. Rev. B **79**, 161303 (2009). — p.31.
- [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). — p.31.
- [14] C. J. Chen, J. Zheng, T. Gu, J. F. McMillan, M. Yu, G.-Q. Lo, D.-L.

- Kwong, and C. W. Wong, *Selective tuning of high-Q silicon photonic crystal nanocavities via laser-assisted local oxidation*, Opt. Express **19**, 12480 (2011). — p.31, 34, 38.
- [15] T. Cai, R. Bose, G. S. Solomon, and E. Waks, *Controlled coupling of photonic crystal cavities using photochromic tuning*, Appl. Phys. Lett. **102**, (2013). — p.31.
- [16] M. Notomi, A. Shinya, S. Mitsugi, G. Kira, E. Kuramochi, and T. Tanabe, *Optical bistable switching action of Si high-Q photonic-crystal nanocavities*, Opt. Express **13**, 2678 (2005). — p.31.
- [17] B. A. Ruzicka, L. K. Werake, H. Samassekou, and H. Zhao, *Ambipolar diffusion of photoexcited carriers in bulk GaAs*, Appl. Phys. Lett. **97**, 262119 (2010). — p.31.
- [18] S. Sokolov, J. Lian, E. Yüce, S. Combrié, G. Lehoucq, A. De Rossi, and A. P. Mosk, *Local thermal resonance control of GaInP photonic crystal membrane cavities using ambient gas cooling*, Appl. Phys. Lett. **106**, 171113 (2015). — p.31, 33, 34, 35.
- [19] S. Combrié, A. De Rossi, Q. V. Tran, and H. Benisty, *GaAs photonic crystal cavity with ultrahigh Q: microwatt nonlinearity at 1.55 μm* , Opt. Lett. **33**, 1908 (2008). — p.33.
- [20] M. Pasienski and B. Demarco, *A high-accuracy algorithm for designing arbitrary holographic atom traps*, Opt. Express **16**, 2176 (2008). — p.33.
- [21] J. Lian, S. Sokolov, E. Yüce, S. Combrié, A. De Rossi, and A. P. Mosk, *Measurement of the profiles of disorder-induced localized resonances by local tuning*, Opt. Express **24**, 21939 (2016). — p.33.
- [22] W. Zhou, D. Zhao, Y. C. Shuai, H. Yang, S. Chuwongin, A. Chadha, J. H. Seo, K. X. Wang, V. Liu, Z. Ma, and S. Fan, *Progress in 2D photonic crystal Fano resonance photonics*, Prog. Quant. Electron. **38**, 1 (2014). — p.33.
- [23] H. A. Haus and W. Huang, *Coupled-mode theory*, Proc. IEEE **79**, 1505 (1991). — p.36, 37.
- [24] J. Joannopoulos, S. G. Johnson, J. N. Winn, and R. D. Meade, *Photonic crystals: Molding the flow of light* (Princeton University Press, Princeton, 2008). — p.37.
- [25] R. Lauter, C. Brendel, S. J. M. Habraken, and F. Marquardt, *Pattern phase diagram for two-dimensional arrays of coupled limit-cycle oscillators*, Phys. Rev. E **92**, 012902 (2015). — p.38.
- [26] K. Nozaki, E. Kuramochi, A. Shinya, and M. Notomi, *25-channel all-optical gate switches realized by integrating silicon photonic crystal nanocavities*, Opt. Express. **22**, 3491 (2014). — p.38.
- [27] A. C. Liapis, B. Gao, M. R. Siddiqui, Z. Shi, and R. W. Boyd, *On-chip spectroscopy with thermally-tuned high-Q photonic crystal cavities*, Appl. Phys. Lett. **108**, 021105 (2016). — p.38.
- [28] X. Gan, N. Pervez, I. Kyrmis, F. Hatami, and D. Englund, *A high-resolution spectrometer based on a compact planar two dimensional photonic crystal cavity array*, Appl. Phys. Lett. **100**, (2012). — p.38.
- [29] S. Mittal, J. Fan, S. Faez, A. Migdall, J. M. Taylor, and M. Hafezi, *Topologically robust transport of photons in a synthetic gauge field*, Phys. Rev. Lett.

- 113**, 087403 (2014). — p.38.
- [30] J. Bertolotti, S. Gottardo, D. S. Wiersma, M. Ghulinyan, and L. Pavesi, *Optical necklace states in Anderson localized 1D systems*, Phys. Rev. Lett. **94**, 1 (2005). — p.38.
- [31] J. B. Spring *et al.*, *Boson Sampling on a Photonic Chip*, Science **339**, 798 (2013). — p.38.
- [32] A. Crespi, R. Osellame, R. Ramponi, D. J. Brod, E. F. Galvão, N. Spagnolo, C. Vitelli, E. Maiorino, P. Mataloni, and F. Sciarrino, *Integrated multimode interferometers with arbitrary designs for photonic boson sampling*, Nat. Photon. **7**, 545 (2013). — p.38.

CHAPTER 5

Dynamic tuning of the coupling constant between photonic crystal nanocavities

Coupled photonic nanocavities play a key role in proposed integrated photonic circuits. Tuning the coupling constant between these nanocavities directly paves the way to devices with tunable bandwidth and tunable delay. Here we experimentally demonstrate reversible tuning of the coupling constant based on local perturbation of the refractive index. We experimentally demonstrate an increase of the coupling constant by more than 100%, corroborated by theory.

5.1 Introduction

Photonic crystal nanocavities have been intensively investigated in the last decade due to their unique combination of high quality factors and small mode-volumes [1–4]. As individual elements they have numerous applications like optical filters [5], all-optical switches [6] and nonlinear optical devices [7]. When such cavities are optically coupled new phenomena and applications arise such as slow light [8, 9], superfluid-insulator phase transitions [10] and quantum optical devices [11]. Therefore coupled photonic crystal nanocavities are building blocks of future classical and quantum nanophotonic circuits. To achieve the full tunability of coupled cavity systems one should be able to individually tune the bare resonance frequency of each resonator as well as the coupling constants between each pair of resonators. While tuning the resonance frequency has been achieved in several systems [12, 13], tuning the coupling constant is more complicated because it requires a change in mode-overlap between nanoresonators. Tuning the coupling constant allows to achieve tunable bandwidth and delay, study exceptional points [14, 15] and obtain topological effects like an effective magnetic field for photons [16]. Several different approaches have been taken to achieve this tunability [17–20], however an easy reversible post-fabrication method which can be used for any type of photonic crystal nanocavities has not yet been experimentally shown.

In this work we demonstrate a new approach based on local perturbation of the refractive index of the photonic crystal. We use local laser-induced heating as a perturbation and experimentally achieve an increase of the coupling constant by more than a factor of 2. We find that the coupling constant is most effectively tuned when the pump spot is placed in between nanocavities. To obtain insight in

the mechanism behind the experimentally observed effects we perform numerical simulations and semi-analytical calculations.

5.2 Description of the experiment

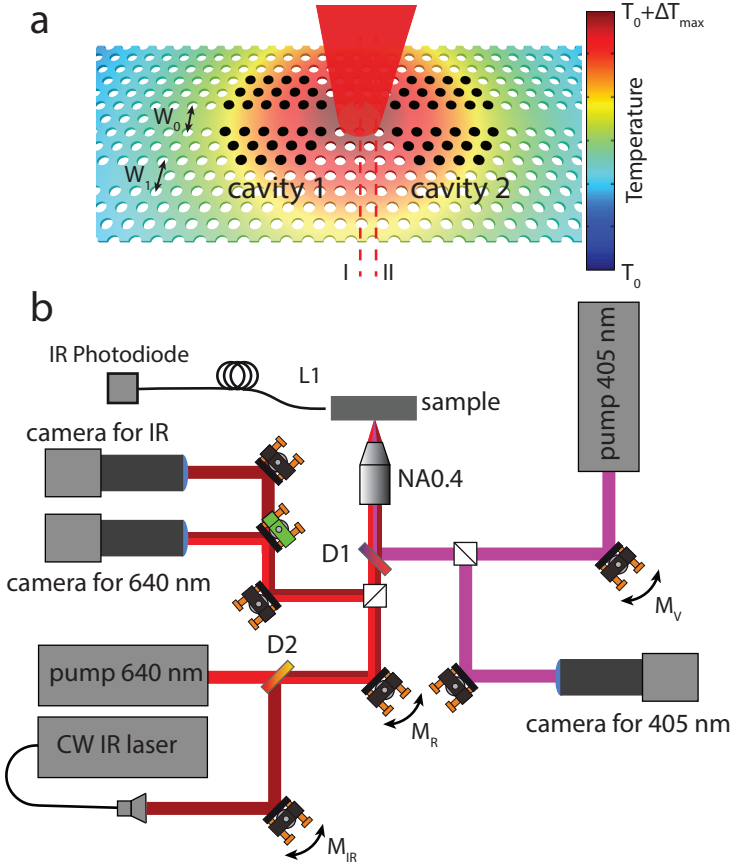


Figure 5.1: Scheme of the sample and experimental setup. a - Sample. Black circles represent displaced holes that define two mode-gap cavities in the photonic crystal waveguide. The red cone represents the focused pump light from the red CW laser. The color scale is linear and represents the temperature distribution created by the red pump beam. Pump positions I and II are indicated with red dashed lines. **b - Experimental setup.** Three beams are combined using one objective. Mirrors M_{IR} , M_{R} and M_{V} are used to manually steer IR, red and violet beams. The mirror shown in green is a flip-mirror to direct light to the camera for 640 nm light. Dichroic mirror D1 reflects violet and passes red/IR beams. Dichroic mirror D2 reflects IR and passes red light.

The layout of the sample used for this experiments is presented in Figure 5.1. The sample consists of a photonic crystal membrane made of $\text{Ga}_{0.51}\text{In}_{0.49}\text{P}$ with two

optically coupled photonic crystal mode-gap cavities [4]. The first row hole shift is $0.0124a$. The membrane is made of $\text{Ga}_{0.51}\text{In}_{0.49}\text{P}$. The lattice period of the photonic crystal $a = 0.485$ nm and the thickness of the membrane $h = 180$ nm. The two mode-gap cavities are separated by distance of $9a$ to achieve a coupling constant of $0.00022\omega_0$. The width of the waveguide where cavities are located is $W_0 = 0.98\sqrt{3}a$. This waveguide is side coupled to the wider photonic crystal waveguide with a width of $W_1 = 1.1\sqrt{3}a$ which is used to collect the IR probe light from the structure. The experimental setup used for measurements is presented in Fig. 5.1b. The IR probe light from the CW tunable laser source was launched into the system by out-of-plane coupling to the cavity 1. The out-of-plane coupling is achieved by focusing light on the cavity using the objective with 0.4 NA. The IR optical power measured after the objective was $2.5\text{ }\mu\text{W}$. Even though the intrinsic Q-factor of this type of cavities is known to be close to 10^6 [21], meaning that out-of-plane scattering losses are small, the light can be coupled in due to the disorder-induced perturbations in the far-field radiation pattern of the cavity [22]. The IR light is then collected from the mode-converter [23] at the end of the waveguide W_1 using a lensed fiber L1 with NA of 0.55. To achieve local perturbation of the waveguide, red pump light from a CW laser light source with a wavelength of 640 nm was focused in the middle between nanocavities. We measure the coupling constant by observing the anticrossing between cavity resonances. To this end, an auxiliary violet pump laser beam with a wavelength of 405 nm was focused on cavity 1. Both pump lasers were focused through the same objective as the IR light. The optical powers of the red and violet pump lasers were measured right after the objective. The red pump power (P_{red}) was changed stepwise through 14 levels and for each power level of the red laser the corresponding anticrossing of two nanocavities was measured by gradually increasing the power of the auxiliary pump laser (P_{aux}) through about 30 power levels. The surface was illuminated for 250 ms each step. The IR spectra were obtained by sweeping the wavelength of the IR laser source over the wavelengths of interest within that time. The experiment was performed in nitrogen atmosphere to reduce the ambient oxygen and water concentrations and avoid heat-assisted and laser-assisted material oxidation effects as well as to reduce water absorption-desorption effects [24–27]. The oxygen concentration was kept below 0.1% and relative humidity was kept below 1%. The temperature of the sample substrate was locked at 41.85 ± 0.001 °C.

5.3 Experimental results

Experimentally two positions for the red pump were considered: position I in the center between two nanocavities and position II which is $0.4\text{ }\mu\text{m}$ away from the center. Anticrossings measured for several selected powers are presented in Figure 5.2. For position I the anticrossing width is equal to 0.434 ± 0.001 nm when P_{red} is equal to $12\text{ }\mu\text{W}$ (Figure **a**). While for $P_{\text{red}} = 80\text{ }\mu\text{W}$ on Figure **b** the anticrossing width is equal to 0.595 ± 0.002 nm. This confirms that the anticrossing width increases with pump power applied to the center between nanocavities. For

position II the anticrossing width is 0.53 ± 0.01 nm at $P_{red} = 94 \mu\text{W}$ and 0.75 ± 0.01 nm at $P_{red} = 190 \mu\text{W}$ as follows from Figures **c** and **d**. Hence the width also increases with pump power for a pump placed off center.

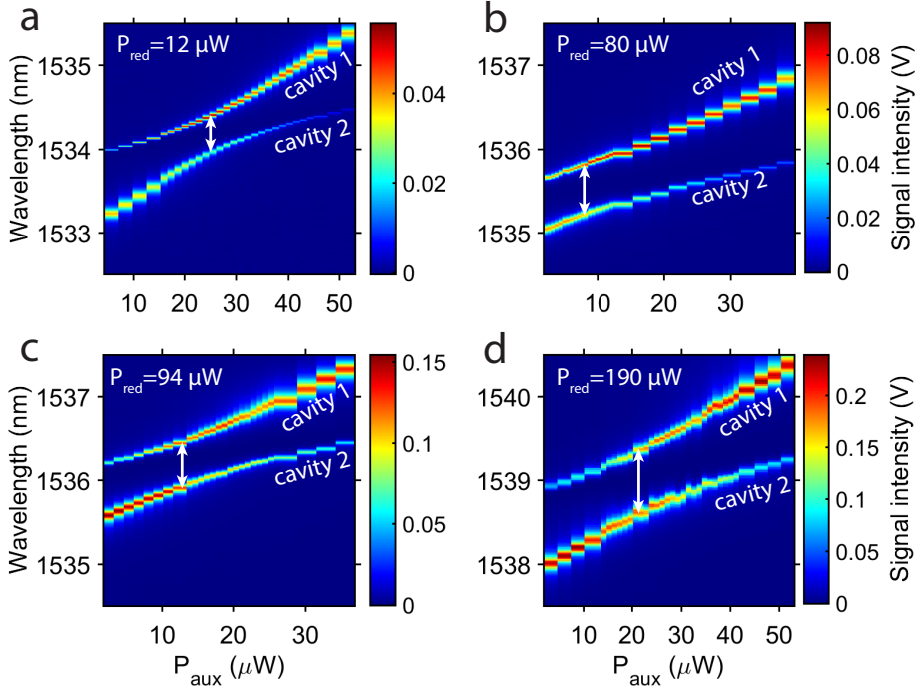


Figure 5.2: Experimentally measured anticrossings. **a,b** - Anticrossing measurements for pump position I and powers 12 and 80 μW . **c,d** - Anticrossing measurements for pump position II and powers 94 and 190 μW . **a**. Size of the vertical axis is the same for all for anticrossings for clarity. The colorscale represents the collected signal intensity. Arrow indicates the position and width of the anticrossing.

The experimental dependence of the anticrossing width on pump power P_{red} is presented in Figure 5.3. The anticrossing width is equal to $2\Gamma_0$, where Γ_0 is the coupling constant between two nanocavities. We neglect the effect of the input waveguide, because the coupling rate of the first waveguide is small ($\gamma_1 = 2.85 \pm 0.03 \cdot 10^{-5} \omega_0$, see Figure 6.20 from Chapter 6). The coupling constant is obtained from the experimental result by fitting the dependence of the intercavity frequency difference for powers close to the anticrossing by the following formula: $\Delta\omega = 2\sqrt{(A \cdot P_{aux} + B)^2 + \Gamma_0^2}$, where A and B are fitting parameters which correspond to the tuning slope and offset of bare frequency difference between nanocavities and P_{aux} is the power of the auxiliary pump laser.

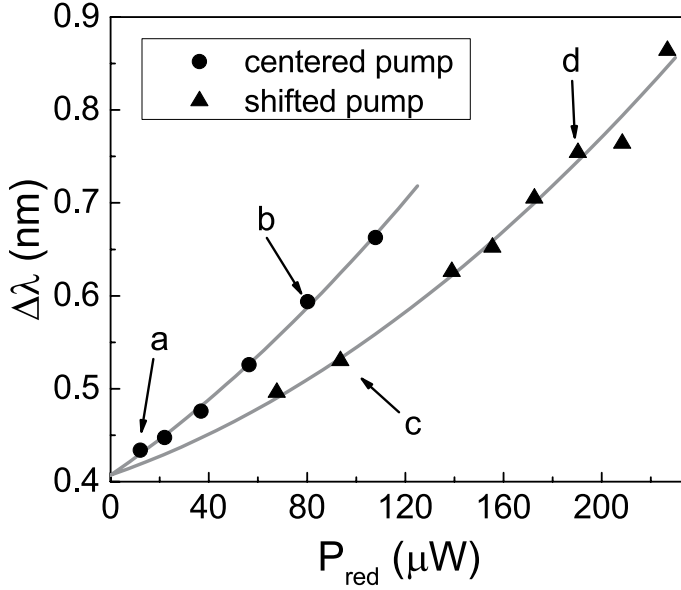


Figure 5.3: Dependence of anticrossing width on pump power. Gray curves represent second order polynomial fits for complete datasets. Datapoints named a, b, c, d correspond to panels of Figure 5.2.

We observe different tuning dependencies for pump positions I and II. For pump positions I the anticrossing width rises faster than for pump position II. Superlinear behavior is observed in both cases, as both datasets are well described by a 2nd order polynomial dependence shown in the Figure 5.3.

To confirm the dependence of coupling constant tuning on position a third experiment was performed where a single pump spot was placed on top of each cavity, red on cavity 1 and violet on cavity 2. No systematic change in the coupling constant was observed with an accuracy of 20 pm. We conclude that a significant change of the coupling constant requires accurate placement of the pump spot in the center between nanocavities.

In total for the results presented in Figure 5.3 we managed to increase the coupling constant more than 2 times by locally heating the membrane with a concomitant redshift of the anticrossing position by 6 nm.

5.4 Numerical simulation of the experiment

To get insight into the mechanism of coupling constant change we performed numerical simulations. We performed 2D FDTD calculations [28] to calculate the anticrossing width. Our numerical system consists of a W_0 waveguide with a length of $68a$ with 8 rows of holes on each side. Lattice period as well as cavity parameters are the same as in the experiment. The Yee-lattice resolution was $a/12$. We model the perturbation induced by the red pump beam by intro-

ducing a local perturbation of the dielectric constant $\Delta\epsilon$ which is proportional to the temperature profile in the membrane averaged over its thickness. The temperature profile was obtained as a solution of the heat diffusion equation by COMSOL for the pump spot with FWHM of $0.8\ \mu\text{m}$ [29]. The resulting $\Delta\epsilon$ is presented in Figure 5.4. The temperature profile was split into rectangular domains with constant permittivity to avoid numerical errors due to overlap between hole boundaries and domain borders [30]. The pump spot was placed exactly in the center between nanocavities. Source positions and spectral widths were selected to excite only the modes of interest.

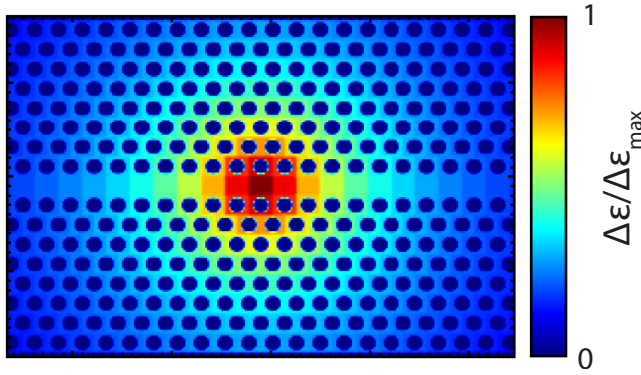


Figure 5.4: Effective perturbation. Spatial distribution of the effective perturbation $\Delta\epsilon$ which is used to numerically model the effect of the pump spot.

The result of the simulation is presented in Figure 5.5a,b. Figure 5.5a shows the dependence of anticrossing width on the magnitude of the perturbation $\Delta\epsilon$. The perturbation is varied between 0 and 1%. At low pump powers the dependence starts off at linear and then slowly turns into superlinear, which can be clearly seen in comparison to the black dashed line. To point out the superlinear behavior we perform a 2nd order polynomial fit which is shown as a red dashed line in Figure 5.5a. The coupled modes of 2 mode-gap cavities experience a red-shift as shown in Figure 5.5b. The low-frequency mode shifts faster than the high-frequency one.

To reproduce the experimentally observed dependence of the tuning slope on pump position we perform an additional simulation with two pump spots each placed on top of the nanocavity. We found a small rise of 7% in coupling constant at 1% perturbation, which is much smaller in comparison to the 89% change obtained in case of pump centered in the middle between nanocavities. This result corroborates the experimentally observed dependence on the position of the pump.

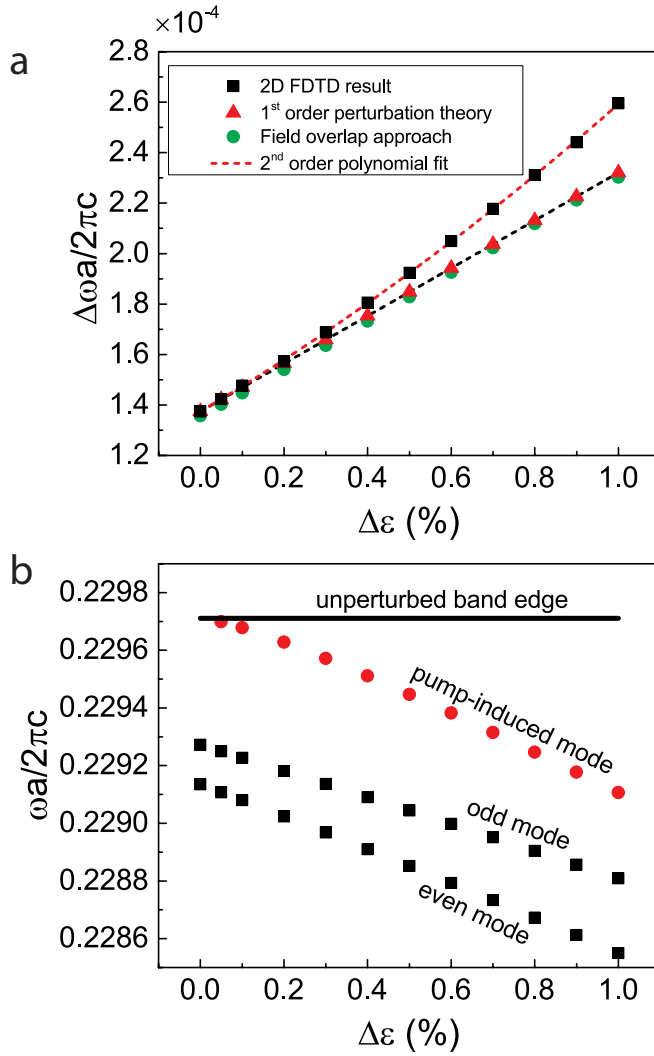


Figure 5.5: Numerical experiment. **a** - Anticrossing width versus the magnitude of the applied perturbation. The black dashed line is a linear fit to first order perturbation theory result. **b** - Frequencies of coupled cavity modes, unperturbed band edge and pump induced mode versus the magnitude of the applied perturbation.

5.5 Semi-analytic model

5.5.1 First-order perturbation theory

To understand the nature of the observed effects we perform semi-analytical calculations. When two identical nanocavities are coupled they form an even and

odd mode which have different mode profiles, similar to the well-known Heitler and London result for the H_2 molecule [31]. The odd mode has nearly 0 field amplitude in the center. According to the coupled mode theory its field is equal to the field difference between two separate nanocavity modes [32]. The even mode is equal to the sum of these fields and therefore it should have much higher envelope in the center region. Crosssections along the waveguide of numerically calculated field amplitudes for these two modes in case of zero perturbation magnitude are presented in Figure 5.6. The even mode has a significantly higher field envelope in the center region than the odd mode.

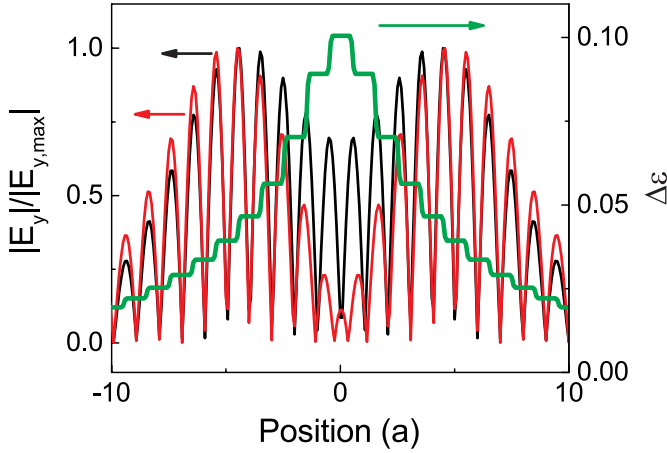


Figure 5.6: Field and perturbation profiles. FDTD calculated field profile crosssections along the center of the photonic crystal waveguide for even (black) and odd (red) modes of two coupled mode-gap cavities. The green curve represents the dielectric perturbation along the same line in case of 1% perturbation.

According to first-order perturbation theory the resonance frequency of the resonance mode experiences a change which is proportional to the overlap integral between the mode and applied perturbation [33]: $\Delta\omega \propto \int \Delta\epsilon |\mathbf{E}|^2 d\mathbf{r}$. When the perturbation profile is placed in the center between cavity 1 and 2 (see green curve in Figure 5.6) we expect the even mode to redshift faster than the odd mode which should result in an increase in mode separation. An increase in the separation between the even and odd modes means the coupling constant is increased. The result of the calculation is presented in Figure 5.5a. The resulting linear dependence describes the effect of weak perturbations very well but deviates from the FDTD results at larger perturbation strengths.

5.5.2 Field-overlap integral approach

The resonance mode tends to concentrate its electric field in the region with high dielectric constant [33], therefore the mode-gap cavity mode is expected to shift toward the pump-induced perturbation at large dielectric perturbations. In other

words the pump spot creates an effective potential [34] in the waveguide defined by the temperature distribution. Another effective potential is in turn created by the waveguide perturbation that defines the mode-gap cavity. The total sum of these two potentials defines a new mode with a shifted center position.

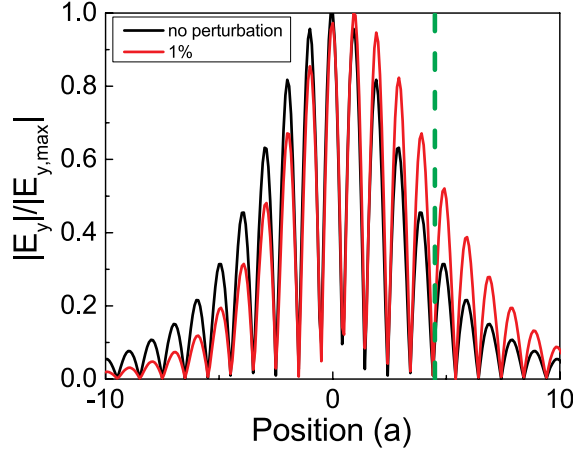


Figure 5.7: Single cavity field profiles. Field amplitude crosssections of a single mode-gap cavity mode along the center of the waveguide for the case 0% and 1% perturbation. The green dashed line indicates the center position of the perturbation.

The crosssections of field amplitude of single mode-gap cavity along the waveguide are plotted in Figure 5.7. The field amplitude shifts in the direction of the maximum of the applied perturbation. The amplitude in the field tail on the left side decreases while it increases on the right side close to the pump. This effectively results in decrease of the distance between nanocavities and increase of the field overlap between them. The coupling constant can be calculated as the field overlap integral between two modes $\Gamma_0 \propto \int \delta\epsilon \mathbf{E}_1 \cdot \mathbf{E}_2 d\mathbf{r}$, where $\delta\epsilon$ is the difference between the dielectric function of two coupled nanocavities and single nanocavity [8]. The resulting coupling constant is presented in Figure 5.5a. The coupling constant has a linear dependence on pump power close to the 1st order perturbation theory result. Hence the superlinear behavior cannot be explained by shift of the modes.

5.5.3 Pump-induced mode effect

The superlinear behavior can be explained by the fact that a perturbation with a positive $\Delta\epsilon$ should pull a mode from the continuum into the bandgap [33, 35]. Such a mode has not been observed directly in experiments. We indeed observe this pump-induced mode at the perturbation levels used in our simulations (see Figure 5.5b). The frequency difference between this pump-induced mode and the bare resonance frequency of the mode-gap cavity decreases with the local perturbation. Because the pump-induced mode is pulled from the band edge

it is rather delocalized at small perturbations and localized around the pump position for large perturbations [35]. It is located in between the two mode-gap nanocavities causing mode overlap which creates additional optical coupling in the system. Therefore this becomes a three resonator system.

When a resonator in the middle is detuned in frequency from two other resonators the adiabatic elimination procedure can be used to reduce the complexity of the system [36, 37]. In coupled mode theory this will result in eliminating the field amplitude of the pump-induced cavity and introducing a correction term to the coupling constant between two mode-gap cavities. The resulting coupling constant will be equal to $\Gamma = \Gamma_0 + \Gamma_1^2/\Delta\omega_{th}$, where Γ_1 is the coupling constant between thermally created nanocavity and the mode-gap cavity, and $\Delta\omega_{th}$ is the frequency difference between them. This positive term explains the increase in the coupling constant at large perturbations. The superlinear tuning curve in Fig. 5.3 can therefore be seen as a first, indirect experimental observation of localized mode pulled from the continuum.

5.6 Conclusion

In conclusion, we experimentally achieved reversible tuning of the coupling constant between two photonic crystal nanocavities by inducing a local refractive index perturbation. The tuning dependence on pump power is superlinear. It was found that the most efficient tuning is achieved when a single pump beam is placed in the middle between two mode-gap cavities, while placing pump beams on the cavities yielded almost no change of the coupling constant. The observed effects were reproduced in FDTD calculations. The linear part of the coupling constant increase is explained analytically using mode symmetry of two coupled cavities. The FDTD calculations show that the superlinear part of the dependence is a result of the interaction with a pump-induced localized mode.

5.7 Outlook

From the consideration presented in section 5.5.1 it follows that using helium as ambient media should give stronger spatial localization of the tuning. As a result, one should obtain stronger tuning of the coupling constants for the same perturbation levels than in case of nitrogen. Indeed, the coupling constant obtained from direct FDTD calculations for 1% perturbation in helium is larger by 9% than in case of nitrogen.

In general, our experimental approach is not limited to thermal perturbation and could be achieved at high rates using other optical nonlinearities such as free-carrier injection or even the electronic Kerr effect.

Bibliography

- [1] Y. Akahane, T. Asano, B. Song, and S. Noda, *High-Q photonic nanocavity in a two-dimensional photonic crystal*, Nature **425**, 944 (2003). — p.43.
- [2] B. Song, S. Noda, T. Asano, and Y. Akahane, *Ultra-high-Q photonic double-heterostructure nanocavity*, Nat. Mater. **4**, 207 (2005). — p.43.
- [3] Z. Zhang and M. Qiu, *Small-volume waveguide-section high Q microcavities in 2D photonic crystal slabs*, Opt. Express **12**, 3988 (2004). — p.43.
- [4] E. Kuramochi, M. Notomi, S. Mitsugi, A. Shinya, T. Tanabe, and T. Watanabe, *Ultrahigh-Q photonic crystal nanocavities realized by the local width modulation of a line defect*, Appl. Phys. Lett. **88**, 041112 (2006). — p.43, 45.
- [5] K. Debnath, K. Welna, M. Ferrera, K. Deasy, D. G. Lidzey, and L. O’Faolain, *Highly efficient optical filter based on vertically coupled photonic crystal cavity and bus waveguide*, Opt. Lett. **38**, 154 (2013). — p.43.
- [6] I. Fushman, E. Waks, D. Englund, N. Stoltz, P. Petroff, and J. Vučković, *Ultrafast nonlinear optical tuning of photonic crystal cavities*, Appl. Phys. Lett. **90**, 2005 (2007). — p.43.
- [7] A. Martin, G. Moille, S. Combrié, G. Lehoucq, T. Debuisschert, J. Lian, S. Sokolov, A. P. Mosk, and A. De Rossi, *Triply-resonant Continuous Wave Parametric Source with a Microwatt Pump*, ArXiv:1602.04833 [physics.optics] (2016). — p.43.
- [8] A. Yariv, Y. Xu, R. K. Lee, and A. Scherer, *Coupled-resonator optical waveguide: a proposal and analysis*, Opt. Lett. **24**, 711 (1999). — p.43, 51.
- [9] M. Notomi, E. Kuramochi, and T. Tanabe, *Large-scale arrays of ultrahigh-Q coupled nanocavities*, Nat. Photon. **2**, 741 (2008). — p.43.
- [10] A. Tomadin, V. Giovannetti, R. Fazio, D. Gerace, I. Carusotto, H. E. Türeci, and A. Imamoglu, *Signatures of the superfluid-insulator phase transition in laser-driven dissipative nonlinear cavity arrays*, Phys. Rev. A **81**, 1 (2010). — p.43.
- [11] A. Majumdar, A. Rundquist, M. Bajcsy, and J. Vučković, *Cavity quantum electrodynamics with a single quantum dot coupled to a photonic molecule*, Phys. Rev. B **86**, 1 (2012). — p.43.
- [12] T. Cai, R. Bose, G. S. Solomon, and E. Waks, *Controlled coupling of photonic crystal cavities using photochromic tuning*, Appl. Phys. Lett. **102**, (2013). — p.43.
- [13] S. Sokolov, J. Lian, E. Yüce, S. Combrié, A. De Rossi, and A. P. Mosk, *Tuning out disorder-induced localization in nanophotonic cavity arrays*, arXiv:1608.01257 [physics.optics] (2016). — p.43.

- [14] C. Dembowski, H. D. Gräf, H. L. Harney, A. Heine, W. D. Heiss, H. Rehfeld, and A. Richter, *Experimental observation of the topological structure of exceptional points*, Phys. Rev. Lett. **86**, 787 (2001). — p.43.
- [15] W. D. Heiss, *The Physics of exceptional points*, J. Phys. A **44**016, 28 (2012). — p.43.
- [16] K. Fang, Z. Yu, and S. Fan, *Realizing effective magnetic field for photons by controlling the phase of dynamic modulation*, Nat. Photon. **6**, 782 (2012). — p.43.
- [17] G. Gupta, Y.-H. Kuo, H. Tazawa, W. H. Steier, A. Stapleton, and J. D. O'Brien, *Analysis and demonstration of coupling control in polymer microring resonators using photobleaching*, Appl. Opt. **48**, 5324 (2009). — p.43.
- [18] *Post-fabrication control of evanescent tunnelling in photonic crystal molecules*, Appl. Phys. Lett. **101**, 1 (2012). — p.43.
- [19] H. Du, X. Zhang, G. Chen, J. Deng, F. S. Chau, and G. Zhou, *Precise control of coupling strength in photonic molecules over a wide range using nanoelectromechanical systems*, Sci. Rep. **6**, 24766 (2016). — p.43.
- [20] S. Haddadi, P. Hamel, G. Beaudoin, I. Sagnes, C. Sauvan, P. Lalanne, J. A. Levenson, and A. M. Yacomotti, *Photonic molecules: tailoring the coupling strength and sign*, Opt. Express **22**, 12359 (2014). — p.43.
- [21] S. Combrié, A. De Rossi, Q. V. Tran, and H. Benisty, *GaAs photonic crystal cavity with ultrahigh Q: microwatt nonlinearity at 1.55 μm* , Opt. Lett. **33**, 1908 (2008). — p.45.
- [22] H. Hagino, Y. Takahashi, Y. Tanaka, T. Asano, and S. Noda, *Effects of fluctuation in air hole radii and positions on optical characteristics in photonic crystal heterostructure nanocavities*, Phys. Rev. B **79**, 085112 (2009). — p.45.
- [23] Q. Tran, S. Combrié, P. Colman, and A. De Rossi, *Photonic crystal membrane waveguides with low insertion losses*, Appl. Phys. Lett. **95**, 061105 (2009). — p.45.
- [24] C. J. Chen, J. Zheng, T. Gu, J. F. McMillan, M. Yu, G. Lo, D. Kwong, and C. W. Wong, *Selective tuning of high-Q silicon photonic crystal nanocavities via laser-assisted local oxydation*, Opt. Express **19**, 12480 (2011). — p.45.
- [25] F. Intonti, N. Caselli, S. Vignolini, F. Riboli, S. Kumar, A. Rastelli, O. G. Schmidt, M. Francardi, A. Gerardino, L. Balet, L. H. Li, A. Fiore, and M. Gurioli, *Mode tuning of photonic crystal nanocavities by photoinduced non-thermal oxidation*, Appl. Phys. Lett. **100**, (2012). — p.45.
- [26] H. S. Lee, S. Kiravittaya, S. Kumar, J. D. Plumhof, L. Balet, L. H. Li, M. Francardi, A. Gerardino, A. Fiore, A. Rastelli, and O. G. Schmidt, *Local tuning of photonic crystal nanocavity modes by laser-assisted oxidation*, Appl. Phys. Lett. **95**, 191109 (2009). — p.45.
- [27] H. Sekoguchi, Y. Takahashi, T. Asano, and S. Noda, *Photonic crystal nanocavity with a Q-factor of 9 million*, Opt. Express **22**, 916 (2014). — p.45.
- [28] A. F. Oskooi, D. Roundy, M. Ibanescu, P. Bermel, J. D. Joannopoulos, and S. G. Johnson, *Meep: A flexible free-software package for electromagnetic simulations by the FDTD method*, Comp. Phys. Comm. **181**, 687 (2010).

-
- p.47.
- [29] S. Sokolov, J. Lian, E. Yüce, S. Combrié, G. Lehoucq, A. De Rossi, and A. P. Mosk, *Local thermal resonance control of GaInP photonic crystal membrane cavities using ambient gas cooling*, Appl. Phys. Lett. **106**, 171113 (2015). — p.48.
- [30] J. Lian, S. Sokolov, E. Yüce, S. Combrié, A. De Rossi, and A. P. Mosk, *Measurement of the profiles of disorder-induced localized resonances by local tuning*, Opt. Express **24**, 21939 (2016). — p.48.
- [31] W. Heitler and F. London, *Wechselwirkung neutraler Atome und homöopolare Bindung nach der Quantenmechanik*, Z. Phys. **44**, 455 (1927). — p.50.
- [32] H. A. Haus and W. Huang, *Coupled-mode theory*, Proc. IEEE **79**, 1505 (1991). — p.50.
- [33] J. Joannopoulos, S. G. Johnson, J. N. Winn, and R. D. Meade, *Photonic crystals: Molding the flow of light* (Princeton University Press, Princeton, 2008). — p.50, 51.
- [34] M. C. F. Dobbelaar, S. Greveling, and D. van Oosten, *Large area photonic crystal cavities: a local density approach*, Opt. Express **23**, 7481 (2015). — p.51.
- [35] M. Notomi and H. Taniyama, *On-demand ultrahigh-Q cavity formation and photon pinning via dynamic waveguide tuning*, Opt. Express **16**, 18657 (2008). — p.51, 52.
- [36] E. Brion, L. H. Pedersen, and K. Mølmer, *Adiabatic Elimination in a Lambda System*, J. Phys. A **40**, 14 (2006). — p.52.
- [37] C. Cohen-Tannoudji, J. Dupont-Roc, and G. Grynberg, *Atom-photon interactions: Basic processes and applications* (Wiley-Interscience Publication, 1998). — p.52.

CHAPTER 6

Field programmable nanophotonic arrays with ancillary cavities

Parameters of nanophotonic circuits such as the coupling constant between nanocavities as well as loading to the input and output waveguides are defined at fabrication time. Here we propose a novel way to reversibly tune these parameters. Our method is based on ancillary cavities whose resonance frequency is detuned from the frequency of operation, acting as resonant enhancers, where the detuning is controlled by local laser heating. We experimentally show a change of the loading of a cavity to the waveguide by a factor of 3 and a change of the coupling constant between two cavities by a factor of 4.

6.1 Introduction

Nanophotonic circuits consisting of photonic crystal nanocavities attract a lot of attention due to the small size, scalable fabrication and high Q-factor of nanocavities [1, 2]. Circuits can be created due to the optical coupling between nanocavities induced by field overlap. One of the well known examples of such circuits are coupled-resonator optical waveguides or CROWs [3, 4]. The bandwidth of these devices is defined by the coupling constants between neighbor nanocavities, which are fixed by fabrication design of the structure [5–9]. Many applications require coupling constants to be tunable [10, 11]. Using side-cavities has been suggested as a way to change the group velocity of a CROW and even to stop light [12]. We propose a novel approach based on ancillary cavities [13–15] to tune key elements of nanophotonic circuits: coupling constant between nanocavities and coupling rate between a nanocavity and a photonic crystal waveguide. This represents an important step towards field programmable nanophotonic arrays (FPNAs).

In this chapter we experimentally demonstrate the use of ancillary nanocavities to achieve tunable coupling to other cavities and waveguides. Our experiments are supported by analytical and numerical calculations. In Section 6.2 we experimentally demonstrate the change of the loaded Q-factor [16] of a nanocavity. Further in Section 6.3 we demonstrate a tunable coupling rate between two nanocavities. After that in Section 6.4 we propose two types of tunable CROWs, where the tunable coupling constant results in bandwidth tunability. We derive

dispersion diagrams for those two cases, and theoretically study the transmission properties of tunable CROWs consisting of about 20 nanocavities.

6.2 Tuning of the coupling rate between nanocavity and waveguide

6.2.1 Mechanism of coupling rate tuning

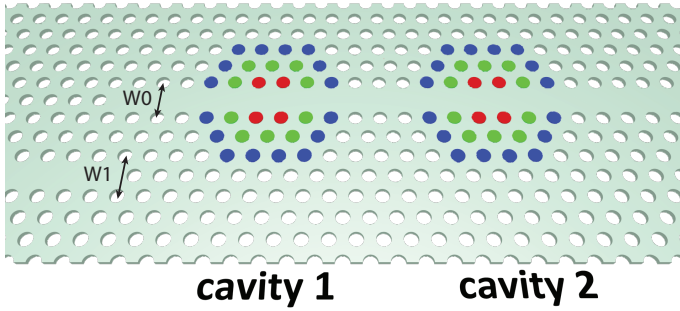


Figure 6.1: Layout of the sample. Two photonic crystal mode-gap cavities are made in a photonic crystal waveguide with width W_0 . Cavities are optically coupled and separated by distance $9a$. Cavity 1 is an ancillary cavity and it is coupled to the photonic crystal waveguide with width W_1 . Colored circles represent holes which were shifted to create a cavity.

To start with we consider an underlying mechanism of tuning of the coupling rate between photonic crystal cavity and the waveguide. The layout of the photonic crystal system required for that is presented in Figure 6.1. It consists of a waveguide with width W_1 coupled to two cavities. Cavity 1 is in turn is coupled to cavity 2 with coupling rate Γ_0 .

Cavity 1 here acts as an ancillary cavity which provides the coupling between the input waveguide and cavity 2. If the resonance frequency of cavity 1 (ω_1) is detuned far away from the frequency of cavity 2 (ω_2), so condition $|\omega_2 - \omega_1| \gg 0$ is valid, then the cavity 1 can be eliminated from the system resulting in the new coupling rate γ' between cavity 2 and waveguide with width W_1 . This concept is well known in atomic physics as adiabatic elimination [17, 18]. Assuming that intrinsic losses of cavities as well as coupling rate of the second cavity to the waveguide are small in comparison to the load of the first cavity to the waveguide, it can be shown (see section 6.A.1 for complete analytical description) that cavity 2 will have an effective coupling rate to the waveguide γ' :

$$\gamma' = \frac{\Gamma_0^2 \gamma_1}{(\omega_2 - \omega_1)^2} \quad (6.1)$$

The effective coupling rate γ' scales as $1/(\omega_2 - \omega_1)^2$. Hence it follows that by changing the resonance frequency of cavity 1 a change of the load of the cavity 2 to

the waveguide happens. This is equivalent also to changing the effective Q-factor of the cavity, because it is related to γ' as $Q' = \frac{\omega_2'}{2\gamma'}$, where ω_2 is an effective resonance frequency of cavity 2. This approach can be used, for instance, for tunable filters and CROW apodization where changing of the load is required [19–21].

6.2.2 Experimental observation

To observe the above described effect, we perform experiments on a nanophotonic sample consisting of two coupled mode-gap photonic crystal nanocavities [22] which are in turn coupled to the photonic crystal waveguide, as it is shown in Figure 6.1. The period of the photonic crystal waveguide is $a = 485$ nm. The sample is an air-suspended membrane made of $\text{Ga}_{0.51}\text{In}_{0.49}\text{P}$ with thickness $h = 180$ nm. The intercavity distance is $9a$. The setup scheme can be found in Section 5.2 of the Chapter 5. Each cavity has a certain intrinsic loss rate due to out-of-plane scattering, therefore light can be coupled into the system via that loss channel. For these experiments the IR laser was focused out-of-plane on cavity 2 and its position was optimized to maximize the output at the resonance wavelength of the cavity 2. The output was measured by a lensed fiber with the $\text{NA}=0.55$ coupled to the waveguide. The typical output spectrum of the system is shown in Figure 6.2. Two resonances of cavity 1 and 2 are presented.

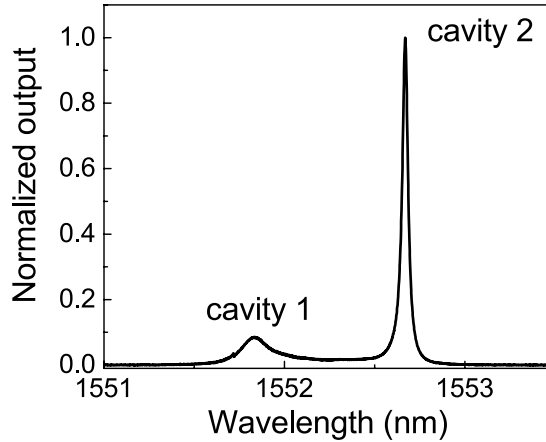


Figure 6.2: Reference spectrum. Normalized output spectrum of 2-cavity system. IR light is coupled to cavity 2. No pump power is applied.

Next, blue (405 nm) and red (605 nm) lasers were used to detune cavities 1 and 2 in and out of the hybridized state. For each experiment only one pump laser was used and it was focused on one single cavity at a time to detune one of the cavities. In Figure 6.3 we show the full width at half maximum (FWHM) of the resonance of the cavity 2 versus the separation of the resonances induced

by the pump. The data were averaged over multiple experiments and binned to estimate errors.

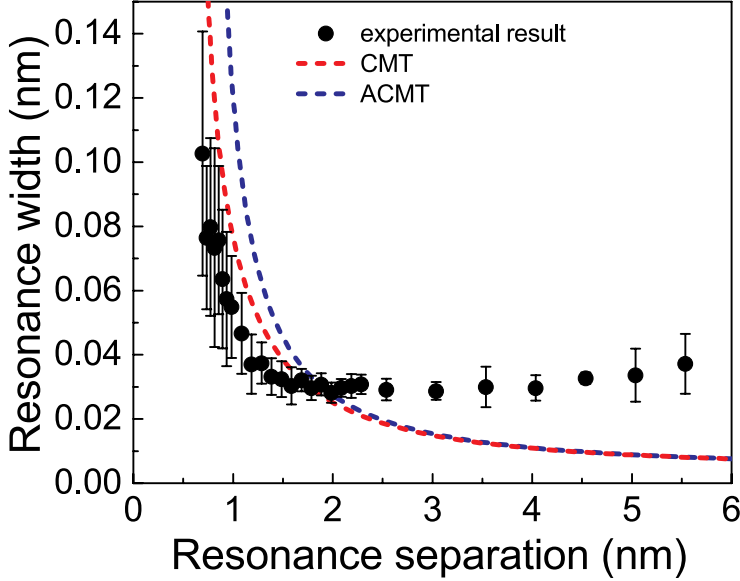


Figure 6.3: Width of the resonance of cavity 2. Dependence of the width of the resonance of the cavity 2 on the wavelength difference between resonances of the cavity 1 and 2.

When the detuning between the resonances increases, the width of the resonance of the cavity 2 decreases to a minimum of about 30 pm which occurs at about 3 nm of resonance separation. Beyond this value the width rises slowly. This rise is not explained by formula 6.1. We attribute it to two experimental factors: in case of cavity 2 being detuned it mostly corresponds to the line broadening due to fluctuations of the pump power. In case of cavity 1 being detuned it appears due to the interaction between cavity 2 and random modes [23–27] which are located close to the band edge of the carrier waveguide. These random modes increase the load of the cavity 2 through the same coupling process where the random mode acts like an ancillary cavity. Since the FWHM of cavity 2 provides a measure of its tuned Q -factor Q' , we conclude that we experimentally changed the Q -factor by more than a factor of 3.

We experimentally obtain essential system parameters (see section 6.A.2) and plot the full theoretical dependence of the coupling constant as well as the adiabatic approximation using coupled mode theory [28] (see section 6.A.1). This theory does not take into account pump noise and auxiliary linker resonances. The result is presented in Figure 6.3 with dashed lines. Two dependencies are shown: one for full coupled mode theory (CMT) and one for adiabatically eliminated theory (ACMT). The CMT dependence has a similar behavior to experimental data, except that it continues to decay for large resonance separations.

At large detunings ACMT and CMT dependencies overlap completely and at small detunings the adiabatically eliminated model diverges, which signifies that the adiabatic approximation is only valid for $|\omega_2 - \omega_1| \gg 0$. When resonances are separated spectrally by more than 2 nm, the deviation between two theories becomes less than 10%.

6.3 Tuning of the coupling constant between two nanocavities

6.3.1 Mechanism of coupling constant tuning

The same principle as used in Section 6.2 can be applied to systems of nanocavities to introduce the effective coupling constant between any two cavities. We consider the system presented in Figure 6.4. It consists of 3 nanocavities which are directly coupled to their nearest neighbors via the coupling constant Γ_1 and Γ_2 . Cavity 1 is also coupled to the input waveguide with width W_1 with coupling rate γ_1 .

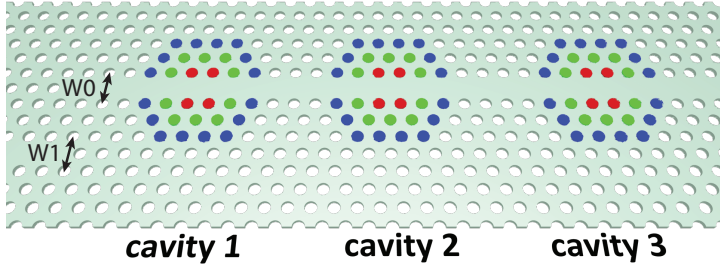


Figure 6.4: Schematic of the sample. System consists of three nanocavities where cavity 1 is directly coupled to cavity 2, cavity 2 is directly coupled to cavity 3 and cavity 1 is coupled to the photonic crystal waveguide used to measure transmission. Different colors for holes correspond to different shifts used to create a cavity mode.

Cavity 2 here acts as the ancillary cavity because it provides coupling between cavities 1 and 3. If ω_0 is the bare frequency of cavities 1 and 3, and ω_2 is the bare frequency of cavity 2 then for large detuning of cavity 2 from cavities 1 and 3, meaning that $|\omega_0 - \omega_2| \gg 0$, cavity 2 can be eliminated which results in the effective coupling constant Γ' between cavity 1 and 3. Assuming the absence of second nearest neighbor coupling and no intrinsic loss we find (see section 6.A.3 for complete analytical description):

$$\Gamma' = \frac{\Gamma_1 \Gamma_2}{\omega_0 - \omega_2} \quad (6.2)$$

The new coupling constant Γ' scales inversely with the detuning of the ancillary cavity. If one is able to manipulate independently the frequencies of different

nanocavities, then it is possible to create tunable CROWs where bandwidth and group velocity can be dynamically tuned.

6.3.2 Experimental observation

To experimentally observe tuning of the coupling constant we consider a system of three directly coupled photonic crystal mode-gap nanocavities. The scheme of the sample used for this experiment is presented in Figure 6.4. The sample consists of a membrane with triangular photonic crystal lattice with a period $a = 485$ nm. The thickness of the membrane $h = 180$ nm. Three mode-gap nanocavities [2, 29] are made in a photonic crystal waveguide with the width $W_0 = 0.98\sqrt{3}$. The center-to-center separations between cavities 1-2 and 2-3 are $9a$ and $10a$. The hole shifts which define the cavities are $0.0124a$, $0.0083a$ and $0.0041a$ for red, green and blue holes in Figure 6.4. The first cavity is coupled to the second photonic crystal waveguide with the width $W_1 = 1.1\sqrt{3}a$. This waveguide is used for transmission measurements while IR light is coupled to one of the nanocavities. The setup scheme is depicted in Figure 5.1b of the Chapter 5.

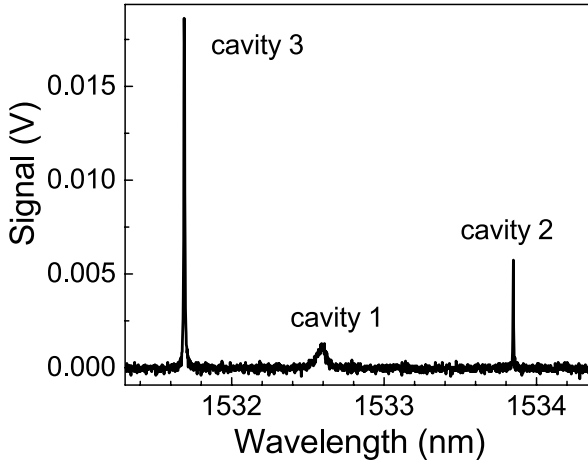


Figure 6.5: Reference output spectrum. Transmission spectrum of the sample when IR light is out-of-plane coupled to cavity 3. No pump power is applied.

The reference output spectrum of the sample when no pump power is applied is presented in Figure 6.5. The IR light was coupled out-of-plane to cavity 3, which allows to see all resonances at the same time. Cavity 2 is redshifted from cavity 1 and 3 by more than 1 nm due to the disorder induced by fabrication imperfections. To obtain results at detuning $\gtrsim 1.5$ nm, we pumped cavity 2 to redshift it further. Conversely, for results at lower detunings we pumped cavities 1 and 3 to shift them closer to cavity 2. For all the measurements the power of the red light (P_r) was fixed, while the power of the violet light (P_v) was varied.

Experimentally measured anticrossings are presented in Figure 6.6. To measure anticrossings of cavities 1 and 3 the IR probe light was coupled to cavity 1. In Figure 6.6a we pump cavities 1 and 3 to reduce the effective detuning. Cavity 3 anticrosses first with cavity 1 at about $P_v = 75 \mu\text{W}$ having anticrossing width of 0.154 nm and then at higher power $P_v \approx 90 \mu\text{W}$ it anticrosses with cavity 2. The resonances can be attributed to specific cavities away from the anticrossings by considering the slopes of the resonance lines in the plot. For Figures **b,c,d** cavity 2 is detuned by pumping it. As a result its resonance is outside the range of the plot. Detuning increases from figure **b** to **d**. Anticrossing widths between cavities 1 and 3 are equal to 0.109 nm, 0.135 nm and 0.338 nm respectively. We see that increasing the detuning decreases the anticrossing width from 0.154 to 0.109 nm, but then surprisingly at the highest power we observe an increase up to 0.338 nm. This is contradictory to the dependence which follows from equation 6.2, which predicts a monotonous decrease.

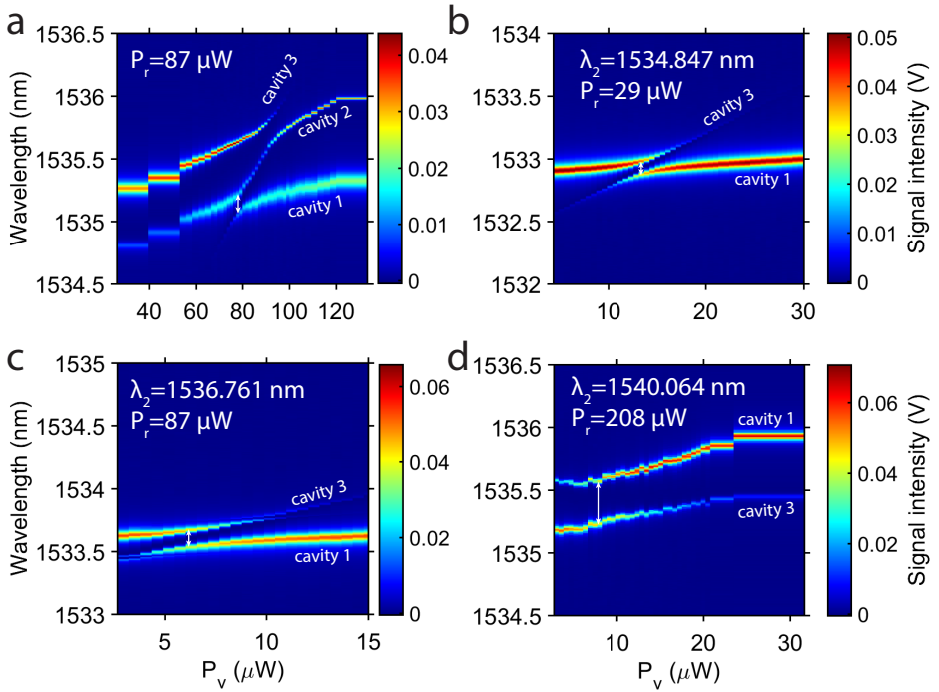


Figure 6.6: Anticrossing of resonances of cavities 1 and 3 for selected pump powers **a** -The anticrossing for small detuning of cavity 2. Red pump was placed on cavity 1 and violet pump was placed on cavity 3. **b,c,d** - Anticrossings for large detunings of cavity 2. Red pump is placed on cavity 2. In cases **b,c** violet pump is on cavity 3, and for **d** it is on cavity 1. White arrow indicates position and width of the anticrossing. IR light is coupled to the cavity 1 for all spectra.

We performed anticrossing measurements for a large number of detunings of cavity 2 and the final result is presented in Figure 6.7. It shows dependence of anticrossing width between cavities 1 and 3 ($\Delta\lambda_{13}$) on detuning of the cavity 2 from the center wavelength of the anticrossing ($\Delta\lambda_2$). For small detunings the anticrossing width decreases as predicted by coupled-mode theory (see red dashed line in Figure 6.7), but for $\Delta\lambda_2 \gtrsim 0.7$ nm the dependence deviates and reaches a minimum at about 1.5 nm of detuning. After that anticrossing width rises and reaches a value close to 400 nm for detunings of about 5 nm. Parameters for coupled-mode theory were obtained experimentally as described in Section 6.A.4. By defining the coupling constant from the anticrossing width as $\Gamma_{13} = \Delta\omega_{13}/2$ we conclude that experimentally we increased the coupling constant by a factor of 4 relative to the minimum value.

We conclude that tuning of the coupling constant is achieved, while there is a significant discrepancy between the experimental data and the simple coupled mode theory model at large detunings. In the experiment larger detunings correspond to larger pump powers which in turn may influence the structure as described in Chapter 5. To explain the observed deviation we perform numerical simulations on a system of 3 coupled cavities.

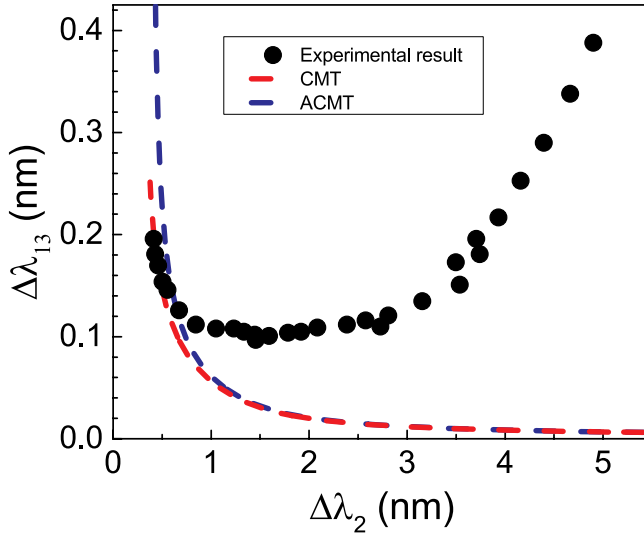


Figure 6.7: Anticrossing width between cavity 1 and 3 versus detuning of cavity 2. Black squares represent experimental data. Dashed lines show analytic theory plot for full and adiabatic coupled-mode theory implementations.

6.3.3 Numerical simulation of the experiment

To understand the nature of observed discrepancy between the experiment and coupled mode theory we perform a 2D FDTD simulation of a system comparable to the experimental one using the open source MEEP package [30].

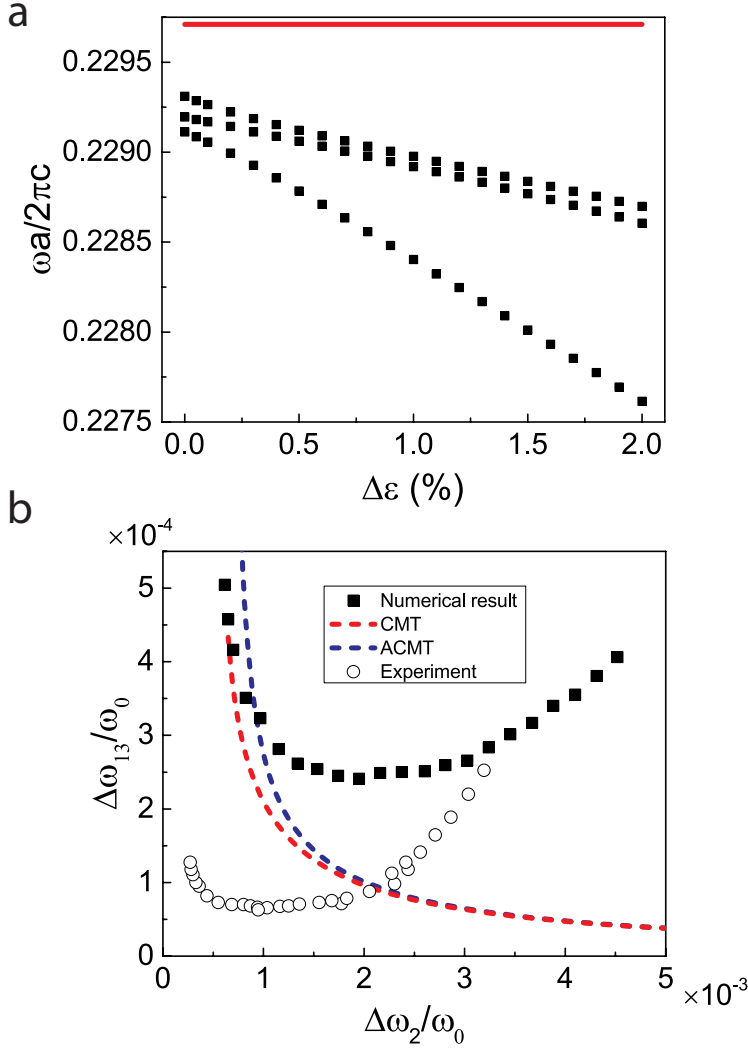


Figure 6.8: Numerical results. **a** - Resonances frequencies of a system of 3 coupled cavities versus perturbation magnitude applied to the cavity 2. The unperturbed band edge frequency of the waveguide W_0 is shown with red line. **b** - Separation between two high-frequency resonances versus detuning of the ancillary cavity from the center frequency of the hybridized cavities. Experiment is also plotted for comparison.

We setup a system which consists of a photonic crystal waveguide with 8 rows of holes on each side of the waveguide and has a length of $87a$. We create 3 mode-gap cavities in the center of the structure, each cavity is separated by $9a$ distance from the neighboring one. This is slightly different from the experiment where distances between cavities were not equal, but it is easier to carry out numerically. Another difference is that in our simulation we start with identical

cavities, which are not perturbed by disorder, therefore in the absence of pump resonances are fully hybridized. This arrangement avoids the need for scans of the detuning between cavities 1 and 3 and thus reduces numerical effort by an order of magnitude. Other cavity and waveguide parameters are kept the same as in the experiment. We induce a perturbation of the dielectric function which models the temperature profile resulting from the pump which is placed on top of cavity 2. The perturbation is the same as presented in Figure 5.4 of Chapter 5. We vary the magnitude of the perturbation and calculate resonance frequencies for the hybridized modes.

The resulting frequencies of hybridized modes are plotted in Figure 6.8a. At zero perturbation resonances of three cavities are fully hybridized. Splitting is not symmetric due to the dispersion in the coupling constant [31]. With increase of the perturbation magnitude the low-frequency resonance becomes localized on cavity 2 and shifts faster. The other two resonances start to approach each other which continues to perturbation level of about 1%, after which splitting increases gradually. In Figure 6.8b we plot together the numerical and experimental result from Figure 6.7 for comparison. We plot the frequency difference between two high-frequency resonances $\Delta\omega_{13}$ on the detuning between resonance of the cavity 2 and anticrossing frequency ($\Delta\omega_2$). Even though our 2D numerical result cannot be directly compared to the experimental one due to differences in considered systems and pump spots, they show very similar behavior, where at small detuning the anticrossing width shrinks and rises at large detunings. This signifies that the observed behavior is universal for the system of 3 coupled cavities where second cavity is thermally detuned. The increase of the anticrossing width between resonances of cavity 1 and 3 corresponds to the increase of the coupling between these two cavities. This additional coupling is provided by the fact that mode-profiles of cavities 1 and 3 shift towards the pump position as it is described in Section 5.5. As a result, the direct coupling constants Γ_{12} and Γ_{23} become pump dependent and increase with pump power. At high pump powers the increase of the direct coupling in the numerator of Eq. 6.2 overtakes the increase of the denominator and the effective coupling increases.

6.4 Proposed tunable CROW structures

Experimentally as well as theoretically we have shown that an ancillary cavity can be used to tune coupling constant between two cavities as well as the coupling constant between a cavity and the waveguide. Tunability of the coupling constant between two cavities immediately opens a way towards tunable bandwidth devices. Several simple schemes of such devices are considered in this section. We address their bandwidth and transmission properties both analytically and numerically.

6.4.1 Band structure properties

To show the tunable bandwidth we consider infinite arrays of photonic crystal nanocavities where certain frequency shifts are applied to particular nanocavities

to achieve conditions of adiabatic elimination. We assume here the absence of second nearest neighbor coupling between resonators.

6.4.1.1 2-frequency structure

The schematic representation of the first structure is presented in Figure 6.9. For simplicity every cavity is coupled to its neighbor with the same coupling constant Γ_0 . Every odd cavity has a frequency ω_0 , but every even cavity is frequency-shifted and has a frequency ω' . The period of this structure is therefore $2R$, where R is the distance between two nanocavities.

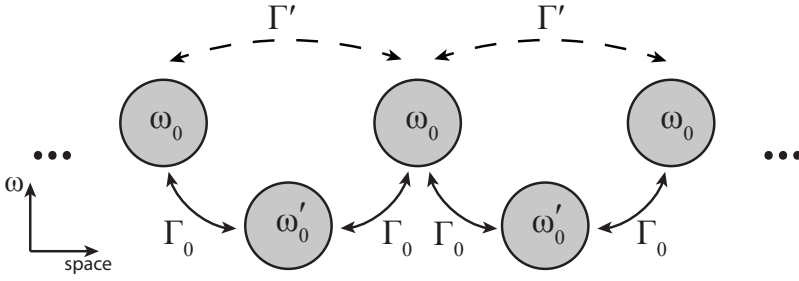


Figure 6.9: Structure of the 2-frequency infinite cavity chain. Every second cavity in the structure is frequency shifted and has a frequency of ω'_0 . These cavities are adiabatically eliminated which results in effective coupling constants Γ' between cavities with frequencies ω_0 . Every gray circle here represents a nanocavity.

When operating at the frequency of the odd cavities, we can view the even cavities as ancillaries and vice versa, therefore the system in Figure 6.9 can be represented with the following system of coupled-mode equations, where $\Delta\omega = \omega_0 - \omega'$:

$$\begin{cases} \frac{da_n}{dt} = i(\omega_0 + \frac{\Gamma_0^2}{\Delta\omega})a_n + i\frac{\Gamma_0^2}{\Delta\omega}a_{n-2} + i\frac{\Gamma_0^2}{\Delta\omega}a_{n+2} \\ \frac{da'_n}{dt} = i(\omega'_0 - \frac{\Gamma_0^2}{\Delta\omega})a'_n - i\frac{\Gamma_0^2}{\Delta\omega}a'_{n-2} - i\frac{\Gamma_0^2}{\Delta\omega}a'_{n+2} \end{cases} \quad (6.3)$$

Using Born-von Karman periodic boundary conditions the band structure can be obtained [32], assuming that a chain of N cavities with adiabatically eliminated coupling is considered where $a_N = a_0$, $a_n \propto e^{i(\omega t - kn2R)}$ and $e^{-ikN2R} = 1$, where k is a Bloch wavevector:

$$\begin{cases} \omega = \omega_0 + 2\Gamma' + 2\Gamma' \cos(2kR) \\ \omega = \omega_0 - \Delta\omega_0 - 2\Gamma' - 2\Gamma' \cos(2kR) \end{cases} \quad (6.4)$$

Here $\Gamma' = \Gamma_0^2/\Delta\omega$ with $\Gamma_0 = 0.0002\omega_0$ and $\Delta\omega$ take values $0.003\omega_0$ and $0.006\omega_0$ the band structure is presented in Figure 6.10. In this structure two bands are present, where the first band appears close to the frequency ω_0 with a band-edge

fixed at ω_0 and second band is close to ω'_0 with a band edge fixed at $\omega_0 - \Delta\omega_0$. Changing the detuning tunes the bandwidth and dispersion.

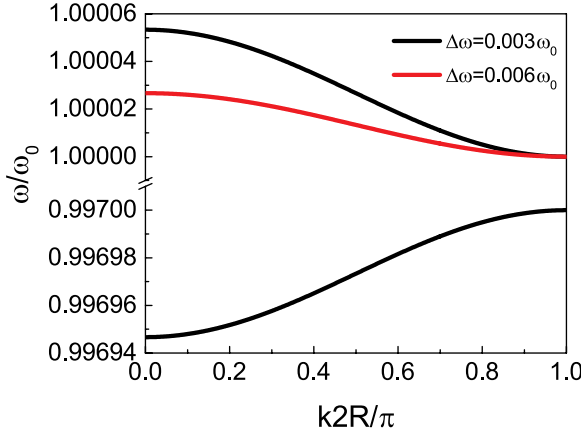


Figure 6.10: Band diagram of the 2-frequency adiabatically eliminated cavity chain. The coupling constant $\Gamma_0 = 0.0002\omega_0$ and the detuning is equal to $0.003\omega_0$ (black) and $0.006\omega_0$ (red), so every second cavity is redshifted. The band structure consists of two bands where low-frequency band shifts according to detuning of every second cavity.

To show that above described tuning of the bandwidth works on real structures we perform a 2D numerical experiment. We use the MPB plane-wave expansion package [33] to calculate the band structure of a cavity chain. As a system for numerical modeling we make a model structure consisting of point defect cavities made in a hexagonal photonic crystal made of dielectric rods placed in air. The refractive index of the material is equal to 3.17. This structure is known to have a TM-bandgap [34], therefore the radius of the cylinder of the photonic crystal lattice is chosen to be $0.18a$, where a is a period of the lattice, to maximize the bandgap. The point defect cavity is created by decreasing the diameter of a single cylinder to $0.08a$ to obtain a single monopole cavity mode away from the band edge. The studied system has a size of 6 periods along the CROW direction and 24 periods in the perpendicular direction. The spacing between 2 neighbor cavities is $3a$. For such spacing the second nearest neighbor coupling is more than 50 times smaller than nearest neighbor coupling as calculated by Bloch method [21]. The truncated super-cell used for calculations is presented in Figure 6.11a.

We induce the frequency shift of every second cavity by changing the dielectric constant of the point defect (ε') which represents thermal or free-carrier tuning. In this case we blue-shift every second cavity to push the resonance away from the photonic crystal band edge, therefore the second band will blueshift (in contrast to Figure 6.10). Field maps of these CROW bands for $k = 0$ in case of $\varepsilon' = 0.3\varepsilon$ are presented in Figure 6.11b,c. In case of low-frequency band the E_z field resides mostly in the left cavity while for high-frequency one it is in the

second cavity. The smaller the difference between first and second cavity the stronger the field in neighbor cavity, as it is shown in Figure 6.11d. This follows from the equation 6.16.

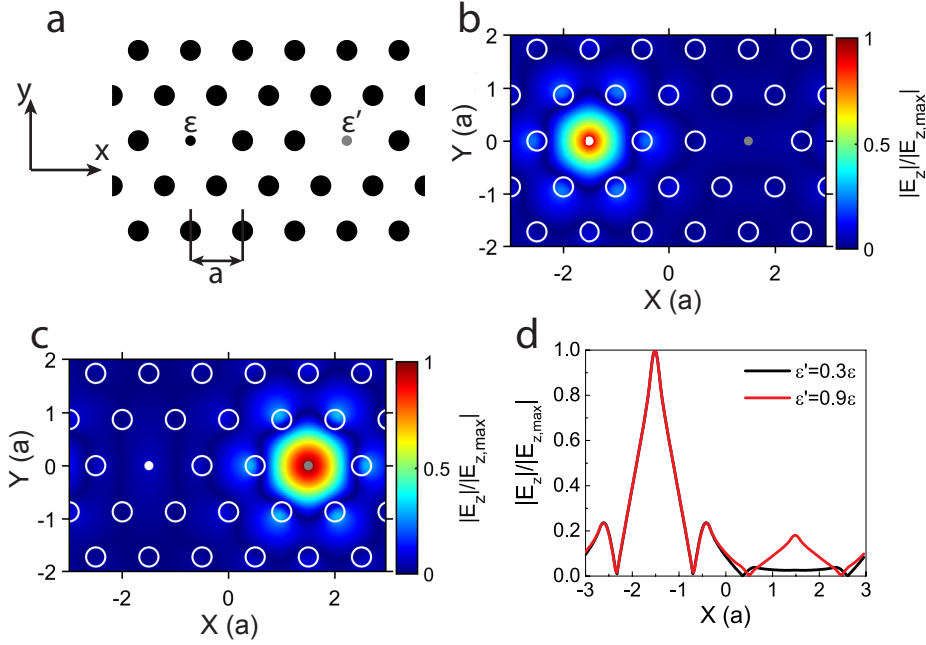


Figure 6.11: Calculational supercell and E_z field amplitudes for CROW bands. a - Supercell for calculation. The picture is truncated in the y direction for convenience. Each black circle represents a pillar with refractive index 3.17. The gray circle represents a cylinder whose permittivity was varied. Two cavities are created by local hole size modulation and separated by a distance of $3a$. b,c - normalized amplitudes of E_z field of CROW mods at $k = 0$. b,c - correspond to low and high frequency bands where the second cavity is made of a pillar with permittivity 0.3ϵ . d - crosssections of E_z field along the x axis for low frequency band where $\epsilon' = 0.3\epsilon$ and $\epsilon' = 0.9\epsilon$.

The complete band diagrams are presented in Figure 6.12a,b. The low-frequency band is shown for 3 different ϵ' . Decreasing the ϵ' results in increase of the frequency difference which shrinks the bandwidth. For convenience we show only one high-frequency band for $\epsilon' = 0.3\epsilon$. All bands can be fitted with cosine dependencies which represent the shape of the band derived for the case of adiabatic elimination (see equations 6.4).

In conclusion, the numerical calculations confirm that this two-frequency structure allows tuning of the dispersion.

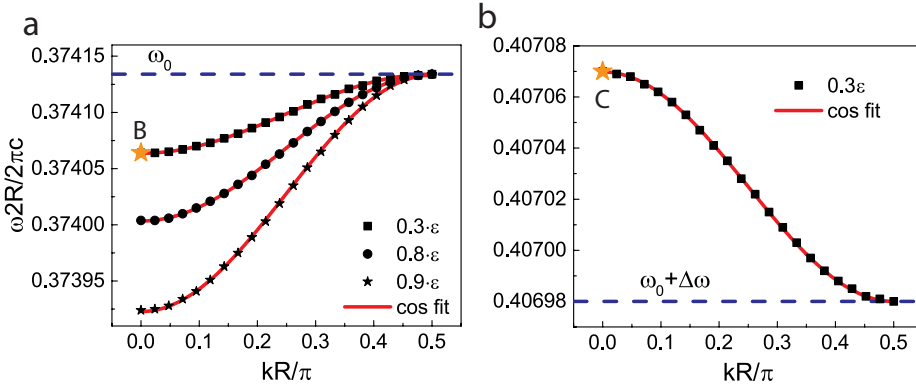


Figure 6.12: Numerically calculated CROW bands. **a** - Low frequency band for ϵ' values of 0.3ϵ , 0.8ϵ and 0.9ϵ . **b** - high frequency band for the case $\epsilon' = 0.3\epsilon$. Discrete points represent the calculated result, red lines represent cosine fits. Stars with letters represent data points for which the field is plotted in Fig. 6.11.

6.4.1.2 3-frequency structure

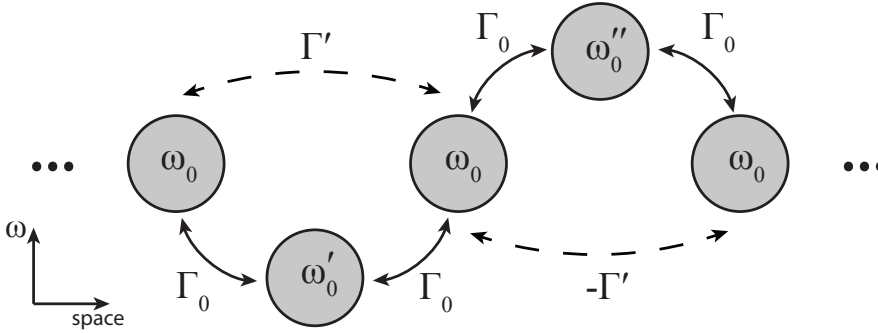


Figure 6.13: Structure of the 3-frequency adiabatically eliminated CROW. Each cavity is coupled to its neighbor by coupling constant Γ_0 . Every second cavity is frequency shifted by $-\Delta\omega$, while every forth cavity is symmetrically shifted by $\Delta\omega$. Every gray circle here represents a nanocavity.

More symmetric system is presented in Figure 6.13. This structure has 3 frequency involved in the adiabatic elimination scheme. Every second cavity here is shifted by $\Delta\omega$ and every forth cavity is shifted by $-\Delta\omega$. The coupled-mode

equations for such system will look like:

$$\begin{cases} \frac{da_n}{dt} = i\omega_0 a_n + i\frac{\Gamma_0^2}{\Delta\omega} a_{n-2} - i\frac{\Gamma_0^2}{\Delta\omega} a_{n+2} \\ \frac{da_{n+2}}{dt} = i\omega_0 a_{n+2} + i\frac{\Gamma_0^2}{\Delta\omega} a_{n+4} - i\frac{\Gamma_0^2}{\Delta\omega} a_n \end{cases} \quad (6.5)$$

This system is comparable to the atomic chain with two atoms per primitive cell [32]. In our case there are two cavities in the primitive cell coupled with coupling constant $-\Gamma'$ while each primitive cell is coupled to another one with coupling constant Γ' . The periodicity of the system is $4R$. Applying Born-von Karman periodic boundary conditions gives equation for the band structure of the 3-frequency CROW:

$$\omega = \omega_0 \pm 2\Gamma' |\sin 2kR| \quad (6.6)$$

The band is completely symmetric with the center at ω_0 , unlike in the 2-frequency case where the center of both bands shifts with change of detuning. We plot the band structure for two detunings $0.003\omega_0$ and $0.006\omega_0$ in figure 6.14.

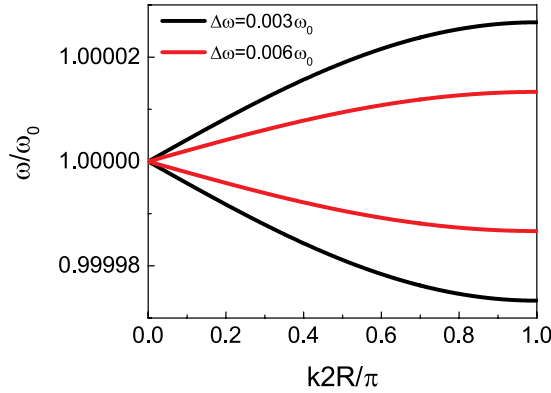


Figure 6.14: Band diagram of the 3-frequency cavity chain. The coupling constant $\Gamma_0 = 0.0002\omega_0$ and the detuning is equal to $0.003\omega_0$ (black curve) and $0.006\omega_0$ (red curve).

6.4.2 Transmission properties of finite crows with tunable coupling strength

In this section we calculate transmission properties of the tunable crow structures that were proposed in previous section.

6.4.2.1 2-frequency structure

To start with we consider the 2-frequency structure. We choose a cavity array consisting of $N = 19$ nanocavities where every second cavity is redshifted. This

results in an effective array of 10 cavities which are coupled with tunable coupling constants as shown of Figure 6.9. The first and the last cavity are coupled to input and output waveguides correspondingly as shown in Figure 6.17a. We choose structure parameters $\Gamma_0 = 0.0002\omega_0$ and $\gamma_1 = 4.5 \cdot 10^{-5}\omega_0$ and bare cavity wavelength of 1550 nm, which are typical for mode-gap nanocavities used in our work [20]. This system is described with the following coupled mode-equations, here $j \in [0, (N - 5)/2]$:

$$\left\{ \begin{array}{l} S_{1-} = -1 + \sqrt{2\gamma_1}a_1 \\ \frac{da_1}{dt} = i(\omega_0 + \Gamma')a_1 + i\Gamma'a_3 - \gamma_1a_1 + \sqrt{2\gamma_1} \\ \frac{da_{2j+3}}{dt} = i(\omega_0 + 2\Gamma')a_{2j+3} + i\Gamma'a_{2j+1} + i\Gamma'a_{2j+5} \\ \frac{da_N}{dt} = i(\omega_0 + \Gamma')a_N + i\Gamma'a_3 - \gamma_1a_{N-2} - \gamma_1a_N \\ S_{2-} = \sqrt{2\gamma_1}a_1 \end{array} \right. \quad (6.7)$$

We plot the transmission spectra for detunings of $0.001\omega_0$ (1.55 nm) and $0.002\omega_0$ (3.1 nm) in Figure 6.15 as calculated from the full coupled mode equations as well as by adiabatically eliminated one. Even though the adiabatically eliminated curve does not completely reproduce the spectrum produced by full CMT there is a bandwidth change in both cases. In general as it was mentioned before, the bigger the detuning the bigger the similarity between two models, as it is seen by comparing Figures a and b.

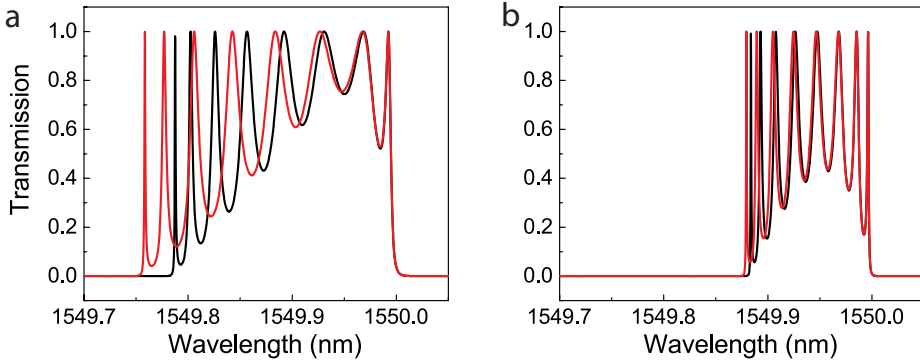


Figure 6.15: Transmission spectra for 2-frequency CROW. CROW consists of 19 cavities. Black curves represent full coupled-mode theory, red ones - adiabatically eliminated one. **a** - detuning 1.55 nm. **b** - detuning 3.1 nm.

6.4.2.2 3-frequency structure

In case of 3-frequency CROW we consider an array of 21 cavities for symmetry reasons. The rest of the CROW parameters are kept the same. Such CROW

system can be also described with coupled-mode equations, where $j_1 \in [0, (N - 5)/4]$ and $j_2 \in [1, (N - 5)/4]$:

$$\left\{ \begin{array}{l} S_{1-} = -1 + \sqrt{2\gamma_1} a_1 \\ \frac{da_1}{dt} = i(\omega_0 + \Gamma') a_1 + i\Gamma' a_3 - \gamma_1 a_1 + \sqrt{2\gamma_1} \\ \frac{da_{4j_1+3}}{dt} = i\omega_0 a_{4j_1+3} + i\Gamma' a_{4j_1+1} - i\Gamma' a_{4j_1+5} \\ \frac{da_{4j_2+1}}{dt} = i\omega_0 a_{4j_2+1} - i\Gamma' a_{4j_2-1} + i\Gamma' a_{4j_2+3} \\ \frac{da_N}{dt} = i(\omega_0 - \Gamma') a_N + i\Gamma' a_{N-2} - \gamma_1 a_N \\ S_{2-} = \sqrt{2\gamma_1} a_1 \end{array} \right. \quad (6.8)$$

We consider the same detuning as used for Figure 6.15 and plot transmission spectra for 3-frequency case in Figure 6.16. The transmission spectra look completely symmetric and bandwidth tuning is observed in both models: full CMT and adiabatically eliminated one. At a detuning of 3.1 nm the adiabatically eliminated model completely reproduces the full model.

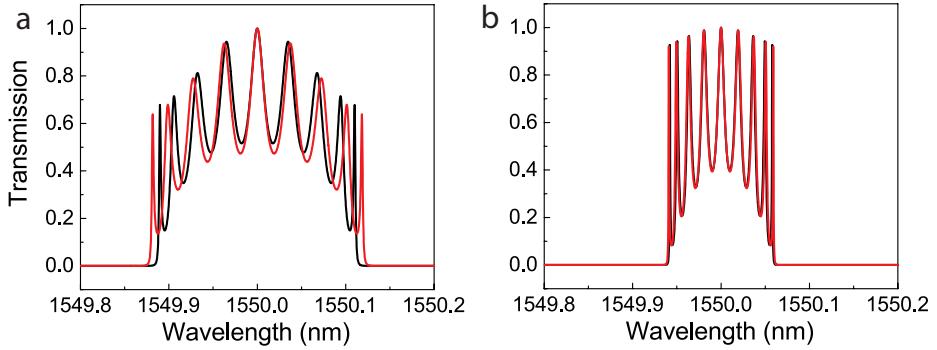


Figure 6.16: Transmission spectra for 2-frequency CROW. CROW consists of 19 cavities. Black curves represent full coupled-mode theory, red ones - adiabatically eliminated one. **a** - detuning 1.55 nm. **b** - detuning 3.1 nm.

6.5 Conclusion

In conclusion, photonic crystal nanocavity arrays with tunable coupling have been studied theoretically and implemented experimentally. We managed to experimentally change the Q-factor of a nanocavity by a factor of 3 by tuning an ancillary linker cavity which controls the load. We controlled the coherent coupling between two nanocavities by a factor of 4 by pumping an ancillary cavity in the middle. We observed a deviation from the coupled-mode model for large

detunings, which is attributed to pump-induced changes of the direct couplings. This result was reproduced in numerical calculations. We proposed 2 types of tunable bandwidth multi-cavity structures, containing one or two frequency-shifted cavities per unit cell. We derived their dispersion diagrams and investigated transmission properties using coupled-mode models. The results described in this Chapter can be easily extended to the time-dependent case, which opens the possibility of a time-dependent change of coupling parameters. Combining results from this Chapter and results from Chapter 4 allows one to achieve the full tunability of nanophotonic circuits where resonance wavelengths as well as coupling rates can be dynamically tuned.

6.A Appendix

6.A.1 Analytic description of tuning of the coupling rate between a nanocavity and a waveguide

The coupled-mode theory model is described in detail here. A visual representation of the model is presented on the Figure 6.17. It consists of a waveguide coupled to two cavities via coupling rates γ_1 and γ_2 . Cavities have bare frequencies ω_1 and ω_2 , and they are inter-coupled with coupling rate Γ_0 .

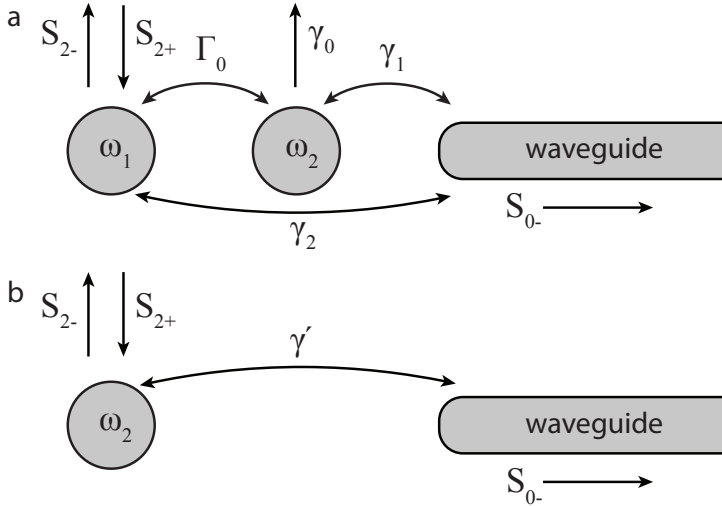


Figure 6.17: Two-cavity system for adiabatic elimination. **a** - A photonic crystal waveguide is coupled to two photonic crystal nanocavities which are coupled among themselves. Light is coupled into cavity 2 and out-coupled via the waveguide. Cavity 1 is the ancillary cavity. **b** - Adiabatically eliminated system, cavity 1 is eliminated resulting in a coupling rate of γ' between photonic crystal nanocavity 2 and the waveguide. Each gray circle represents a nanocavity.

When light is launched from out-of-plane this system can be represented by

the following system of 4 temporal coupled-mode equations [28, 35]:

$$\begin{cases} \frac{da_1}{dt} = i\omega_1 a_1 + i\Gamma_0 a_2 - (\gamma_1 + \gamma_0) a_1 - \sqrt{\gamma_1 \gamma_2} a_2 \\ \frac{da_2}{dt} = i\omega_2 a_2 + i\Gamma_0 a_1 - (\gamma_2 + \gamma'_0) a_2 - \sqrt{\gamma_1 \gamma_2} a_1 + \sqrt{2\gamma_0} S_{2+} \\ S_{0-} = \sqrt{2\gamma_1} a_1 + \sqrt{2\gamma_2} a_2 \\ S_{2-} = -S_{2+} + \sqrt{2\gamma'_0} a_2 \end{cases} \quad (6.9)$$

Where a_1 and a_2 are field amplitude in the cavities 1 and 2. Further, γ_0 and γ'_0 represent the intrinsic loss rate of cavity 1 and 2, S_{0-} is the amplitude of the mode in the waveguide which propagates away from the cavity, S_{2+} is amplitude of the free-space mode coupled into the cavity and S_{2-} represents intrinsic loss. Terms proportional to $\sqrt{\gamma_1 \gamma_2}$ correspond to the coupling induced between cavities by the presence of the waveguide.

If cavity 1 is detuned far away from cavity 2, then it is possible to simplify the system of equations 6.9 and eliminate the equation that describes the time evolution of the amplitude a_1 in the first cavity. To perform this adiabatic elimination one has to switch to a rotation frame which rotates with the frequency ω_2 , so $a' = a \cdot e^{-i\omega_2 t}$, and set $da'_1/dt = 0$, where a and a' represent field amplitudes in laboratory and rotation frames correspondingly. Eventually this leads to the following simplified system of 3 equations:

$$\begin{cases} \frac{da_2}{dt} = i\omega'_2 a_2 - \gamma' a_2 - \gamma'_0 a_2 + \sqrt{2\gamma_0} S_{2+} \\ S_{0-} = \left(\frac{\sqrt{2\gamma_1}(i\Gamma_0 - \sqrt{\gamma_1 \gamma_2})}{i(\omega_2 - \omega_1) + \gamma_1 + \gamma_0} + \sqrt{2\gamma_2} \right) a_2 \\ S_{2-} = -S_{2+} + \sqrt{2\gamma'_0} a_2 \end{cases} \quad (6.10)$$

Where ω'_2 and γ' have the following form:

$$\omega'_2 = \omega_2 + \frac{(\omega_2 - \omega_1)\Gamma_0^2 - 2\Gamma_0(\gamma_1 + \gamma_0)\sqrt{\gamma_1 \gamma_2} - (\omega_2 - \omega_1)\gamma_1 \gamma_2}{(\gamma_1 + \gamma_0)^2 + (\omega_2 - \omega_1)^2} \quad (6.11)$$

$$\gamma' = \gamma_2 + \frac{\Gamma_0^2(\gamma_1 + \gamma_0) + 2\Gamma_0\sqrt{\gamma_1 \gamma_2}(\omega_2 - \omega_1) - \gamma_1 \gamma_2(\gamma_1 + \gamma_0)}{(\gamma_1 + \gamma_0)^2 + (\omega_2 - \omega_1)^2} \quad (6.12)$$

From the first equation of the system 6.10 one can see that the load of cavity 2 to the waveguide is determined by coupling rate γ' . In addition the resonance frequency ω'_2 of the cavity changes according to the formula 6.11. Assuming that $\gamma_0 = \gamma'_0 \approx 0$, $\gamma_2 \approx 0$, $|\omega_2 - \omega_1| \gg \gamma_1$, formulas 6.11 and 6.12 can be simplified to:

$$\omega'_2 = \omega_2 + \frac{\Gamma_0^2}{\omega_2 - \omega_1} \quad (6.13)$$

$$\gamma' = \frac{\Gamma_0^2 \gamma_1}{(\omega_2 - \omega_1)^2} \quad (6.14)$$

Both ω'_2 and γ' decay as a function of frequency detuning between cavity 1 and 2.

6.A.2 Determination of parameters for the system with tunable load to the waveguide

The experimental loading rate γ_1 is obtained by placing the IR probe spot on cavity 1. Simultaneously the red pump focus with a power of $319 \mu\text{W}$ was placed on cavity 1 to detune it from cavity 2 by more than 5 nm . The resulting spectra can be found in Figure 6.18a. The coupling rate then is obtained from the cavity Q-factor, where $Q = \frac{\omega_0}{2\gamma_1}$, assuming that the intrinsic loss can be neglected, and it is equal to $\gamma_1 = 1.23 \pm 0.07 \cdot 10^{-4} \omega_0$. The unloaded Q-factor of our mode-gap cavities as well as the loaded Q-factor of the second cavity is $> 10^6$ according to our 3D FDTD calculations. We evaluate our theory for parameters $\gamma_0 = \gamma_2 = 0.5 \cdot 10^{-6} \omega_0$, noting that the results do not depend on the exact values. The bare coupling constant between the nanocavities is determined from the experimentally measured anticrossing width between nanocavities. The anticrossing is presented in Figure 6.18b. The coupling constant is equal to $\Gamma_0 = 2.41 \pm 0.02 \cdot 10^{-4} \omega_0$.

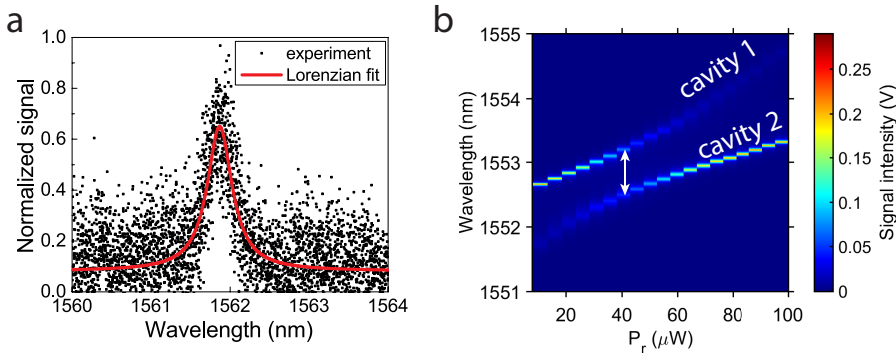


Figure 6.18: Determination of structural parameters. **a-** Resonance of the cavity 1 detuned away from the rest of the resonances. **b-** Anticrossing of resonances of cavity 1 and 2. Red pump spot is placed on cavity 1.

6.A.3 Analytic description of tuning of the coupling constant between two nanocavities

The model of two nanocavities coupled via an ancillary cavity is described in detail here. A visualization of the model is presented in Figure 6.19. It has 3 nanocavities coupled with coupling constants Γ_1 and Γ_2 . Cavities 1 and 2 are in resonance and their bare frequencies are equal to ω_0 , while cavity 2 is shifted to frequency ω_2 . This system can be represented as the system with 2 cavities which consists of a cavity 1 and cavity 3 coupled with coupling constant Γ' which appears as result of a presence of the ancillary cavity 2.

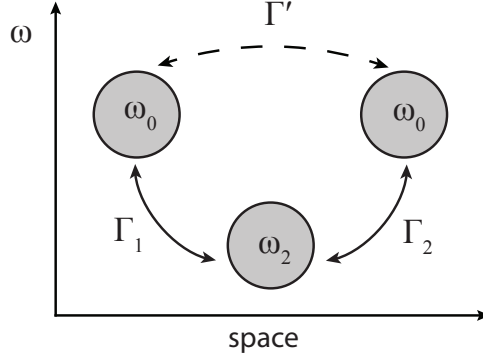


Figure 6.19: Adiabatic elimination scheme for coupling constant between two cavities. Cavity 1 and 3 have same frequencies while cavity 2 is redshifted which results in the effective coupling constant Γ' between cavity 1 and 3. Each gray circle represents a nanocavity.

The full system of 3 nanocavities, assuming no intrinsic losses, can be represented by the system of 3 coupled-mode equations [35]:

$$\begin{cases} \frac{da_1}{dt} = i\omega_0 a_1 + i\Gamma_1 a_2 \\ \frac{da_2}{dt} = i\omega_2 a_2 + i\Gamma_1 a_1 + i\Gamma_2 a_3 \\ \frac{da_3}{dt} = i\omega_0 a_3 + i\Gamma_2 a_2 \end{cases} \quad (6.15)$$

Here a_1, a_2 and a_3 represent field amplitudes in cavities 1, 2 and 3 correspondingly. Assuming that the frequency shift of the cavity 2 is large, we change to the rotation frame to perform adiabatic elimination of cavity 2. This result in the following formula for a_2 :

$$a_2 = \frac{\Gamma_1 a_1 + \Gamma_2 a_3}{\omega_2 - \omega_1} \quad (6.16)$$

By substituting equation 6.16 into system 6.15 we obtain the new reduced system of equations, where again one equation is eliminated:

$$\begin{cases} \frac{da_1}{dt} = i(\omega_0 + \frac{\Gamma_1^2}{\omega_0 - \omega_2})a_1 + i\frac{\Gamma_1 \Gamma_2}{\omega_0 - \omega_2}a_3 \\ \frac{da_3}{dt} = i(\omega_0 + \frac{\Gamma_2^2}{\omega_0 - \omega_2})a_3 + i\frac{\Gamma_1 \Gamma_2}{\omega_0 - \omega_2}a_1 \end{cases} \quad (6.17)$$

The new coupling constant Γ' is equal here to $\Gamma_1 \Gamma_2 / (\omega_0 - \omega_2)$ and it scales inversely with the frequency spacing between nanocavities. In addition to the coupling cavities 1 and 3 get frequency offsets equal to $\Gamma_1^2 / (\omega_0 - \omega_2)$ and $\Gamma_2^2 / (\omega_0 - \omega_2)$. The formalism considered in this section is not limited only to photonic crystal nanocavities and can be applied to other types of resonators. These methods of tuning coupling parameters do not require any dispersion properties of the system and rely only on frequency detunings between nanocavities.

6.A.4 Determination of parameters for the system with tunable coupling constant between two nanocavities

To plot the coupled-mode theory dependencies presented in Figure 6.7, we experimentally measured required system parameters. We first obtained the coupling rate (γ_1) of the first cavity to the photonic crystal waveguide W_1 by detuning it away from the resonance with cavity 2 and 3, so that a single resonance is observed, as shown in Figure 6.20a.

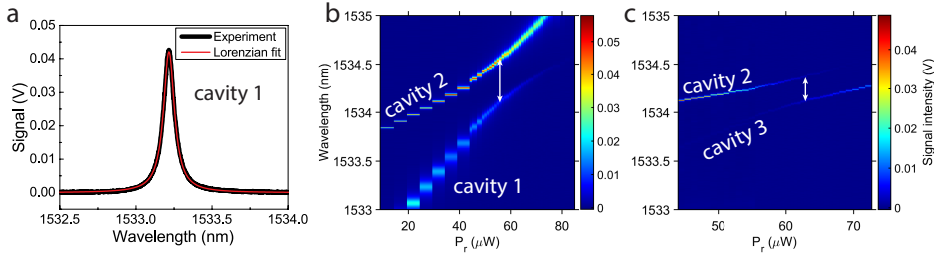


Figure 6.20: Sample parameter determination. **a** - Output spectrum of the loaded cavity 1 to determine γ_1 . **b** - Anticrossing of the cavity 1 and 2 to determine Γ_1 . Red pump spot is placed on cavity 1. **c** - Anticrossing of the cavity 2 and 3 to determine Γ_2 . Red pump spot is placed on cavity 3.

The coupling rate is $\gamma_1 = 2.85 \pm 0.03 \cdot 10^{-5} \omega_0$, which corresponds to the loaded Q-factor of 17500 ± 500 . Then coupling constants between cavity 1 and 2 (Γ_1) and between cavity 2 and 3 (Γ_2) are taken from anticrossing measurements with the smallest possible power applied to the sample, so only a single pump spot was focused on the sample at a time. To determine Γ_1 the pump was focused on cavity 1 and to determine Γ_2 the pump was focused on cavity 3. The resulting anticrossings are present in Figure 6.20b,c. Coupling constants are equal to $\Gamma_1 = 1.45 \pm 0.01 \cdot 10^{-4} \omega_0$ and $\Gamma_2 = 8.3 \pm 0.3 \cdot 10^{-5} \omega_0$. The direct coupling between cavities 1 and 3 (Γ_{13}) can be neglected, because according to our calculations using field-integration method [3] $(\Gamma_1 + \Gamma_2)/(2\Gamma_{13}) \approx 350$. After all the parameters are obtained the theory curves can be calculated from systems of equations 6.15 and 6.17 where in addition the influence of the input waveguide is taken into account as in system 6.9.

Bibliography

- [1] Y. Akahane, T. Asano, B. Song, and S. Noda, *High-Q photonic nanocavity in a two-dimensional photonic crystal*, Nature **425**, 944 (2003). — p.57.
- [2] E. Kuramochi, M. Notomi, S. Mitsugi, A. Shinya, T. Tanabe, and T. Watanabe, *Ultrahigh-Q photonic crystal nanocavities realized by the local width modulation of a line defect*, Appl. Phys. Lett. **88**, 041112 (2006). — p.57, 62.
- [3] A. Yariv, Y. Xu, R. K. Lee, and A. Scherer, *Coupled-resonator optical waveguide: a proposal and analysis*, Opt. Lett. **24**, 711 (1999). — p.57, 78.
- [4] S. Mookherjea and A. Yariv, *Coupled resonator optical waveguides*, IEEE J. Sel. Topics Quantum Electron. **8**, 448 (2002). — p.57.
- [5] M. L. Cooper, G. Gupta, M. a. Schneider, W. M. J. Green, S. Assefa, F. Xia, Y. a. Vlasov, and S. Mookherjea, *Statistics of light transport in 235-ring silicon coupled-resonator optical waveguides*, Opt. Express **18**, 26505 (2010). — p.57.
- [6] C. Ferrari, A. Canciamilla, F. Morichetti, M. Sorel, and A. Melloni, *Penalty-free transmission in a silicon coupled resonator optical waveguide over the full C-band*, Opt. Lett. **36**, 3948 (2011). — p.57.
- [7] J. Jágerská, N. Le Thomas, V. Zabelin, R. Houdré, W. Bogaerts, P. Dumon, and R. Baets, *Experimental observation of slow mode dispersion in photonic crystal coupled-cavity waveguides*, Opt. Lett. **34**, 359 (2009). — p.57.
- [8] F. Morichetti, C. Ferrari, A. Canciamilla, and A. Melloni, *The first decade of coupled resonator optical waveguides: Bringing slow light to applications*, Laser Photon. Rev. **6**, 74 (2012). — p.57.
- [9] M. Minkov and V. Savona, *Wide-band slow light in compact photonic crystal coupled-cavity waveguides*, Optica **2**, 631 (2015). — p.57.
- [10] W. D. Heiss, *The Physics of exceptional points*, J. Phys. A **44**016, 28 (2012). — p.57.
- [11] K. Fang, Z. Yu, and S. Fan, *Realizing effective magnetic field for photons by controlling the phase of dynamic modulation*, Nat. Photon. **6**, 782 (2012). — p.57.
- [12] M. F. Yanik and S. Fan, *Stopping light all optically.*, Phys. Rev. Lett. **92**, 083901 (2004). — p.57.
- [13] S. Keshavamurthy and P. Schlagheck, *Dynamic tunneling. theory and experiment.* (CRC Press, 2011). — p.57.
- [14] M. Mrejen, H. Suchowski, T. Hatakeyama, C. Wu, L. Feng, K. O'Brien, Y. Wang, and X. Zhang, *Adiabatic elimination-based coupling control in densely packed subwavelength waveguides*, Nat. Commun. **6**, 7565 (2015). — p.57.

- [15] R. Menchon-Enrich, A. Benseny, V. Ahufinger, A. D. Greentree, T. Busch, and J. Mompart, *Spatial adiabatic passage: a review of recent progress*, Rep. Prog. Phys. **074401**, 74401 (2016). — p.57.
- [16] Y. Tanaka, J. Upham, T. Nagashima, T. Sugiya, T. Asano, and S. Noda, *Dynamic control of the Q factor in a photonic crystal nanocavity*, Nat. Mater. **6**, 862 (2007). — p.57.
- [17] C. Cohen-Tannoudji, J. Dupont-Roc, and G. Grynberg, *Atom-photon interactions: Basic processes and applications* (Wiley-Interscience Publication, 1998). — p.58.
- [18] E. Brion, L. H. Pedersen, and K. Mølmer, *Adiabatic Elimination in a Lambda System*, J. Phys. A **40**, 14 (2006). — p.58.
- [19] P. Chak and J. E. Sipe, *Minimizing finite-size effects in artificial resonance tunneling structures*, Opt. Lett. **31**, 2568 (2006). — p.59.
- [20] M. Notomi, E. Kuramochi, and T. Tanabe, *Large-scale arrays of ultrahigh-Q coupled nanocavities*, Nat. Photon. **2**, 741 (2008). — p.59, 72.
- [21] J. Lian, *Control of resonances in photonic crystal waveguides* (Ph.D. thesis, Enschede, 2016). — p.59, 68.
- [22] S. Combrié, Q. V. Tran, A. De Rossi, C. Husko, and P. Colman, *High quality GaInP nonlinear photonic crystals with minimized nonlinear absorption*, Appl. Phys. Lett. **95**, 221108 (2009). — p.59.
- [23] J. Lian, S. Sokolov, E. Yüce, S. Combrié, A. De Rossi, and A. P. Mosk, *Measurement of the profiles of disorder-induced localized resonances by local tuning*, Opt. Express **24**, 21939 (2016). — p.60.
- [24] F. Riboli, N. Caselli, S. Vignolini, F. Intonti, K. Vynck, P. Barthelemy, A. Gerardino, L. Balet, L. H. Li, A. Fiore, M. Gurioli, and D. S. Wiersma, *Engineering of light confinement in strongly scattering disordered media*, Nat. Mater. **13**, 1 (2014). — p.60.
- [25] N. Mann, A. Javadi, P. D. García, P. Lodahl, and S. Hughes, *Theory and experiments of disorder-induced resonance shifts and mode edge broadening in deliberately disordered photonic crystal waveguides*, Phys. Rev. A **92**, 023849 (2015). — p.60.
- [26] R. Faggiani, A. Baron, X. Zang, L. Lalouat, S. a. Schulz, B. O'Regan, K. Vynck, B. Cluzel, F. de Fornel, T. F. Krauss, and P. Lalanne, *Lower bound for the spatial extent of localized modes in one-dimensional disordered periodic media*, Sci. Rep. **6**, 27037 (2016). — p.60.
- [27] V. Savona, *Electromagnetic modes of a disordered photonic crystal*, Phys. Rev. B **83**, 085301 (2011). — p.60.
- [28] W. Suh, Z. Wang, and S. Fan, *Temporal coupled-mode theory and the presence of non-orthogonal modes in lossless multimode cavities*, IEEE Journal of Quantum Electronics **40**, 1511 (2004). — p.60, 75.
- [29] S. Combrié, A. De Rossi, Q. V. Tran, and H. Benisty, *GaAs photonic crystal cavity with ultrahigh Q: microwatt nonlinearity at 1.55 μm* , Opt. Lett. **33**, 1908 (2008). — p.62.
- [30] A. F. Oskooi, D. Roundy, M. Ibanescu, P. Bermel, J. D. Joannopoulos, and S. G. Johnson, *Meep: A flexible free-software package for electromagnetic simulations by the FDTD method*, Comp. Phys. Comm. **181**, 687 (2010).

- p.64.
- [31] J. Lian, S. Sokolov, E. Yüce, S. Combrié, A. De Rossi, and A. P. Mosk, *Dispersion of coupled mode-gap cavities*, Opt. Lett. **40**, 4488 (2015). — p.66.
- [32] N. W. Ashcroft and N. D. Mermin, *Solid state physics* (Harcourt College Publishers, 1979). — p.67, 71.
- [33] S. G. Johnson and J. D. Joannopoulos, *Block-iterative frequency-domain methods for maxwell's equations in a planewave basis*, Opt. Express **8**, 173 (2001). — p.68.
- [34] A. Matthews, X. H. Wang, Y. Kivshar, and M. Gu, *Band-gap properties of two-dimensional low-index photonic crystals*, Appl. Phys. B **81**, 189 (2005). — p.68.
- [35] J. Joannopoulos, S. G. Johnson, J. N. Winn, and R. D. Meade, *Photonic crystals: Molding the flow of light* (Princeton University Press, Princeton, 2008). — p.75, 77.

CHAPTER 7

Non-thermal effects of local thermal tuning with laser light

As a result of local heating with laser light we observe, apart from immediate tuning, effects that are reversible on a long timescale of minutes to days or that appear irreversible. Here we report temporal and permanent resonance wavelength change as well as permanent Q-factor change of nanocavities. We describe a data-processing method to cancel the effect of small resonance wavelength changes and report initial experiments on immersion of samples in liquids, which may reduce interface-related slow changes.

7.1 Introduction

Thermal tuning is a versatile tool to locally change the refractive index of various materials used in nanophotonics field [1–4]. Therefore it can be used to effectively tune resonance frequency of nanocavities as well as coupling constants between nanocavities. In the ideal case of pure semiconductors with clean surfaces placed in a chemically inert atmosphere this method can be used to perform completely reversible tuning, up to the point where the temperature of the material becomes too high, at which point chemical structure change, reshaping and eventually melting of the structure occur.

In real nanostructures the situation is slightly different. Ambient media typically contain some concentration of oxygen, and the sample will be locally oxidized due to the heat- and laser-assisted oxidation effects [5–7]. Oxidation leads to blueshift of nanocavity resonances [8, 9]. In case when water is present in the ambient media there is typically a water film on the surface of the sample with a thickness between one molecule layer and several nanometers, which causes resonance wavelength changes and losses [10, 11]. If there is a polymer or residuals of some organic materials on the surface of the sample then they may be burned and their refractive index may be changed by light which again may cause wavelength change [12, 13].

In this chapter we describe slow and irreversible effects which occur during and after our thermal tuning experiments. We report time-dependent as well as permanent redshifts and blueshifts of resonances which do not always have repeatable behavior. We see that some resonances blueshift while other red-

shift being exposed to similar conditions. Also we observe Q-factor change in some cases. We estimate the effects of water film evaporation 3D FDTD calculations. We describe a method to take into account these slow wavelength shifts in datasets where only relative frequencies matter and finally report initial experiments on immersion of nanophotonics samples in liquids which is a possible solution to reduce any surface-related effects.

7.2 Reversible, slow laser-induced changes

7.2.1 Steady-state experiments

Usually each thermal tuning experiment for the setup described in Chapter 2 has a duration from 200 ms to several seconds depending on wavelength range and scanning speed. The temperature of the tuned nanocavities reacts to changes in laser power on a time-scale of $\sim 10 \mu\text{s}$ (Chapter 3). Within the illumination time pump light constantly illuminates the surface. In all of our experiments after a pump pulse a reference spectrum of the sample is taken, where no pump light is applied. In those reference measurements blueshifts and redshifts of resonances were observed with respect to the reference taken before the experiment. In most cases the cavity which was illuminated experiences the biggest change. As an example of such change we present in Figure 7.1 the reference wavelength measurements during the final experiment of anticrossing of 3 cavity resonances from Chapter 4.

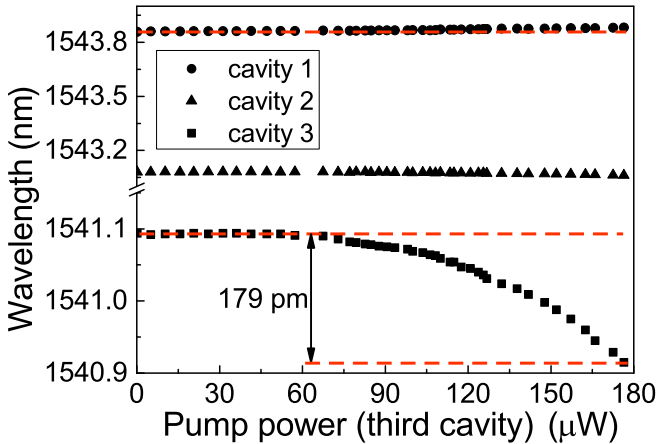


Figure 7.1: Reference resonance wavelength change of 3 coupled nanocavities. Measurement is taken right after each experiment with pump light. The duration of each experiment with pump light is kept constant. Red lines represent the blueshift range for cavity 3 and wavelength of cavity 1 at pump power of $0 \mu\text{W}$. The measurements were taken in order of increasing pump power.

Cavity 1 was illuminated with the tiny power of $9 \mu\text{W}$, while cavity 3 was

heavily illuminated to measure the anticrossing with power up to $180 \mu\text{W}$. The exposure time was the same for all datapoints. As it is seen from the figure the resonance of the cavity 3 blueshifts by about 180 pm. For small powers up to $60 \mu\text{W}$ the blueshift is negligible, while for large powers it increases with power. In contrast, cavity 1 shows a redshift of 24 pm in total. So while both cavity 1 and cavity 3 were illuminated, they experience resonance shift of opposite sign.

7.2.2 Reversibility of the wavelength change

In the experiments in Fig. 7.1 the reference scans were taken immediately after the pump scans. To examine whether the change of the resonance wavelength is reversible we exposed the surface of the sample with a holographic pattern containing 32 pump foci. The image of the holographic pattern is presented in Figure 7.2. This pattern should create a homogeneous temperature distribution in the center where the waveguide with nanocavities is placed. For this experiment we used a sample containing multiple nanocavities. The sample parameters are same as described in Chapter 4. The temperature of the sample was locked at 315 K. The pattern is aligned such that three nanocavities are placed in the center of the pattern. The setup description can be found in Chapter 2.

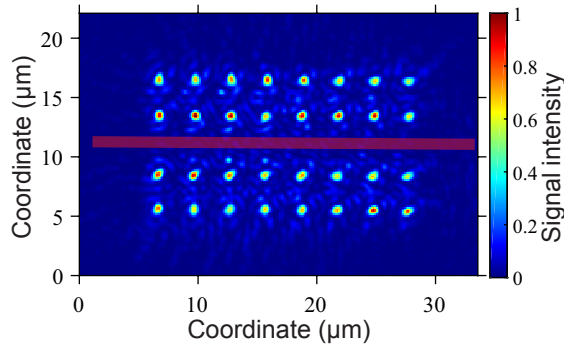


Figure 7.2: Pump pattern to heat the sample Image of the pump pattern used to heat the sample which consists of 32 focused pump spots.

During the experiment we kept the pump light on for 3 minutes and then turned it off to observe the relaxation behavior of the system. Transmission spectra of the sample were constantly measured to track the change of the resonance wavelength of an isolated resonance of cavity 3. The sample was kept in nitrogen atmosphere with oxygen content less than 0.1 %. The result of the experiment is presented in Figure 7.3. Two experiments are shown, Experiment 1 with total power of 32 spots equal to $418 \mu\text{W}$ and Experiment 2 with total power $855 \mu\text{W}$. We note that temperature-wise these experiments are steady-state because rise and decay of the temperature due to pump pattern happens during the time of $\sim 10 \mu\text{s}$ [4, 14], therefore we observe only the time-dependent behavior of non-thermal effects. Temperature fluctuations of the sample substrate, detected by

the temperature controller were no more than ± 0.005 K which eliminates the possibility of the wavelength change induced by the response of the temperature controller caused by pump light.

In Figure 7.3a we show the resonance wavelength in Experiment 1 during the pump light exposure. It initially changes fast and then appears to saturate. The total change is about 300 pm. The initial value of the resonance wavelength before the Experiment 1 was 1539.538 nm, therefore the redshift due to the local temperature rise at the time when the pump light had just been switched on was about 1.8 nm. This shift corresponds to an increase of the local temperature at the position of the cavity by about 19 °C.

After the pump is switched off, cavity relaxes back to its previous state as shown in Figure 7.3b for Experiments 1 and 2. In both cases the resonance slowly redshifts, but does not reach the initial wavelength measured before the experiment. In the beginning relaxation is fast, gaining a change of several hundred picometers within 2 minutes, after which saturation seems to occur. Then the speed slows down and continues over a long time. The time difference between the end of the Experiment 1 and start of the Experiment 2 was more than 2 hours. During that time the resonance was continuously redshifting reaching the wavelength of 1539.503 nm after 2.5 hours, which is still smaller than the initial wavelength before the Experiment 1. The blueshift for the Experiment 2 is nearly twice as large as for Experiment 1, which is not unexpected as total power is twice as large.

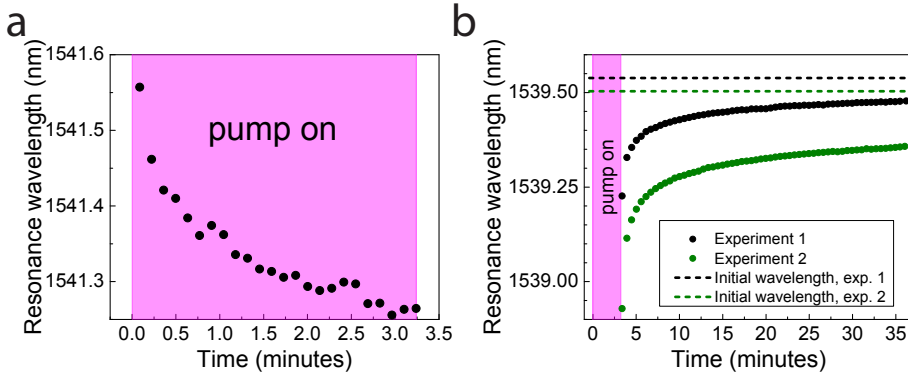


Figure 7.3: Time-dependence of wavelength change. **a** - time-evolution of resonance wavelength for cavity 3 during exposure with 418 μ W (Experiment 1). **b** - time-evolution of resonance wavelength of cavity 3 after exposure for Experiment 1 and Experiment 2 (power 855 μ W). Dashed lines represent the initial wavelength of the resonance right before the experiment. The purple area represents the exposure time.

We performed multiple kinetics experiments with different pump powers and different heating stage temperatures and observed both redshifts and blueshifts occurring during and after exposure, therefore the direction of the shift is not always the same. Consistently these resonance shifts have a time dependence

comparable to Figure 7.3, i.e. they increase when pump laser is on and partially relax to the initial state when the pump laser is off. The dependencies are not well described by an exponential. These kinetics may correspond to water diffusion and water film evaporation/formation as well as to other surface chemistry reactions, therefore they may have a quite complicated shape [15].

7.2.3 FDTD evaluation of water effects

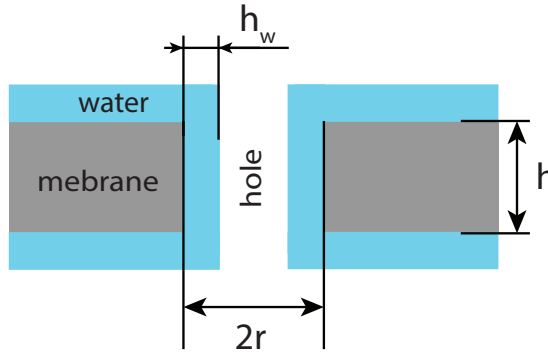


Figure 7.4: Scheme of the sample for numerical simulation. The cross-section of one hole in a photonic crystal membrane is present. Gray area represents membrane material and blue area represents water film. White color inside the hole represents air.

There is always a thin film of water with thickness up to several nanometers on top of every object depending on ambient conditions. Moreover in low-humidity media and even in vacuum systems there still may be water on the surface [16, 17]. The blueshift effect observed for nanocavity resonances can be in part explained by the decrease of the thickness of this water film on the surface of our samples [11]. To estimate the possible influence of water films on resonances of mode-gap cavities we perform 3D FDTD simulations. We consider a GaInP membrane with thickness $h = 180$ nm. In this membrane we define a triangular photonic crystal with period $a = 485$ nm and hole radius $r = 0.25$ nm. The cavity is created in a waveguide of width $W_0 = 0.98\sqrt{3}a$ by applying hole shifts of 10.4, 6.9 and 3.5 nm as described in Ref. 18. The length of the structure is $52a$ and the width is $12a$. We consider the model of the water film presented in Figure 7.4. We assume the water film homogeneously covers the surface of the membrane from both sides as well as inside the holes and has a thickness h_w . We vary the thickness between 0 and 8 nm to obtain the resonance shift. The dependence of resonance shift on film thickness is presented in Figure 7.5.

The resonance wavelength increases with the thickness of the water layer. The redshift reaches the value of 1 nm at a film thickness of about 2 nm. The quality factor of the nanocavity for all data-points is more than 10^6 . Experimentally we observed blueshifts and redshifts up to about 2 nm. The observed blueshifts can be explained by local evaporation of the water film. When the

pump is placed on a particular cavity, evaporation happens mostly at the position of the cavity therefore the resonance wavelength of that cavity should shift the most, as observed for cavity 3 in Figure 7.1. It is unclear though why for different cavities or different pump positions we observe a different sign of the effect. We surmise that local surface conditions [19] and morphology may play a critical role.

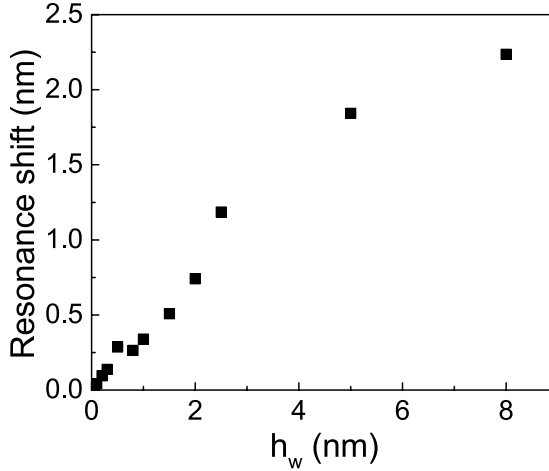


Figure 7.5: Numerically calculated dependence of resonance position on thickness of the water layer. The resonance frequencies are extracted with an error bar smaller than the data point size. The observed fluctuations are attributed to discretization error.

7.3 Irreversible effects

In addition to the reversible effects described above, we observe several irreversible effects. They are described in detail in this section.

7.3.1 Optical darkening of the surface

According to our observations the darkening of the surface happens at some surface positions which were illuminated by pump light. Surprisingly, we noticed no straightforward correlation between the pump power, illumination time and the place where darkening appears, which signifies that it is probably related to local material and surface chemistry. One of the possible causes of this could be residue of organic materials used during the fabrication process. Being illuminated by pump light they may burn, obtain refractive index changes or photo-darkening [20] which lead to darkening of sample surface observed in reflection. An example of such darkening on the surface of one of our samples is presented in Figure 7.6. This sample was used for the experiments described in Chapter 4. The dark spot appears on the position of the cavity 1 although the cavity 3 was exposed

to higher intensities of 405 nm light. We note that this darkening of the surface perturbs the image of the pump beam when viewed in reflection. We have observed darkening after exposure in air as well as in nitrogen atmosphere.

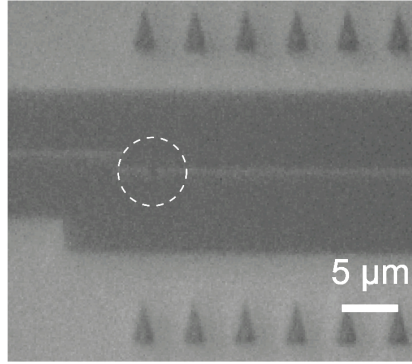


Figure 7.6: Image of the sample. Image of the sample made in the setup with violet light illumination. The dark spot is marked by the white circle. Black triangles are markers indicating cavity positions (markers are shifted from actual cavity positions). The bright line in the middle is the line defect determining the waveguide. The dark rectangular area is the photonic crystal membrane.

7.3.2 Non-reversible changes of resonance frequency and Q-factor

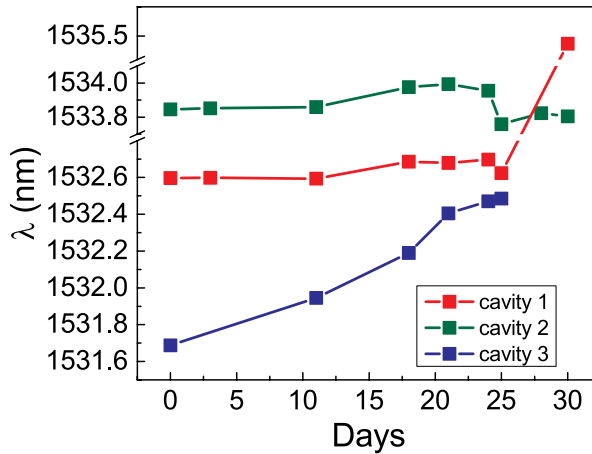


Figure 7.7: Irreversible change of the resonance wavelength. The dependence of resonance wavelength of the cavities 1, 2 and 3 on time. Each square represents a day when experiments were performed. Each measurement is taken in the beginning of the day before exposure to pump light.

We also investigated whether fully irreversible changes occur. In Figure 7.7 we plot the change of resonance wavelengths of 3 nanocavities for one of our samples over a time of one month. Within that time multiple experiments were performed, notably this sample was used for experiments from Chapter 5 and section 6.3 from Chapter 6. Cavities 1, 2 and 3 were exposed to different powers of pump light within that time. The data points in Fig. 7.7 correspond to the first reference measurement of the day, so no pump was applied and any reversible changes have had time to relax. This sorts out reversible effects described in previous section.

We see that resonances redshift as well as blueshift. On day 25 the resonance wavelength of cavity 3 is redshifted by 800 pm compared to day 1. There is a large jump of resonance wavelength of cavity 1 from day 25 to day 30 by 2.8 nm. This redshift comes together with a drop of the Q-factor to $6.1 \pm 0.2 \cdot 10^2$, while on day 24 it was $2.65 \pm 0.02 \cdot 10^4$.

7.4 Data analysis procedure to correct for post-pump effects

To accomplish accurate tuning, it is essential to accurately measure tuning slopes of resonance frequencies. Slow, non-thermal effects of the pump make it difficult to obtain such accurate measurements. Here we describe a method to correct measurements for these effects and obtain precise tuning. Our procedure is based on reference measurements taken immediately after each experiment involving pump light (further referred to as pump measurements), and the following assumptions are valid:

1. No mode-profile change happens as a result of the post-pump effects.
2. For systems with optically coupled resonances, no a priori unknown coupling constant change occurs as a result of above mentioned effects.
3. Reference measurement represents the state of the sample on the moment of a pump measurement, so no change happens to the system during the short time between pump and reference measurements.

In the case when resonances are rather isolated one can subtract reference resonance wavelengths from the initial reference wavelengths taken before any pump experiments and apply the difference to resonance wavelengths for pump measurements. In practice quite often it happens that resonance wavelengths are spaced quite closely, and resonances are optically coupled even in the reference case. In that case a model is required for a sample which allows to calculate bare resonance frequencies from both reference and pumped measurement data. The data is corrected by calculating bare frequencies for pump and reference measurements, applying corrections obtained from the reference measurements and calculate back frequencies of the coupled resonances.

A simple example is a system of 2 optically coupled cavities where first cavity is coupled to the waveguide, like it is shown in Figure 5.1a from Chapter 5. In case where the coupling constant Γ_0 between the nanocavities is significantly

bigger than the load of the first cavity to the waveguide γ_1 , the bare resonances frequencies of two nanocavities can be found by inventing the following formula [21]:

$$\omega_{1,2} = \frac{\omega_{0,1} + \omega_{0,2}}{2} \pm \sqrt{\left(\frac{\omega_{0,1} - \omega_{0,2}}{2}\right)^2 + \Gamma_0^2} \quad (7.1)$$

Here $\omega_{0,1}$ and $\omega_{0,2}$ are the bare frequencies of resonances. As an experimental example for this procedure we consider the case from Chapter 5 where the coupling constant is changed by the pump light. In our case the power of the red laser which is focused between nanocavities is $22 \mu\text{W}$. The coupling constant for reference data is equal to $\Gamma_0 = 1.34 \pm 0.15 \cdot 10^{-4}$, while for the pumped data it is equal to $1.460 \pm 0.003 \cdot 10^{-4}$. The pump spot from the violet laser was focused on cavity 1 and its power was varied to measure the anticrossing. The reference data from this experiment are presented in Figure 7.8a.

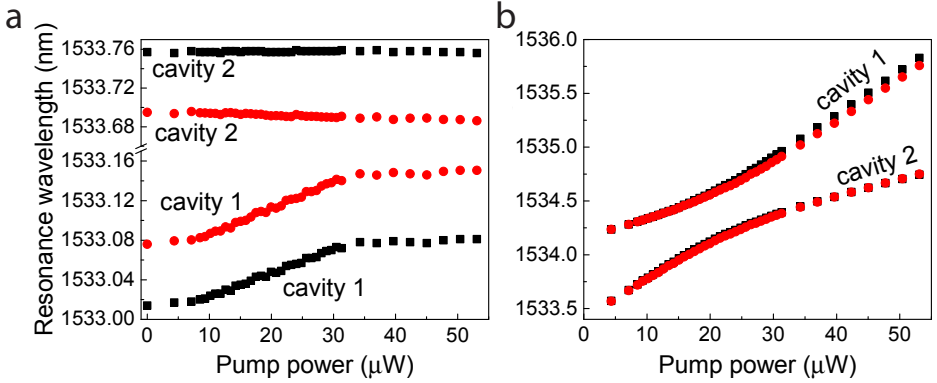


Figure 7.8: Removal of post-pump effects. **a** - Reference measurements. Measurement for power equal to $0 \mu\text{W}$ are initial reference measurements. Black squares represent resonance wavelengths of coupled resonances, while red circles represent their bare resonance wavelengths. **b** - Pump measurements. Black squares represent uncorrected result and red circles represent corrected one.

Remarkably, the coupled resonance wavelength of cavity 2 barely see blue-shifts while the bare one shifts by 9 pm. Cavity 1 was in total redshifted by 75 pm. We calculate corrections which are the difference of reference measurements from the initial one, and apply them to pump measurements. The comparison between corrected and uncorrected data is shown in Figure 7.8b. At small power the difference is not obvious, while for larger pump powers the reference resonance change accumulates and a significant difference appears. The corrected measurements, which include the direct thermal effects of the pump but exclude the slow post-pump effects, should be used to accurately calculate tuning slope and anticrossing position.

7.5 Immersion of samples in liquids

Short-term and long-term effects described above may be possibly removed by submersing the whole system in liquid which will block any material exchange with ambient gas. In case of water-related effects this would stop the evaporation and relaxation of the water film. There are several requirements for the immersion liquid:

1. **Low refractive index.** The refractive index of the liquid should be as low as possible to have high-Q cavity modes confined in the membrane without making a new cavity design.
2. **Large thermal conductivity.** The liquid should preferably conduct heat well to provide better heat localization [4] and decrease the thermal crosstalk between cavities when several of them are heated.
3. **Non-volatile.** During the thermal tuning experiments liquid will be heated therefore it is preferable that liquid does not evaporate easily, which would limit the experiment time.
4. **Chemically inert.** Liquid should not chemically react with the membrane material, and it should not change under laser light irradiation.
5. **Non-absorptive.** Liquid should not absorb IR light, to avoid Q-factor drops.

One of the candidates for immersion liquid is water, which has refractive index of 1.318 at the wavelength of $1.55 \mu\text{m}$. Water has a large thermal conductivity, but it can be easily evaporated when heated. A much better candidate is Galden HT270 heat transfer fluid which has a lower refractive index of 1.29, thermal conductivity about 3 times larger than for nitrogen and extremely small evaporative loss rate.

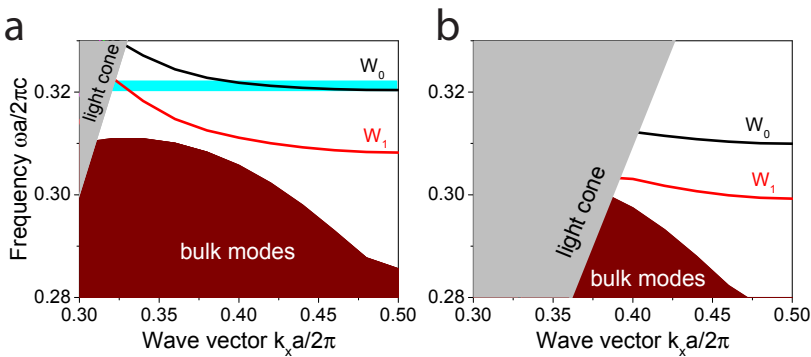


Figure 7.9: Band diagrams. **a** - Band diagram of a photonic crystal waveguide for the case of air as surrounding media. Light blue area indicates the overlap between waveguide bands for waveguides with widths W_0 and W_1 . **b** - Band diagram for the case of sample immersed in Galden liquid. Gray area represents light cone, while dark red area represents bulk modes of the photonic crystal.

Unfortunately our current structures of interest which are used in Chapters 4, 5, 6 and 8 are not suitable for immersion. These structures have waveguides with width $W_1 = 1.1\sqrt{3}a$ to launch and collect light and barrier waveguide with width $W_0 = 0.98\sqrt{3}a$ where nanocavities are located (see Figure 6.4 from Chapter 6). Widths of these waveguides are matched such that in air the waveguide bands overlap and light can be coupled from one waveguide to another and to resonance states near the band edge for a limited wavelength range. The band diagram for this case is presented in Figure 7.9a. The overlap between two bands is highlighted in blue. When the sample is immersed in Galden liquid these bands separate as shown in Figure 7.9b. That means that light cannot be launched from waveguide W_1 to the waveguide W_0 , therefore we do not have optical access to the resonators through the waveguides.

However, modes of mode-gap cavities should still exist when cavities are immersed in liquid, which is verified by 3D FDTD calculations. Simulation parameters are described in the Section 7.2.3. The resonance wavelength of the mode should redshift by 47 nm and the intrinsic Q-factor should drop from $9 \cdot 10^6$ to 10^6 . Coupling constants between nanocavities for center-to-center separations of $9a$ and $10a$ used in this thesis should increase by a factor of 2, as calculated using the field integration method (see Ch. 5).

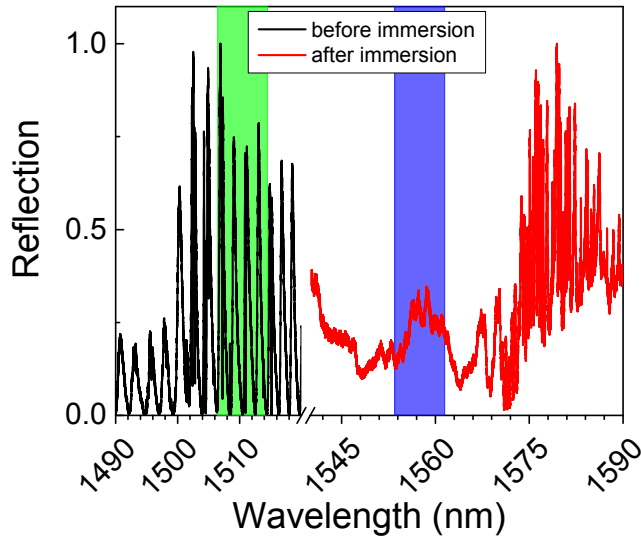


Figure 7.10: Reflection spectra. Reflection spectra of a structure with nanocavities before and after immersion in Galden liquid. Green bar highlights the wavelength range where resonance of mode-gap cavities and random modes were found. Blue bar represents the expected wavelength range for those resonance after immersion.

We performed several experiments on samples containing mode-gap nanocavities similar to ones described in Chapters 4,5,6 and 8, without a waveguide to collect transmission. A drop of Galden liquid was placed on the surface of the

sample, letting it spread all over the surface. We compared reflection spectra before and after immersion, in addition we performed pump line scans to identify cavity resonances. As a result of visual examination under the microscope we conclude that the liquid film covers the whole surface, but the thickness is increasing from edge of the sample to the center. An example of reflection spectra before and after immersion is presented in Figure 7.10.

For the spectra before immersion we see mostly interference fringes [22], but for the frequency range highlighted with a green bar in Fig. 7.10 mode-gap cavity resonances as well as random modes were found. The wavelength range which corresponds to these modes for a sample immersed in liquid is highlighted with a blue bar. Unfortunately no resonances were found, which is verified by pump line-scans. From out-of-plane scattering measurements with the IR camera we observe that there is a lot of light emitted from the input waveguide for wavelengths between 1570 and 1585 nm where a lot of fringes are present. This signifies that the lower bandedge (see Figure 7.9) of the input waveguide is at about 1585 nm. We found also the emission of IR light from the barrier waveguide for wavelengths between 1550 and 1560 nm.

We notice that the shape of the reflection image of the pump beam fluctuates in time which signifies that liquid thickness changes over time. For future experiments this could be possibly stabilized with cover glass. More experiments are required to verify the presence of resonances in an immersed sample. In order to use input and output waveguides, redesigned samples are needed.

7.6 Conclusion

To summarize we reported here non-thermal reversible and irreversible effects which we observed during and after thermal tuning experiments. We observed permanent as well as time-dependent redshifts and blueshifts of nanophotonic resonances together with permanent Q-factor changes. The magnitude of wavelength shifts increases with pump power. It is hard to conclude the nature of these effects, as they seem to depend on pump position. At some pump positions darkening of the surface was observed. In some cases these wavelength shifts can be removed from datasets using a post-processing scheme which we described. Immersion of the sample in an inert liquid may be able to reduce such effects but requires a redesign of the sample waveguides.

Bibliography

- [1] A. C. Liapis, B. Gao, M. R. Siddiqui, Z. Shi, and R. W. Boyd, *On-chip spectroscopy with thermally-tuned high-Q photonic crystal cavities*, Appl. Phys. Lett. **108**, 021105 (2016). — p.83.
- [2] P. A. Morton, J. Cardenas, J. B. Khurgin, and M. Lipson, *Fast Thermal Switching of Wideband Optical Delay Line With No Long-Term Transient*, IEEE Photon. Technol. Lett. **24**, 512 (2012). — p.83.
- [3] J. Pan, Y. Huo, K. Yamanaka, S. Sandhu, L. S. R. Timp, M. L. Povinelli, S. Fan, M. M. Fejer, and J. S. Harris, *Aligning microcavity resonances in silicon photonic-crystal slabs using laser-pumped thermal tuning*, Appl. Phys. Lett. **92**, 103114 (2008). — p.83.
- [4] S. Sokolov, J. Lian, E. Yüce, S. Combrié, G. Lehoucq, A. De Rossi, and A. P. Mosk, *Local thermal resonance control of GaInP photonic crystal membrane cavities using ambient gas cooling*, Appl. Phys. Lett. **106**, 171113 (2015). — p.83, 85, 92.
- [5] M. Fukuda and K. Takahei, *Optically enhanced oxidation of III-V compound semiconductors*, J. of Appl. Phys. **57**, 129 (1985). — p.83.
- [6] H. S. Lee, S. Kiravittaya, S. Kumar, J. D. Plumhof, L. Balet, L. H. Li, M. Francardi, A. Gerardino, A. Fiore, A. Rastelli, and O. G. Schmidt, *Local tuning of photonic crystal nanocavity modes by laser-assisted oxidation*, Appl. Phys. Lett. **95**, 191109 (2009). — p.83.
- [7] B. E. Deal and a. S. Grove, *General relationship for the thermal oxidation of silicon*, J. Appl. Phys. **36**, 3770 (1965). — p.83.
- [8] F. Riboli, N. Caselli, S. Vignolini, F. Intonti, K. Vynck, P. Barthelemy, A. Gerardino, L. Balet, L. H. Li, A. Fiore, M. Gurioli, and D. S. Wiersma, *Engineering of light confinement in strongly scattering disordered media*, Nat. Mater. **13**, 1 (2014). — p.83.
- [9] A. Y. Piggott, K. G. Lagoudakis, T. Sarmiento, M. Bajcsy, G. Shambat, and J. Vuckovic, *Photo-oxidative tuning of individual and coupled GaAs photonic crystal cavities*, Opt. Express **22**, 15017 (2014). — p.83.
- [10] H. Sekoguchi, Y. Takahashi, T. Asano, and S. Noda, *Photonic crystal nanocavity with a Q-factor of 9 million*, Opt. Express **22**, 916 (2014). — p.83.
- [11] C. J. Chen, J. Zheng, T. Gu, J. F. McMillan, M. Yu, G. Lo, D. Kwong, and C. W. Wong, *Selective tuning of high-Q silicon photonic crystal nanocavities via laser-assisted local oxydation*, Opt. Express **19**, 12480 (2011). — p.83, 87.
- [12] T. Cai, R. Bose, G. S. Solomon, and E. Waks, *Controlled coupling of photonic*

- crystal cavities using photochromic tuning*, Appl. Phys. Lett. **102**, (2013). — p.83.
- [13] G. Gupta, Y.-H. Kuo, H. Tazawa, W. H. Steier, A. Stapleton, and J. D. O'Brien, *Analysis and demonstration of coupling control in polymer microring resonators using photobleaching*, Appl. Opt. **48**, 5324 (2009). — p.83.
- [14] M. Brunstein, R. Braive, R. Hostein, a. Beveratos, I. Rober-Philip, I. Sagnes, T. J. Karle, a. M. Yacomotti, J. a. Levenson, V. Moreau, G. Tessier, and Y. De Wilde, *Thermo-optical dynamics in an optically pumped Photonic Crystal nano-cavity*, Opt. Express **17**, 17118 (2009). — p.85.
- [15] J. H. Sharp, G. W. Brindley, and B. N. N. Achar, *Numerical Data for Some Commonly Used Solid State Reaction Equations*, J. Am. Ceram. Soc. **49**, 379 (1966). — p.87.
- [16] G. Lewin, *Fundamentals of vacuum science and technology* (McGraw-Hill book company, 1965). — p.87.
- [17] X. Zhang and S. Ptasinska, *Dissociative Adsorption of Water on an H₂O/GaAs(100) Interface: In Situ Near-Ambient Pressure XPS Studies*, J. Phys. Chem. C **118**, 4259 (2014). — p.87.
- [18] E. Kuramochi, M. Notomi, S. Mitsugi, A. Shinya, T. Tanabe, and T. Watanabe, *Ultra-high-Q photonic crystal nanocavities realized by the local width modulation of a line defect*, Appl. Phys. Lett. **88**, 041112 (2006). — p.87.
- [19] S. Kalashnikov and V. Bonch-Bruевич, *The physics of semiconductors* (Main Editorial Board for Physical and Mathematical Literature, 1990). — p.88.
- [20] N. Grassie and N. A. Weir, *The photooxidation of polymers. IV. A note on the coloration of polystyrene*, J. Appl. Polym. Sci. **9**, 999 (1965). — p.88.
- [21] H. A. Haus and W. Huang, *Coupled-mode theory*, Proc. IEEE **79**, 1505 (1991). — p.91.
- [22] J. Lian, *Control of resonances in photonic crystal waveguides* (Ph.D. thesis, Enschede, 2016). — p.94.

CHAPTER 8

Measurement of the linear thermo-optical coefficient of $\text{Ga}_{0.51}\text{In}_{0.49}\text{P}$ using photonic crystal nanocavities

GaInP is a promising candidate for thermally tunable nanophotonic devices due to its low thermal conductivity. In this work we study its thermo-optical response. We obtain the linear thermo-optical coefficient dn/dT by investigating the transmission properties of a single mode-gap photonic crystal nanocavity.

8.1 Introduction

Several III-V semiconductors are used for nanophotonic devices, such as GaAs [1], GaP [2], InP [3] for their specific properties such as optical tunability. For local thermal tuning, the high thermal conductivity of Si or Si_3N_4 is unfavorable. A promising candidate for thermally tunable nanophotonic devices is GaInP which became popular during recent years [4–8]. Its thermal conductivity [9] is more than 6 times smaller than for Si and Si_3N_4 , which in addition to absence of two-photon absorption at 1550 nm and favorable nonlinear properties [7] makes it a promising candidate for thermally tunable photonics. In this work we investigate the thermal response of a single photonic crystal nanocavity made of $\text{Ga}_{0.51}\text{In}_{0.49}\text{P}$. Our analysis allows us to obtain the thermo-optic coefficient of refractive index for this material whose precise value has not been reported in the literature to our knowledge.

8.2 Sample and experimental setup

To experimentally measure the thermo-optical coefficient of the $\text{Ga}_{0.51}\text{In}_{0.49}\text{P}$ a nanophotonic sample containing photonic crystal nanocavities was mounted on a thermally controlled stage, so the sample was homogeneously heated and the temperature was locked with a precision of $\pm 0.001\text{ K}$. The sample is an air-suspended photonic crystal membrane with a linear array of 10 directly coupled

This chapter has been published as: S. Sokolov, J. Lian, S. Combri , A. De Rossi, A. P. Mosk, arXiv:1612.05544 [physics.optics]

mode-gap photonic crystal nanocavities made of $\text{Ga}_{0.51}\text{In}_{0.49}\text{P}$. The thickness of semiconductor membrane is 180 nm.

The structure of a single cavity is presented as the inset in Figure 8.1. It is made in a photonic crystal waveguide with $W_0 = 0.98\sqrt{3}a$ where $a=485$ nm is a period of a triangular photonic crystal lattice. Red holes are shifted away from the waveguide by 6 nm, green - by 4 nm and purple ones are shifted by 2 nm to create a cavity mode. Such cavities are known for large experimentally measured Q-factors [10, 11] and therefore they are suitable for precise thermal measurements. The first and last cavities in the array are coupled to input and output photonic crystal waveguides with width $W_1 = 1.1\sqrt{3}a$ which are used to launch and collect light from the structure.

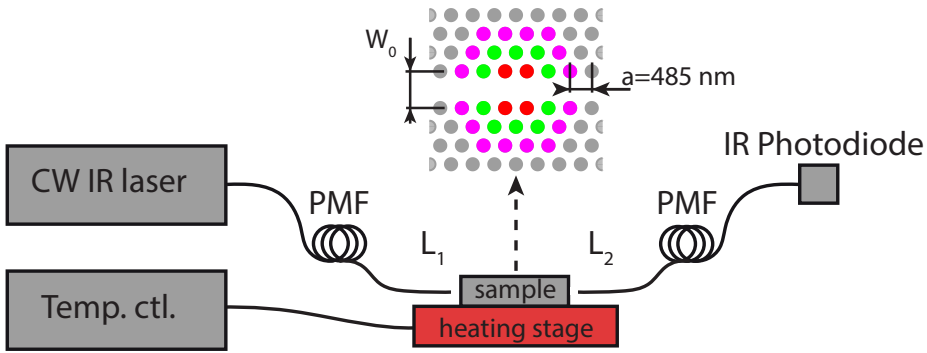


Figure 8.1: Experimental setup. Transmission through the sample is measured. The sample temperature is locked to $\pm 0.001^\circ\text{C}$ using a temperature controller. Inset shows the cavity structure. Holes are represented with circles. Different colors correspond to different hole shifts.

The structure was probed by IR light with a wavelength around 1550 nm from the CW tunable laser. The light was coupled into and out-coupled from the structure with polarization-maintaining lensed fibers L_1 and L_2 with $\text{NA}=0.55$. The out-coupled light was collected on an IR photodiode for transmission measurements. The sample was kept in nitrogen atmosphere to avoid oxidation [12, 13]. The resonance frequencies of cavities are perturbed by unavoidable disorder, which breaks the resonance hybridization. This normally undesired effect allowed us to pick an isolated single cavity resonance. We picked the single resonance corresponding to the 3rd cavity in the array, which was verified by our pump line-scan technique [4, 5, 14]. The transmission spectrum of the resonance at 48.2°C is presented in Figure 8.2. The spectrum has a clear Fano-like shape due to the interference with transmitted TM light [15]. The spectrum is fitted with a Fano lineshape function [16, 17] and a 1st order polynomial for the background. The lineshape is perfectly described by the fit, so it is used to obtain line parameters. The loaded Q-factor of the resonance is $Q = 1.6 \pm 0.1 \cdot 10^5$.

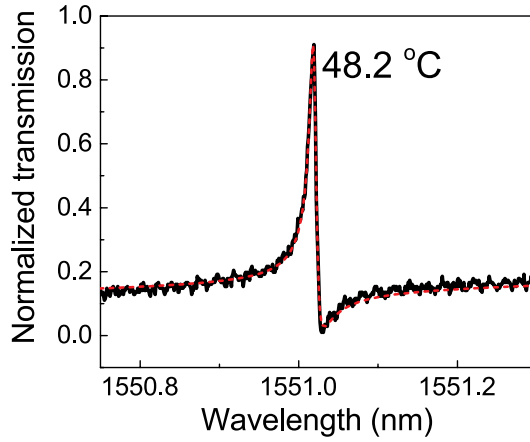


Figure 8.2: Transmission spectrum. Transmission spectra of the sample at 48.2 °C. Dashed line represents Fano lineshape fit.

8.3 Experiment description

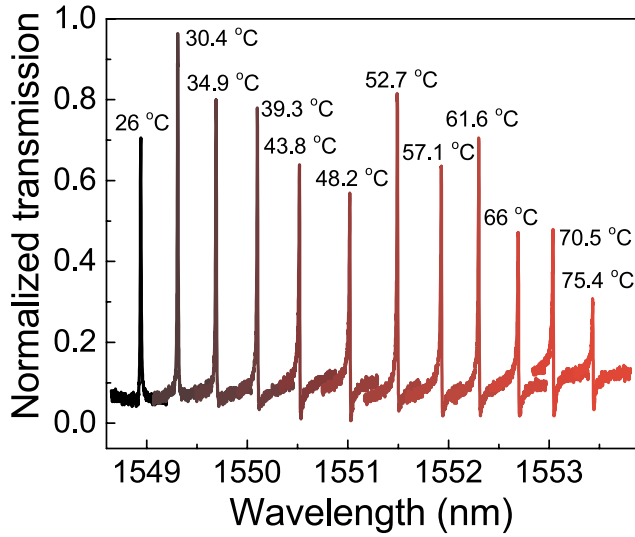


Figure 8.3: Transmission spectra. Patched graph showing all transmission spectra collected in this experiment. Color of lines changes from black to red to emphasize the temperature difference.

For the measurement of the thermo-optical coefficient the resonance wavelength was measured for several temperatures of the sample ranging from 26 to 76 °C.

Spectra for all temperatures are presented in Figure 8.3. The resonance experiences a redshift which signifies that the material has a positive thermo-optical response. All spectra have a Fano-like line shape. There was no systematic change of the Q-factor which signifies that within this temperature range the mode-profile of the cavity does not change. In total the resonance redshifts by about 4.5 nm when the temperature rises by approximately 49.5 °C. The dependence of resonance wavelength on the temperature of the sample is presented in Figure 8.4. The resonance wavelength changes linearly with increasing temperature, with a tuning slope of $9.4 \pm 0.3 \cdot 10^{-2} \text{ nm/K}$.

When a sample is heated, any water film is evaporated from the surface which causes a resonance blueshift [12]. The exact magnitude of this resonance shift depends on details of the surface condition. In laser heating experiments with similar temperature changes we have observed this shift to be 360 pm or less. To account for this a priori unknown shift we add an error term of 5%, resulting in $d\lambda/dT = 9.4 \pm 0.6 \cdot 10^{-2} \text{ nm/K}$.

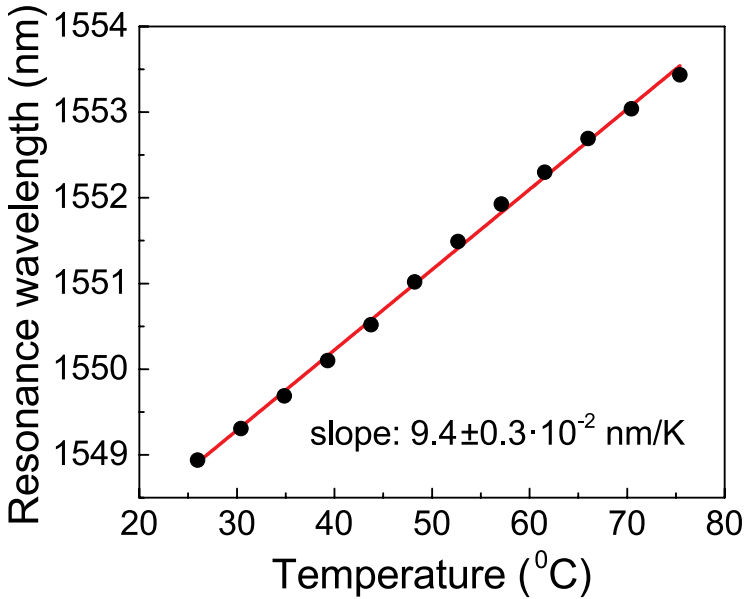


Figure 8.4: Resonance wavelength versus temperature of the sample. The red line represents a line fit of the experimental data. The error for experimental data is smaller than the datapoint size.

Using first order perturbation theory and scaling of Maxwell equations one can get a precise value of linear thermo-optic coefficient dn/dT of the refractive index of $\text{Ga}_{0.51}\text{In}_{0.49}\text{P}$. To first order, it can be shown that [18]:

$$\frac{\Delta\lambda}{\lambda} = \frac{\Delta\lambda_n}{\lambda} + \frac{\Delta\lambda_a}{\lambda} \quad (8.1)$$

Where $\Delta\lambda_n/\lambda$ and $\Delta\lambda_a/\lambda$ are equal to :

$$\frac{\Delta\lambda_n}{\lambda} = \frac{\Delta n}{n} \cdot \frac{\int_{\text{membrane}} \varepsilon |\mathbf{E}(\mathbf{r})|^2 d\mathbf{r}}{\int_{\text{all}} \varepsilon |\mathbf{E}(\mathbf{r})|^2 d\mathbf{r}} = \frac{1}{n} \frac{dn}{dT} \Delta T \mathcal{E}_m \quad (8.2)$$

$$\frac{\Delta\lambda_a}{\lambda} = \frac{\Delta a}{a} = \alpha_T \Delta T \quad (8.3)$$

Here $\Delta\lambda_n/\lambda$ is the relative resonance wavelength change caused by the refractive index change Δn , ε is the dielectric constant of the membrane material and $\mathbf{E}(\mathbf{r})$ is the electric field of the cavity mode. As follows from Eq. 8.2 the change of the resonance wavelength is proportional to the fraction of the electric-field energy inside the membrane $\mathcal{E}_m$, taking into account that the change in the refractive index of ambient nitrogen is negligible. According to our 3D FDTD calculations the fraction of electric-field energy in the membrane is 0.88. $\Delta\lambda_a/\lambda$ is the relative wavelength change due to the thermal expansion of the membrane, where α_T is the thermal expansion coefficient. The dn/dT value can be finally obtained from:

$$\frac{dn}{dT} = \frac{n}{\lambda \mathcal{E}_m} \left(\frac{d\lambda}{dT} - \alpha_T \lambda \right) \quad (8.4)$$

The thermal expansion coefficient [19] α_T for $\text{Ga}_{0.51}\text{In}_{0.49}\text{P}$ is equal to $5.4 \pm 0.3 \cdot 10^{-6} \text{ K}^{-1}$. The experimentally measured value of dn/dT is then equal to $dn/dT = 2.0 \pm 0.1 \cdot 10^{-4} \text{ K}^{-1}$. We note that in case of GaInP linear expansion gives a noticeable contribution to the tuning slope of the cavity resonance. Without taking into account that effect the value of dn/dT would be about 10% larger.

The value for dn/dT is about 30% smaller than the value obtained earlier in the Chapter 3. The previous value was obtained as a result of comparison between complex modeling and experiment. We surmise that uncertainty of thermal conductivity of materials as well as laser power estimation in the focus may have led to overestimation of the result. Moreover, in this chapter the sample was heated homogeneously so $(\frac{dn}{dT})_P$ was measured, while for the experiment with local laser heating, described in Chapter 3, $(\frac{dn}{dT})_V$ was measured, which is actually a value for a stressed material as the membrane could not expand. The present experiment does not depend on laser pump power and thermal conductivity of the membrane material and therefore the obtained value of dn/dT corresponds to stress-free $\text{Ga}_{0.51}\text{In}_{0.49}\text{P}$.

8.4 Conclusion

In conclusion, we investigated the thermo-optical effect of the refractive index for $\text{Ga}_{0.51}\text{In}_{0.49}\text{P}$. Our measurement took place for a freely expanding membrane and we took into account the effect of thermal expansion of the material. We found no significant Q-factor change during our measurement which guarantees that the working wavelength of photonic devices based on nanocavities made of $\text{Ga}_{0.51}\text{In}_{0.49}\text{P}$ can be safely biased with temperature within the range of about 5

nm. This work enables precise thermal tuning of GaInP based photonic devices, which is relevant as one of the lowest thermal conductivity semiconductors used in photonics.

Bibliography

- [1] A. D. Rossi, M. Lauritano, S. Combrié, Q. V. Tran, and C. Husko, *Interplay of plasma-induced and fast thermal nonlinearities in a GaAs-based photonic crystal nanocavity*, Phys. Rev. A **79**, 043818 (2009). — p.97.
- [2] K. Rivoire, Z. Lin, F. Hatami, and J. Vučković, *Sum-frequency generation in doubly resonant GaP photonic crystal nanocavities*, Appl. Phys. Lett. **97**, 95 (2010). — p.97.
- [3] Y. Yu, E. Palushani, M. Heuck, N. Kuznetsova, P. Trøst, S. Ek, D. Vukovic, C. Peucheret, L. Katsuo, S. Combrié, A. D. Rossi, K. Yvind, and J. Mørk, *Switching characteristics of an InP photonic crystal nanocavity : Experiment and theory*, Opt. Express **21**, 9221 (2013). — p.97.
- [4] S. Sokolov, J. Lian, E. Yüce, S. Combrié, G. Lehoucq, A. De Rossi, and A. P. Mosk, *Local thermal resonance control of GaInP photonic crystal membrane cavities using ambient gas cooling*, Appl. Phys. Lett. **106**, 171113 (2015). — p.97, 98.
- [5] J. Lian, S. Sokolov, E. Yüce, S. Combrié, A. De Rossi, and A. P. Mosk, *Measurement of the profiles of disorder-induced localized resonances by local tuning*, Opt. Express **24**, 21939 (2016). — p.97, 98.
- [6] A. Martin, G. Moille, S. Combrié, G. Lehoucq, T. Debuisschert, J. Lian, S. Sokolov, A. P. Mosk, and A. De Rossi, *Triply-resonant Continuous Wave Parametric Source with a Microwatt Pump*, ArXiv:1602.04833 [physics.optics] (2016). — p.97.
- [7] S. Combrié, Q. V. Tran, A. De Rossi, C. Husko, and P. Colman, *High quality GaInP nonlinear photonic crystals with minimized nonlinear absorption*, Appl. Phys. Lett. **95**, 221108 (2009). — p.97.
- [8] A. S. Clark, C. Husko, M. J. Collins, G. Lehoucq, S. Xavier, A. D. De Rossi, S. Combrié, C. Xiong, and B. J. Eggleton, *Heralded single-photon source in a III-V photonic crystal*, Opt. Lett. **38**, 649 (2013). — p.97.
- [9] S. Adachi, *Lattice thermal conductivity of group-IV and III-V semiconductor alloys*, J. Appl. Phys. **102**, 063502 (2007). — p.97.
- [10] E. Kuramochi, M. Notomi, S. Mitsugi, A. Shinya, T. Tanabe, and T. Watanabe, *Ultrahigh-Q photonic crystal nanocavities realized by the local width modulation of a line defect*, Appl. Phys. Lett. **88**, 041112 (2006). — p.98.
- [11] S. Combrié, A. De Rossi, Q. V. Tran, and H. Benisty, *GaAs photonic crystal cavity with ultrahigh Q: microwatt nonlinearity at 1.55 μm* , Opt. Lett. **33**, 1908 (2008). — p.98.
- [12] C. J. Chen, J. Zheng, T. Gu, J. F. McMillan, M. Yu, G. Lo, D. Kwong, and C. W. Wong, *Selective tuning of high-Q silicon photonic crystal nanocavities*

- via laser-assisted local oxydation*, Opt. Express **19**, 12480 (2011). — p.98, 100.
- [13] K. Navr, *Thermal oxidation of gallium arsenide*, Czech. J. Phys. B **18**, 266 (1968). — p.98.
- [14] S. Sokolov, J. Lian, E. Yüce, S. Combrié, A. De Rossi, and A. P. Mosk, *Tuning out disorder-induced localization in nanophotonic cavity arrays*, arXiv:1608.01257 [physics.optics] (2016). — p.98.
- [15] J. Lian, *Control of resonances in photonic crystal waveguides* (Ph.D. thesis, Enschede, 2016). — p.98.
- [16] U. Fano, *Effects of Configuration Interaction on Intensities and Phase Shifts*, Phys. Rev. **124**, 1866 (1961). — p.98.
- [17] W. Zhou, D. Zhao, Y. C. Shuai, H. Yang, S. Chuwongin, A. Chadha, J. H. Seo, K. X. Wang, V. Liu, Z. Ma, and S. Fan, *Progress in 2D photonic crystal Fano resonance photonics*, Prog. Quant. Electron. **38**, 1 (2014). — p.98.
- [18] J. Joannopoulos, S. G. Johnson, J. N. Winn, and R. D. Meade, *Photonic crystals: Molding the flow of light* (Princeton University Press, Princeton, 2008). — p.100.
- [19] I. Kudman and R. J. Paff, *Thermal expansion of $\text{In}_x\text{Ga}_{1-x}\text{P}$ alloys*, J. Appl. Phys. **43**, 3760 (1972). — p.101.

CHAPTER 9

Summary

Photonic crystal nanocavities play an important part in the future of nanophotonics. For many systems containing nanocavities it is necessary to be able to tune their essential parameters. In this thesis we presented experimental investigation and control of properties of single and coupled photonic crystal nanocavities. Our experiments are supported by analytical and numerical calculations.

We used nanostructures based on $\text{Ga}_{0.51}\text{In}_{0.49}\text{P}$ for all the experiments. This material is suitable due to its optical and thermal properties. Remarkably, it is able to localize heat much better than Si or GaAs, which makes it a perfect material for thermally tunable devices. It is not yet as well studied as other III-V materials. For instance, the precise value of the linear thermo-optical coefficient for a freely expanding material is not reported. We fill in this gap by measuring it using resonances of isolated photonic crystal nanocavities (Chapter 8). The obtained value is important for precise thermal tuning of nanostructures made of $\text{Ga}_{0.51}\text{In}_{0.49}\text{P}$.

An apparatus was built to measure reflection and transmission as well as out-of-plane scattered light from nanophotonic samples over a wide wavelength range of IR light (Chapter 2). In addition we selectively coupled light into cavities by out-of-plane focusing. It is interesting that out-of-plane-scattered signal as well as the signal measured when light is coupled from out-of-plane into a cavity have Lorentzian lineshapes, which simplifies the data processing in comparison to reflection and transmission measurements. Local control of nanostructures was achieved with two pump lasers, where one of them can be shaped by a spatial light modulator. The spatial light modulator allows to distribute laser light between several spatial regions, for instance, to have independent tuning of several coupled nanocavities (Chapter 4) or to homogeneously heat up a certain area (Chapter 7). To suppress non-thermal pump-induced effects (Chapter 7) we developed an external laser wavelength reference scheme, which being synchronized with optical shutters for pump lasers, allows to perform measurement over tens of nanometers within a short time of hundreds of milliseconds with a high resolution of better than 1 pm.

All the post-pump effects observed in the experiments which mostly result in time-dependent and permanent changes of the resonance wavelength and Q-factors are summarized in Chapter 7. While for some applications these changes are unwanted, for other ones they may be favorable, for example, permanent frequency shift may be applied to compensate disorder.

The local thermal tuning greatly depends on the material of the nanostruc-

ture as well as on the ambient medium around the sample (Chapter 3). We discovered that changing the media from nitrogen to helium produces a change in the width of the temperature distribution caused by the pump by 30%. The change of ambient gas does not by itself change any of the photonic properties of the system and therefore easily allows an increase of the integration density of cavities on a nanophotonic chip.

Fully tunable photonic circuits is a future dream, and we performed several important steps to achieve it. Firstly, we managed to control several coupled nanocavities independently in the presence of thermal crosstalk (Chapter 4). Moreover, we annulled the disorder and restored the intended state of the system. Secondly, we successfully tuned the coupling constant between nanocavities experimentally. To this end, we developed two methods where we either locally perturb the area between two nanocavities (Chapter 5) or use an ancillary cavity (Chapter 6). Additionally, we experimentally tuned the coupling rate between a nanocavity and a photonic crystal waveguide (Chapter 6). As a result of our findings we proposed two new types of tunable bandwidth coupled resonator optical waveguides (CROW).

The results described in this thesis extend boundaries of what can be achieved in nanophotonic circuits based on coupled nanocavities. Although we performed experiments with steady-state tuning, all our methods can also be applied for the time-dependent tuning of properties of coupled nanocavities. This can be done thermally by gating pump light sources used in this thesis on the microsecond scale or by using pulsed lasers to achieve free-carrier injection and Kerr effect at time scales shorter than the propagation time of a probe pulse.

Nederlandse samenvatting

Fotonisch kristal nanoresonatoren spelen een belangrijke rol in de toekomst van de nanofotonica. In systemen die nanoresonatoren bevatten is het nodig om hun belangrijkste eigenschappen te kunnen verstemmen. Dit proefschrift gaat over een experimenteel onderzoek van enkele en gekoppelde fotonische kristallen nanoresonatoren. Onze experimenten worden ondersteund door analytische en numerieke modellen.

In alle experimenten zijn nanostructuren gebaseerd op $\text{Ga}_{0.51}\text{In}_{0.49}\text{P}$ gebruikt. Dit materiaal is geschikt vanwege zijn optische en thermische eigenschappen. Daarnaast is het veel beter in staat om warmte te lokaliseren dan Si of GaAs, waardoor het een perfect materiaal is om thermisch afstembare schakelingen te maken. Het is nog niet zo goed bestudeerd als andere III-V materialen. Zo is de precieze waarde van de lineaire thermo-optische coëfficiënt van een vrij expandierend materiaal bijvoorbeeld nog niet gerapporteerd. Wij meten deze waarde met behulp van resonanties van geïsoleerde fotonische kristal nanoresonatoren (Hoofdstuk 8). De gemeten waarde is belangrijk voor de precieze thermische afstemming van nanostructuren gemaakt van $\text{Ga}_{0.51}\text{In}_{0.49}\text{P}$.

Met de door ons gebouwde opstelling kan in een breed golflengtedomein de reflectie, transmissie en verstrooiing uit het vlak van nanofotonische plaatstructuren worden gemeten (Hoofdstuk 2). Door het uit het vlak verstrooide licht te meten of door het licht in te koppelen van uit het vlak vinden we Lorentziaanvormige spectraallijnen in transmissie en reflectie. Dit vereenvoudigt de data-verwerking ten opzichte van directe transmissie of reflectiemetingen. Plaatselijke beïnvloeding van nanostructuren wordt bereikt door het gebruik van twee pomplasers. Eén van de pomplaserbundels kan door een spatiële licht modulator worden omgevormd, om zo het licht te verdelen tussen verschillende plaatsen. Hierdoor kunnen bijvoorbeeld individuele gekoppelde trilholtes worden afgestemd (Hoofdstuk 4), of bepaalde gebieden worden opgewarmd (Hoofdstuk 7). Om niet-thermische pomp geïnduceerde effecten (Hoofdstuk 7) te onderdrukken hebben we een externe golflengte referentie methode ontwikkeld, die het door synchronisatie met optische sluiters mogelijk maakt om metingen te verrichten over tientallen nanometers binnen enkele honderden milliseconden met een resolutie beter dan 1pm.

De pomp geïnduceerde effecten geobserveerd in de experimenten zorgen voor tijdsafhankelijke en permanente veranderingen in de resonantie golflentes en de Q-factor (Hoofdstuk 7). Hoewel deze effecten in sommige toepassingen ongewenst zijn, zijn ze voor anderen juist wenselijk, bijvoorbeeld als permanente golflengte verschuiving om wanorde te compenseren.

De plaatselijke thermische afstemming is sterk afhankelijk van het materiaal van de nanostructuur en het omringende medium (Hoofdstuk 3). Een verandering van het medium stikstof naar helium zorgt voor een vernauwing van 30% van de breedte van het thermische profiel geïnduceerd door de pomplaser. De verandering van het omringende medium heeft geen invloed op de fotonische eigenschappen van het systeem en laat daardoor een hogere dichtheid van trilholtes op een chip toe.

Volledig afstembare fotonische schakelingen zijn een toekomstdroom, en we hebben enkele belangrijke stappen in die richting gezet. Ten eerste zijn we in staat geweest om enkele gekoppelde nanotrillholtes individueel te controleren met de aanwezigheid van thermische overspraak (Hoofdstuk 4). Bovendien zijn we de effecten van wanorde effectief tegengegaan waarmee we een schakeling hebben teruggebracht naar de beoogde staat. Ten tweede hebben we succesvol de koppelingsconstante tussen trilholtes veranderd. Hiervoor hebben we twee methodes ontwikkeld waarbij we het gebied tussen twee trilholtes verstoren (Hoofdstuk 5), of gebruik maken van een derde hulp trillholte (Hoofdstuk 6). Als resultaat van dit onderzoek stellen we twee nieuwe types coupled resonator optical waveguide (CROW) voor, waarvan de bandbreedte afstembaar is.

De resultaten in dit proefschrift bieden nieuwe mogelijkheden voor nanofotonische schakelingen. Hoewel alle experimenten in een stabiele toestand zijn verricht, is het ook mogelijk om dynamisch, tijdsafhankelijk de eigenschappen van gekoppelde nanotrillholtes te controleren. Dit kan thermisch worden gedaan door het pompplicht op een microsecondeschaal te schakelen, door gebruik te maken van gepulste lasers en het Kerr-effect of de creatie van vrije ladingsdragers op tijdschalen korter dan de propagatietijd van de meetpuls.

List of publications related to this thesis

- S. Sokolov, J. Lian, E. Yüce, S. Combrié, A. De Rossi, A.P. Mosk, “*Local thermal resonance control of GaInP photonic crystal membrane cavities using ambient gas cooling*”, Appl. Phys. Lett., **106**, 171113 (2015)
- J. Lian, S. Sokolov, E. Yüce, S. Combrié, A. De Rossi, A.P. Mosk, “*Dispersion of coupled mode-gap cavities*”, Opt. Lett., **40**(19), 4380 (2015)
- J. Lian, S. Sokolov, E. Yüce, S. Combrié, A. De Rossi, A.P. Mosk, “*Measurement of the profiles of disorder-induced localized resonances in photonic crystal waveguides by local tuning*”, Opt. Express, **24**(19), 21939 (2016)
- S. Sokolov, J. Lian, E. Yüce, S. Combrié, A. De Rossi, A.P. Mosk, “*Tuning out disorder-induced localization in nanophotonic cavity arrays*”, arXiv:1608.01257 [physics.optics] (2016)
- J. Lian, S. Sokolov, E. Yüce, S. Combrié, A. De Rossi, A.P. Mosk, “*Fano lines in the reflection spectrum of directly coupled systems of waveguides and cavities: measurements, modeling and manipulation of the Fano asymmetry*”, arXiv:1610.08351 [physics.optics] (2016)
- A. Martin, G. Moille, S. Combrié, G. Lehoucq, T. Debuisschert, J. Lian, S. Sokolov, A.P. Mosk and A. De Rossi, “*Triply-resonant Continuous Wave Parametric Source with a Microwatt Pump*”, arXiv:1602.04833 [physics.optics] (2016)
- S. Sokolov, J. Lian, S. Combrié, A. De Rossi, A.P. Mosk, “*Measurement of the linear thermo-optical coefficient of $\text{Ga}_{0.51}\text{In}_{0.49}\text{P}$ using photonic crystal nanocavities*”, ArXiv:1612.05544 [physics.optics]
- E. Yüce, J. Lian, S. Sokolov, J. Bertolotti, S. Combrié, A. De Rossi and A.P. Mosk, “*The control of necklace states in a photonic crystal waveguide*”, to be submitted

Acknowledgments

Working at the COPS group changed me for the better and sculpted me over the years as a mature researcher. Moving then to Utrecht as a member of the new NanoLINX group was a pleasant surprise which influenced the last year of my Ph.D. I must say that I enjoyed both groups very much and these four years are the greatest experience I had in my life. I can call these four years a ‘school of life’. In general, doing a Ph.D. is a great experience which teaches you to solve complex problems and puzzles. Solving those puzzles would be impossible without the great help of my colleagues, and I would like to thank them here.

First I want to acknowledge my supervisor Allard Mosk. I am extremely lucky and thankful to do my Ph.D. research under his supervision. I was really glad to work on a completely new project where we basically started from scratch. At the beginning we had a completely empty optical table and several ideas of what we wanted to do. During 4 years of my Ph.D., we then built piece by piece a great setup where many great experiments were performed. Allard has an incredibly deep knowledge in many areas of science and is always willing to share it. We had a lot of interesting discussions during our project meetings and coffee breaks. Quite often a lot of brainstorming happened and great ideas were generated, which later on, transformed into successful experiments. I greatly appreciate, that even though Allard has an extremely busy schedule he can always find a minute to discuss science.

I want to thank Willem Vos who from my first day at COPS started to shape me not only as a scientist but also as a person. During our group meetings and discussions, I received invaluable comments and advice. The quality I really like is that he never hesitates to make a critical remark, and this stimulated my personal and professional development. I also would like to thank Pepijn Pinkse and Ad Lagendijk for their precious advice and interactions with me.

During more than 3 years of my work, I had a great project buddy - Jin Lian. I truly enjoyed working together with him. I am delighted that after some time we managed to work as a fully functioning team. I especially appreciate his great help in setting up numerical models and simulations. I also want to thank Emre Yüce, who joined the project as a postdoc, for sharing his knowledge and experience.

Accomplishing the work described in this thesis would not be possible without our great collaborators Alfredo De Rossi and Sylvain Combré from Thales. I really appreciate that they shared their great experience in nanophotonics and fabricated complex structures used in this work.

I want to thank my colleagues from COPS who contributed to my work in

various ways: Amandev, Andreas, Bill, Bas, Daniel, Devashish, Duygu, Diana, Elahe, Evangelos, Femi, Georgios, Ivo, Jacopo, Jan, Jochen, Lyuba, Maryna, Michael, Mehdi, Peilong, Shakeeb, Simon, Sjoerd, Sina, Thomas, Tom, Timmo, Tristan, Vanessa and Willem Tjerkstra. I want to especially thank Ravi and Henri. These two brilliant postdocs were always willing to help and share their great knowledge of experimental techniques, theory and numerical methods. In addition I want to thank Evangelos for his extreme friendliness and kindness. I thank Cock Harteveld for his advice and constant experimental support. He was always there to order missing components which had to be installed the day before. I also acknowledge Marlon Gomperts for solving various computer related issues. I like that I could call Marlon and my problem was fixed within the following hour. I thank Nilda, Nienke, Jacqueline and Carla for taking over the bureaucratic issues during my PhD project at COPS.

I want to thank Marco, Jörn, Youwen, Yin, Caterina Tadeei, Caterina Tanalione, Peter, Ron, Claus and Bert from the neighboring LPNO group for discussions and assistance and their constant readiness to lend equipment. I also want to thank Jeroen Korterik from the OS group for his help with electronics.

After I moved to Utrecht, my surroundings were enriched with other brilliant people and I want to acknowledge them as well. I thank Abhilash, Bohdan, Dashdeleg, Dries, Floor, Fatemeh, Jasper, Jeroen, Kevin, Marcel, Otto, Ole, Peter, Siddharth, Suzan, Sandy, Tom and Xiaoqing for helpful discussions. I would especially like to thank Sanli for his genuine interest in my project and his constant willingness to help and discuss. I would like to thank Cees, Dante, Frits and Paul for assisting in setting up the experimental setup after moving to Utrecht. Also, I would like to thank our secretary Mijke who is always willing to assist and take over administrative duties. I also acknowledge Jeroen for translating the summary of my thesis. Last but not least I want to thank Arjon, Pritam and Sebastiaan for making work breaks full of fun.

Finally, I am indebted to my family for their love and constant support during my adventurous Ph.D. journey. Also, I deeply thank my beloved Anna, who makes every day of my life wonderful.

