Optofluidic and photothermal control of InGaAsP photonic crystal nanocavities

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Chapter 1

Introduction

This chapter gives a brief introduction to photonic crystals, underlying theoretical concepts and their possible use in photonic applications. Photonic crystal cavities and waveguides will be briefly introduced and their application areas will be demonstrated. After explaining the motivation and the goal of the thesis, the outline of the thesis will be given at the end of the chapter.

1.1 General introduction

After the invention of the laser in the 1950s, the field of "photonics" has emerged whose main goal is to use the light to build faster, cheaper and ultra compact devices in the areas of optoelectronics, telecommunication, information processing and sensing. Over the last decades, a large number of photonic devices have been proposed and some of them are used in these areas as an alternative to the electronic devices. The use of photons as the information carriers rather than electrons has offered many advantages such as reduced crosstalk and high speed transmission.

In the intervening four decades, a particular attention has been given to improve the telecommunication systems due to the increase of data transmission worldwide. Optical fibers have been installed over long distances to transmit a large amount of data at higher speeds with low propagation losses. The information is carried by the optical signals through these fibers with a high speed; however, the bottleneck of this system is the electronic circuitry placed at either side of the fibers to process the data. These electronic devices convert the optical signals to the electronic signals which is a slow and an inefficient process for the realization of high-speed data transmission. Therefore, the signal conversion should be replaced by an all optical process for which a photonic circuitry system is needed.

The photonic devices can function as a highly sensitive on-chip sensor by monitoring the changes in the spectral characteristics of photonic devices. The
strong light-matter interaction enhances the sensitivity of the device to the environment, which can be exploited for tuning and sensing. Since the interaction occurs in a very small area, large scale integration of many sensors to detect single or multi species is possible for lab-on-a-chip applications.

In this thesis, the optical properties of the two dimensional membrane type photonic crystal structures are explored by means of fluidic and photothermal effects to promote their functionalities for future photonic integrated circuits. An integration of fluidic circuits with photonic crystal devices will enable the realization of largely tunable, reconfigurable, controllable, functional and flexible devices in the areas of communication, sensing, information processing, imaging and so on. A photothermal effect could enhance the possible applications in the field of optoelectronics and telecommunication where a single photonic device can be activated locally without perturbing the entire chip by an optical beam. The combination of these two effects, the optofluidics and the photothermal, is explored in this thesis, and will further expand the application domains.

1.2 Towards the photonic integrated circuit

The groundbreaking idea of Kilby in 1958 to create an integrated circuit (monolithic circuit) from the same block of the semiconductor material had a profound impact on the semiconductor chip industry. The integrated circuit forms the basis of the current electronic devices which is now a multi billion dollar market. Computer processors, for instance, benefit from the developments in the integrated circuit devices where an abundant number of transistors can be placed in a single chip. In 1965, Gordon Moore observed that the number of transistors per chip approximately doubles every two years, which is known as Moore’s law and it has been valid for 40 years. As predicted by the Moore’s law, in 2010 over one billion transistors with a size of less than 45 nm could fit into a 216 square millimeter silicon chip. Intel’s road map shows an 8 nm size transistor by 2017.

The miniaturization of the microprocessors results in a dense packaging of the metallic wires which decreases the efficiency of the chip due the parasitic capacitance and increases the dissipated power density. Currently, it is considered as one of the major limitations to realize high-speed computers. As the amount of the information processed in the computer microchip increases, the communication delay between the different ports of the chip must be minimal to process the information in a short time. Recently, the delay due to the communication between the ports has approached the delay due to the computation itself.

In the present time, fiber-optic communication systems are used to transfer a huge amount of data over long distances. The information is carried by optical
signals through the fiber and is converted to electronic signals by electronic devices at the end of the fiber. The optical-electrical conversion is a slow and costly process which limits the network speed.

Photonic integrated devices provide potential solutions for maintaining the Moore’s law by reducing the effect of the parasitic capacitance and decrease power dissipation. Since the photonic devices are manufactured from standard electronic materials, complex hybrid devices can be constructed from side by side integration of the photonic and electronic devices. The use of optical signals instead of electrical signals on a chip would require a dense integration of optical devices with sizes scaled down to an ultimate size that dielectric optics can afford. In other words the formation of a photonic Moore’s law is expected [1]. Moreover, a photonic integrated circuit system can eliminate the need of the signal conversion in fiber-optic data transmission systems.

The photonic integrated circuit can be realized in different material systems such as silicon (Si), indium phosphide (InP), gallium arsenide (GaAs). The silicon based devices have already entered into the telecommunication systems; however, an effective light generation from these devices is still lacking. Since InP devices enable light generation, amplification, propagation and detection at the telecom wavelength band, the devices having these functionalities can be integrated in a single chip to maximize the efficiency and the speed of the optical communication network. Moreover, constructing all-optical devices in a single photonic circuit reduces the coupling and packaging steps which result in reliable, cost and power effective, efficient, easily integrable and small size devices.

1.3 Photonic crystals

A photonic crystal (PhC) is an artificial dielectric structure having a periodic modulation in the refractive index. The “photonic crystal”, which was introduced by Yablonovitch [2], is also called photonic-band gap material because the periodicity creates a forbidden frequency range of light where the light does not propagate. This phenomenon is also analogous to semiconductor materials where the periodicity of the electronic potential resulting from the regular arrangement of atoms in a lattice creates an electronic band-gap where electron states do not exist. The periodicity in the refractive index can occur in all three dimensions bringing different classes of photonic crystals as shown in figure 1.1[3].

A one dimensional photonic crystal, which is also called Distributed Bragg Mirror, has been investigated for several decades. Diverse applications have been realized, among them the vertical cavity surface emitting lasers (VCSEL) [4]. The higher dimensional photonic crystal has been proposed simultaneously by Yablonovitch [2] and John [5] independently. Yablonovitch, in his work,
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Figure 1.1: Schematic representation of a photonic crystal in three different classes of dimensions. The figure represents a one dimensional (1-D), a two dimensional (2-D) and a three dimensional (3-D) photonic crystal. The image is taken from [3].

focused on the control of spontaneous emission of the emitters when they are placed in the photonic crystals while John focused on the localization of the light in the photonic crystal. The "Yablonovite" which was the first fabricated 3D photonic crystal was successfully demonstrated with a complete photonic band-gap by Yablonovitch’s team [6]; however, to fabricate a small scale 3D photonic crystal is still a challenging task. A two dimensional photonic crystal has appeared as a promising route to overcome the fabrication limitation of its 3D counterparts because it is easier to fabricate and analyze. After the demonstration of a 2D PhC by Thomas Krauss [7] in 1996, various photonic crystal devices such as splitters [8, 9], high Q microcavities [10–12] and add/drop filters [13, 14] have been investigated both theoretically and experimentally.

The optical properties of PhC structures can be understood by solving classical Maxwell equations under some simplifying conditions. First, we assume that the field strength is so small that we can consider a linear regime and we assume that the material is isotropic. Next, the material has low loss so the permittivity is treated as a purely real function and we ignore the frequency dependence of the permittivity. So, the electric displacement field $\vec{D}$ can be written as $\vec{D}(r) = \varepsilon_0 \varepsilon(r) \vec{E}(r)$ where $\varepsilon_0$ is the vacuum permittivity. We assume the system is nonmagnetic where magnetic permeability of the system is close to 1, i.e. $\vec{B}(r) = \mu_0 \mu(r) \vec{H}(r) = \mu_0 \vec{H}(r)$. We also consider no free charges or free currents. Under these considerations, the Maxwell equations are written as [3];

$$\nabla \cdot \varepsilon_0 \varepsilon(r) \vec{E}(r, t) = 0$$  \hspace{1cm} (1.1)

$$\nabla \cdot \vec{B}(r, t) = 0$$  \hspace{1cm} (1.2)

$$\nabla \times \vec{E}(r, t) = -\frac{\partial}{\partial t} \vec{B}(r, t)$$  \hspace{1cm} (1.3)
∇ × \vec{H}(r, t) = \epsilon_0\epsilon(r) \frac{\partial \vec{E}(r, t)}{\partial t} \tag{1.4}

where \vec{E} and \vec{H} are macroscopic electric and magnetic fields, respectively, as a function of time and space. So we can write \vec{E}(r, t) = \vec{E}(\vec{r})e^{-i\omega t} and \vec{H}(r, t) = \vec{H}(\vec{r})e^{-i\omega t}. When we insert these equations into the above equations and taking the curl of Eqn. 1.4, the \vec{H}(\vec{r}) becomes

(\nabla \times \frac{1}{\epsilon(r)} \nabla \times \vec{H}(\vec{r}) = (\frac{\omega^2}{c^2})\vec{H}(\vec{r}) \tag{1.5}

where \(c = (\sqrt{\mu_0\epsilon_0})^{-1}\) is the speed of light in the vacuum. The Eqn.1.5 is called master equation [3] which is analogous to the Schrödinger's equation in quantum mechanics. The corresponding electric field becomes;

\vec{E}(\vec{r}) = (\frac{-i}{\omega\epsilon_0(\vec{r})})\nabla \times \vec{H}(\vec{r}) \tag{1.6}

The left hand side of the Eqn.1.5 can be represented as an operator \(\Lambda\);

\[\Lambda \equiv \nabla \times (\frac{1}{\epsilon_0(\vec{r})}\nabla \times)\]

So the master equation is rewritten as;

\[\Lambda \vec{H}(\vec{r}) = (\frac{\omega^2}{c^2})\vec{H}(\vec{r}) \tag{1.8}\]

The Eqns. 1.7 and 1.8 show that \(\Lambda\) is a linear Hermitian operator having real eigenvalues \((\omega^2/c^2)\). Since \(\Lambda\) is linear, any linear combination of solutions for \(\vec{H}(\vec{r})\) is a solution of the eigenvalue equation.

When we introduce the modulation of the refractive index as \(\epsilon(\vec{r} + \vec{R}) = \epsilon(\vec{r})\) where \(\vec{R}\) is the lattice vector of the crystal, then the solution of the eqn.1.5 can be represented according to Bloch's theorem as

\[\vec{H}_n(\vec{k}, \vec{r}) = \tilde{\vec{H}}_{n,k}(\vec{r})e^{i\vec{k}\vec{r}} \tag{1.9}\]

where \(\vec{k}\) is the Bloch wavevector that specifies the eigensolutions with eigenvalues \(\omega_n(\vec{k})\) which is labeled by the wavevector \(\vec{k}\) and bandnumber \(n\). The \(\tilde{\vec{H}}_{n,k}\) is a periodic function of position. Placing eqn.1.9 into the eqn.1.5 re-forms the Hermitian operator as[3]

\[\Lambda_{\vec{k}} = (i\vec{k} + \nabla) \times (\frac{1}{\epsilon_0(\vec{r})}(i\vec{k} + \nabla) \times) \tag{1.10}\]

And \(\tilde{\vec{H}}_{n,k}(\vec{r})\) is a solution of the \(\Lambda_{\vec{k}}\tilde{\vec{H}}_{n,k} = (\frac{\omega^2}{c^2})\tilde{\vec{H}}_{n,k}\)

The eqn.1.9 and eqn.1.10 have some important consequences. First the
eqn. 1.9 is an envelope function combined with a function that has a spatial periodicity of the lattice \(a\). In one dimension, every eigensolution has wavevector components \(k + p \left( \frac{2\pi}{a} \right)\) where \(a\) is the 1-D lattice constant and \(p\) is an integer. Then it is sufficient to restrict \(k\) within the range of \(-\frac{\pi}{a} \leq k \leq \frac{\pi}{a}\) which is called the first Brillouin zone for a one dimensional periodic structure. Similarly, in two dimensional structures, the Brillouin zone is given by the Wigner Seitz cell of the reciprocal lattice. High symmetry points in the reciprocal lattice are labeled as \(\Gamma, K, M, \ldots\). Second, as \(k\) varies within the Brillouin zone, the corresponding eigenvalues \(\omega_n(k)\) change gradually which gives a set of functions \(\omega_n(k)\) in different directions corresponding to the dispersion relations of the photonic crystal. The master equation is scale invariant so the dispersion diagram can be represented by the dimensionless wavenumber \(k' = \frac{k}{\frac{a}{\pi}}\) and frequency \(\omega' = \frac{\omega}{\frac{a}{2\pi}}\).

In this work, InGaAsP PhC membrane type of structures having a triangular array of air holes were chosen as schematically shown in figure 1.2. By choosing both the In-Ga and the As-P ratios of the quaternary compound, both the lattice parameter (for matching to the InP substrate) and the electronic bandgap can be independently varied. We work with the lattice matched material to InP throughout and bandgap corresponding to a wavelength of \(\lambda = 1.25\ \mu m\). Figure 1.2(a) shows the geometric parameters of a triangular lattice of air holes with a lattice spacing of \(a\) and radius \(r\). The high symmetry directions are labeled by \(\Gamma M\) and \(\Gamma K\). The hexagon in figure 1.2(b) represents the first Brillouin zone and the highlighted area is the irreducible Brillouin zone with the coordinates \(\Gamma = (0, 0, 0)\), \(M = (2\pi/a\sqrt{3})(\sqrt{3}/2, 1/2, 0)\) and \(K = (4\pi/3a)(1, 0, 0)\). Figure 1.2(c) shows the schematic of the cross section of the PhC structure with a thickness of \(d\).

### 1.4 The origin of the band gap

The periodicity created in the refractive index of a dielectric slab by patterning an array of a dielectric material having a lower dielectric constant results in a photonic bandgap. By providing an adequate dielectric contrast, a bandgap will open up at the edge of the Brillouin zone. The bandstructure of the photonic crystal can be obtained by calculating the eigenvalues \(\omega_n(\vec{k})\) along the path that connects the high symmetry points of the Brillouin zone.

To illustrate the existence of the photonic bandgap, the dispersion relations of the unpatterned and patterned InGaAsP block are plotted in figure 1.3 by considering only \(\Gamma K\) direction. Figure 1.3(a) shows the dispersion relation of the unpatterned InGaAsP block considering an artificial lattice with a period of \(a\). Addition of an array of low dielectric constant, i.e. air holes, opens up a bandgap at the edge of the Brillouin zone \((k_\alpha/\pi = 1)\) as shown in figure 1.3(b) where the radius-to-lattice spacing ratio \((r/a)\) is 0.2. As the diameter of the air holes
holes gets bigger, the bandgap becomes wider and shifts to higher frequencies because of the increased overlap between the light and the air hole which is demonstrated in figure 1.3(c) where the $r/a$ is 0.4.

For wavevectors near $k/a$, the wave is backscattered due to Bragg reflection, which leads to coupling of the $+\pi/a$ and $-\pi/a$ wavevector solutions. The resulting standing waves may have their intensity localized either in the high-index regions or low-index regions, which leads to the opening of a gap at $\pm\pi/a$.

The bandstructure of a 2D photonic crystal having an array of air holes is depicted in figure 1.4(a) by considering the light propagation in both $ΓK$ and $ΓM$ directions. Figure 1.4(a) shows four bands where a complete photonic bandgap for the electric field polarized perpendicular to the axis of the holes (TE polarization) is obtained between the $M$ point of the second band and the $K$ point of the first band. The first and the second bands are known as the “dielectric” and “air” bands, which are derived from the distribution of the electric field. The magnetic field profiles of the dielectric and the air modes at the $K$ point of the first and the second bands respectively are plotted in figure 1.4(b) and (c). It can be seen that the dielectric band mode localizes its magnetic field in the air holes (or in the low refractive index material), see figure 1.4(b), whereas the air mode localizes its magnetic field in the dielectric material (or in the high index material), see figure 1.4(c).

The 2D calculations of the bandstructures can be applied if the photonic crystal structure is infinitely extended in the third dimension. In a planar photonic crystal suspended in air with a finite thickness, the third dimension is not periodic nor infinite. Therefore, the photons incident to the air/slab interface can escape from the slab if the incident angle is smaller than the critical angle.
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Figure 1.3: Dispersion diagrams for light propagating in one direction, $\Gamma K$, of (a) an unpatterned InGaAsP block, (b) patterned slab with a $r/a$ of 0.2 and (c) 0.4. As the hole size gets bigger a gap opens up at the edge of the zone.

Figure 1.4: (a) The band structure of the triangular lattice of air holes having the first four bands. The photonic bandgap is sandwiched between the first (dielectric) and the second (air) bands and shown in the gray region. The magnetic field distribution of (b) the dielectric and (c) the air band. The corresponding electric field has a curl relation with the magnetic field as in the Eqns.1.3 and 1.4. Therefore the node (antinode) of the magnetic field is the antinode (node) of the electric field.
These photons couple into the continuum of radiation modes and introduce an additional loss. It is thus important to consider the light cone above which the modes are leaky.

Figure 1.5 shows the band diagram of a triangular array of photonic crystal holes having a semiconductor refractive index of 3.4 which corresponds the dielectric constant of InGaAsP. The thickness of the slab is 0.44a and the radius is 0.3a where a is the lattice spacing. The band diagram is calculated by using a three dimensional plane wave expansion method which expresses the normal modes as a superposition of a set of plane waves. The calculation is done by using a commercially available software package, Crystalwave from Photon Design. Because of the lack of the symmetry in the vertical direction, the states are not purely TE (electric field perpendicular to the hole axis) or TM (electric field parallel to the hole axis) polarized, but are called even or odd modes considering their symmetry with respect to the horizontal mirror plane of the slab. The band diagrams show the even (TE-like) and odd (TM-like) eigenmodes where the first order band-gap is open for the guided modes that have even symmetries see figure 1.5(a). The black region is the continuum of radiation modes above the light line. In this region, the modes are leaky modes and not guided by the slab.

The width and the position of the photonic bandgap depend on some optical and geometrical parameters of the PhC. The width of the gap is determined by the radius-to-lattice constant ratio (r/a) and the refractive index ratio between the PhC material and the surrounding (n_{slab}/n_{env}). A sufficient r/a and n_{slab}/n_{env} will start to open a bandgap at the edge of the zone, see figure 1.5(a). For a constant index contrast, if the r/a ratio becomes higher, the bandgap becomes smaller because the air band edges shift towards higher frequencies due to the increased overlap with air. If the holes are too large or too small the bandgap closes. The air band modes, localizing their energy in the air-holes, are sensi-
tive to the holes refractive index when the air is replaced by a dielectric. Therefore, changing its refractive index, decreasing $n_{\text{slab}}/n_{\text{env}}$, decreases the width of the gap. The lattice type of the holes, i.e triangular or square, determines also the width of the bandgap. Keeping the other parameters the same, triangular array of the holes shows a wider bandgap. For thin PhC slabs, the slab thickness ($d$) is another important parameter to determine the width of the gap. The slab thickness should be properly chosen to have a wide bandgap; however, if the thickness is too thick the higher order modes will be present in the gap and will result in a closing of the bandgap. Therefore these modes must be suppressed by choosing the thickness of the slab approximately half the wavelength of the light in the semiconductor. The position of the bandgap depends on the geometrical parameters only, $r,a,d$, and can be altered by varying them.

1.5 Cavities and waveguides: Basic elements of photonic applications

Although the photonic crystal does not allow the propagation of a range of frequency of light in the photonic band gap, localized modes are possible. These modes originate from an intentionally introduced defect. The defect creates confined states where the field at a frequency in the band gap exists, but decreases exponentially away from the defect. The defect can be obtained by locally modifying the size, the shape, the position, or the dielectric constant of the photonic crystal structures which has been exploited to create cavities and waveguides [15–19]. The quality factor ($Q$), which is defined as the energy build up inside the defects by a resonant mode with respect to the energy which is lost per cycle of the mode, can be very high which makes these defects attractive to use in the investigation of the cavity quantum electrodynamics (cQED) [20, 21] and Purcell effect [22]. So far, various point-defect cavities and line-defect PhC waveguides have been demonstrated. In those geometries the horizontal confinement of light is provided by the photonic crystal holes which create a nearly perfect horizontal confinement if the defect is surrounded by a sufficient number of holes that act as a mirror. The vertical confinement of the light is provided by the total internal reflection. The primary cause for photon loss is usually in the vertical direction, from the slab to the surrounding medium. In order to minimize the photon loss of a cavity, i.e. to increase the $Q$ factor, the defect geometry should be optimized by modifying the size and/or position of the holes surrounding the cavity. Very high $Q$ values up to $10^5$ have been obtained by modifying the innermost holes of a single air hole removed photonic crystal cavity. The record $Q$ value up to $10^6$ has been obtained in double heterostructure cavities which are realized in waveguides [23].

A point-defect cavity which generates and localizes the light within a small modal volume can be constructed in a PhC structure by removing one (H1),
three (L3) air hole(s) or only by modifying two adjacent air holes in size or position (H0) without removing a hole as shown in figure 1.6.

The PhC waveguides are important elements in the photonic integrated circuits. They have been used to guide and transmit the electromagnetic waves between various devices which allow a large scale of optical device integration in a chip. When a row of the air holes is removed (W1) from the PhC structures as in figure 1.6(d), the line defect acts as an optical waveguide where light is guided with minimum propagation losses. The smallest propagation loss of 2 \text{db/cm} in silicon PhC has been reported for an air-bridge waveguide [17].

The point and the line defect cavities are realized in both deeply etched structures and membranes [7, 11, 15, 24–26]. The deeply etched structures have a core waveguide layer which is sandwiched between two cladding layers that have slightly lower refractive indices. The InP/InGaAsP/InP system is an example of such construction. This geometry provides a good heat sinking and makes the structures mechanically robust for device applications. However, the construction suffers from the fabrication limitations since a high aspect ratio is required; the holes must be deeply etched while preserving the verticality of the sidewalls. Another drawback is huge optical losses caused by the small refractive index contrast. Due to the index contrast, all the modes in the band gap may couple to the substrate which increases the optical losses. The highest Q factor of \sim 300 is obtained from a single missing row InP/InGaAsP/InP
Fabry-Pérot type cavity [27]. The relatively low $Q$ limits the applications of these structures.

The membrane structures, however, have a thin layer of the semiconductor, typically between 200 nm and 400 nm, and are freely suspended in air after etching the cladding layers and dissolving the underlying sacrificial layer. Due to the high refractive index contrast, the photonic crystal membrane type cavities offer a better confinement of the mode in the slab. Very high $Q$ factors can be obtained from the membrane structures while suppressing out-of-slab photon leakage with a small modifications in the lattice [15, 23]. The fabrication of the membrane structures is relatively easier and straightforward, and requires a low aspect ratio between the depth and diameter, which is generally not larger than unity, which results in a better verticality in the sidewalls. However, these structures are brittle and have a poor heat sinking which are the main drawbacks for device applications.

An interesting variant of the free standing membrane is to realize it on a low-index substrate without etching bottom cladding, for instance silica with index $n=1.48$. This kind of arrangement could provide a better mechanical stability and answers a series of mechanical problems inherent to membranes. Even though the silica is a poor thermal conductor, such an arrangement could provide a better heat sinking.

1.6 Application of the photonic crystal devices

The photonic crystal appears a strong candidate that can enable the miniaturization of the photonic devices and their large scale integration. Various active, i.e. lasers, splitters, and passive devices, i.e. photonic crystal waveguides, can be realized in a single chip with the sophisticated fabrication techniques. Owing to its light generation, manipulation and propagation inside the bandgap, the PhC device can form the basis of future optoelectronic and sensor devices which are becoming more ubiquitous in a commercial market.

Figure 1.7 represents some applications envisioned for the PhC structures to the field of the photonic integrated circuit. The very well known is the vertical-cavity surface-emitting laser (VCSEL) [4], as a one dimensional PhC, which has found a widespread use in consumer electronics, optical communication and printing. Near infra-red emission close to telecommunications wavelength of $1.5 \mu m$ was demonstrated in 1979 [28] by using a GaInAsP/InP system. The 5 cm x 5 cm 2D array of VCSEL having a record output power of $\sim 200$ W has been demonstrated [29].

The two dimensional photonic crystal membrane type nanocavities can confine the light in a small modal volume ($V_{\text{mode}}$) with an ultra high quality factor ($Q$). The high $Q/V_{\text{mode}}$ can give rise to obtain ultralow threshold powers of photonic crystal nanolasers. The membrane lasers having low threshold laser
power have been demonstrated in III-V semiconductor material systems in the telecommunication window of 1.3 $\mu$m and 1.5 $\mu$m [18, 30, 31]. Moreover, the PhC has been used to increase the efficiency of light emitting diodes (LED) by suppressing the light radiating in unwanted directions. They can be placed in the lateral side of the active semiconductor region and function as highly reflecting mirrors to reflect the radiation.

The photonic crystals form also various functional devices to manipulate optical signals in the telecommunication systems. The optical signals can be extracted from the network or inserted into it by using a PhC based add/drop filter which can be implemented in wavelength division multiplexed (WDM) optical communication systems. This add/drop function of the photonic crystal has been intensively researched [13, 14, 32, 33]. The simplest way to achieve an add/drop system is the selective coupling of a guided wave to a photonic crystal cavity where the energy is transferred to the cavity only at the frequency of the cavity mode not the other frequencies. The PhC can function as a polarization filter [9] due to its strong dielectric anisotropy. It can separate transverse-electric (TE) and transverse-magnetic (TM) polarization states of a signal. In the current data transmission systems electro-optical switches are intrinsically limited in terms of speed and power consumption. As an all-optical switch, the PhC offers an ultrafast switching time, switch-on time is on the order of a few picoseconds, and an ultralow switch energy of 13 fJ [34].

The classical light guiding mechanism provided by an optical fiber or a ridge waveguide, index guiding mechanism, leads to high propagation loss at the curvature of the bend. For this reason, PhC waveguides have been suggested for small curvature waveguides in micrometer size photonic chips.

Due to the genuine property of the PhC structures, they provide a new form of light guiding mechanism, bandgap guiding, which can be alternative to the
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index guiding for the photonic integrated circuit. This principle has been exploited in photonic crystal fibers [35]. A lateral guiding of light can be achieved by using a PhC waveguide. A waveguide is the key element of planar integrated optical circuits. These structures in principle could have abrupt bends over $90^\circ$. Nowadays, purely passive functions as guiding and bending of light are considered of secondary importance as compared to active functions.

1.7 Motivation and goal

The unique properties of the photonic crystal cavities have stimulated to realize a large scale integration of photonic devices; however, once the photonic crystal structures are fabricated, their optical properties are determined by the geometry of the structures and the electromagnetic property of the semiconductor material. As a result, their spectral properties are fixed. Therefore, these devices have been limited in their functionality, due to the lack of active and large tuning of resonant modes. The ideal device should be largely tunable, flexible, reliable, controllable and reconfigurable which are the key features that a photonic integrated circuit should have.

The extraction of the multiple wavelengths can be carried out by a series of drop filters which are the building blocks of an optical spectrometer whose role is to separate the signals. Many optical spectrometers have been realized using different technologies such as array waveguide gratings (AWGs) [36, 37]. However, these devices have the dimensions in the range of centimeters.

Recently, microfluidics has been successfully integrated in microphotonics devices to synergetically create highly functional devices [38, 39]. Since the advent of "optofluidics", many flexible, tunable and reconfigurable compact devices have been demonstrated in biomedical analysis and optoelectronic systems. In biomedical analysis, the optofluidic devices can act as highly sensitive sensors bringing many advantages such as a minimum consumption of the substance, portability and scalability of the devices, and cost effective automated packaging. The fluids in these systems can be used to dissolve the substance and to transfer it to the area to be analyzed optically.

Many functional microphotonics devices can be realized by combining with microfluidics. The realization of tunable devices, relying on the change in the refractive index, is becoming a more challenging task when the size of the device is miniaturized, since the refractive index change should be large enough to obtain large tuning. A large tuning has been introduced by immersing the device with various fluids such as water, alcohol, and glycerol [40–42]. Moreover, constructing microchannels in the chip could promote a local tuning of the devices while transferring the liquid through the channels. Since the fluids are easy to control, they offer reconfigurable and rewritable devices [43, 44]. Among various liquids, a liquid crystal (LC) is known to change its optical prop-
erties via electric field or temperature. A photonic device can be immersed into the LC and its optical properties can be modified by temperature.

A largely tunable photonic device can also be obtained by relying on photothermal effects [45–49]. The refractive index of the device can be modulated by temperature changes [50, 51]. Since the refractive index of a semiconductor is temperature dependent, the device does not require any additional material. The thermal tuning can be obtained by heating the device [50, 52–54], whereas the photothermal tuning can be achieved by heating the device as a consequence of the absorption of a laser beam.

A combination of two effects, optofluidic and photothermal, provides a control on active tuning of InGaAsP photonic crystal nanocavities. The optofluidic control of the cavities is achieved by infiltrating a liquid crystal material into the photonic crystal holes. The use of the LC offers many advantages over using other liquids as the infill source. One is the ability to change the effective refractive index of the cavity by temperature. A large tuning of the cavities has been demonstrated for LC infiltrated photonic crystal devices by employing temperature or electric field. Moreover, a local activation of the LC infiltrated devices, without perturbing any other device on the chip, can be achieved by relying on the photothermal effect where a laser beam is used for both excitation and heating.

The global infiltration of the liquids is less desirable when the device consists of different optical components because it can distort or eliminate the functionality of the other devices. Therefore, the ultimate tuning method can be obtained by locally infiltrating the liquids into the part of the structure. A local infiltration with the LC or with any liquid, i.e. glycerol or oil, can change the refractive index distribution of the PhC structures, which creates liquid cavities in the semiconductor material. These type of cavities offer an additional tunability when the infiltrated liquid is controlled by means of the photothermal effect.

Photonic crystals, in contrast to the AWGs, could provide an optical channel separation with much smaller footprints [13, 55]. A single PhC cavity with embedded luminescent material can be used as a tunable source by means of the photothermal effect. The photothermally tuned radiation can be coupled in a waveguide and guided to other parts of a circuit. This mechanism can be used to create on-chip spectrometer devices.

1.8 Thesis outline

This thesis concentrates on the optofluidic and photothermal control of PhC nanocavities to obtain tunable systems for photonic applications. To this end, different types of InGaAsP based PhC structures have been designed, fabricated and characterized.

Chapter 2 contains the fabrication procedure of the PhC structures and
their optical characterization. The chapter includes a brief overview of the state of art instruments used in the fabrication process. Various types of PhC structures were measured in a custom-modified photoluminescence set-up which integrated conventional far-field and near-field-scanning optical microscopy (NSOM), Atomic Force Microscopy, and lateral lensed-fiber light injection and extraction, and which allowed for in situ local liquid infiltration of the samples. Three dimensional finite difference time domain calculation results are included to determine the mode types.

Chapter 3 demonstrates the lithographic and photothermal tuning of the fabricated cavities. A lithographic control of the cavity resonances was achieved by varying PhCs’ geometrical parameters. A photothermal tuning of the cavities was demonstrated as a calibration experiment for LC infiltrated cavities.

Chapter 4 shows a study of the spatial intensity distribution of the resonant modes by infiltration of the PhC holes with fluids of varying refractive index, consisting of water-sugar solutions. The shift of the resonance frequency with variation of the refractive index of the holes, is a direct measure of the overlap of the mode with the holes. By systematically varying the lithographically defined parameters of a given cavity type, the mode intensity distributions for different cavity types were obtained. These results can be applied for the design of PhC cavity sensors.

Chapter 5 describes thermal and photothermal tuning of LC infiltrated PhC cavities. As the temperature of the LC infiltrated PhC structures was varied, a birefringence induced mode dependent tuning has been demonstrated where the orthogonal modes were shifted in opposite directions.

Chapter 6 shows photothermally tunable coupled cavity systems. The coupling of two very dissimilar cavities is investigated with different coupling configurations to obtain a strong coupling. The photothermal effect is employed to control the resonance wavelengths of the coupled modes.

Appendix A shows our ongoing work which describes tunable optofluidic devices constructed from selective infiltration of liquids. By selective infiltration of PhC waveguide holes, an optofluidic cavity was artificially realized and the photothermal control of its modes demonstrated.
Chapter 2

Fabrication process and characterization of the cavities

2.1 Introduction

This chapter covers the fabrication process, the calculation and the characterization methods of the photonic crystal structures. A 220 nm thick InGaAsP membrane type photonic crystal nanocavity was fabricated by using the state of the art nanofabrication techniques, see section 2.2. The computation method is explained in section 2.3 and is used to obtain the design parameters and mode profiles. The experimental characterization of the fabricated structures is conducted by using a room temperature custom-modified photoluminescence set-up, see section 2.4.

The InGaAsP semiconductor is a standard material for use at the telecommunication wavelength window near 1.55 micron. Therefore, the InGaAsP devices can be easily implemented into devices for the fiber-optic telecommunication system where they can function as waveguide multiplexer, demultiplexer, optical switch or add/drop filter. Furthermore, various semiconductor light sources can be embedded into InGaAsP materials. The InGaAs and InGaAsP quantum wells (QW's) have been widely used as internal light source for PhC structures [18, 30, 56]. However, the use of the quantum dots (QD's) has advantages over the QW's in certain applications. With QW's, there is larger radiation loss due to surface recombination of photoexcited carriers at the edges of the cavity holes [57]. Since both the central part of the cavity and the PhC cavity mirrors absorb light, these types of cavities suffer from reabsorption losses when passive application parts on a device have to be combined with active parts. This results in lower quality factors [58]. Because of
the much smaller absorption and reduced surface recombination loss, quantum dots are attractive alternatives especially for InGaAsP type materials. Colloidal and self-assembled quantum dots realized in various semiconductor materials have been available as light emission sources [59, 60]. The self-assembled quantum dots are the mostly used for device applications because of their reliability and availability as a planar semiconductor material. The reliability is a direct consequence of crystal quality, high purity and size reproducibility and controllability. The Stranski-Krastanov [59] mode is used to epitaxially grow the quantum dots. Recently, InAs quantum dots (QDs) have been successfully grown in a InGaAsP material system by using metalorganic vapour phase epitaxy (MOVPE) [61]. The QD’s can serve as efficient light sources in PhC structures with the emission wavelength determined by their size which is controlled during the epitaxial growth.

Figure 2.1 shows the schematic representation of the InGaAsP/InP material system used for the fabrication. A 220 nm thick InGaAsP quaternary layer has been grown on 1 μm InP buffer layer by MOVPE. The quaternary layer has one monolayer of self assembled InAs QD’s with a density of $3 \times 10^{10} \text{cm}^{-2}$. The 20 nm InP capping layer was grown on the top to protect the sample.

**2.2 Fabrication method**

The fabrication process includes a mask deposition, a resist coating, a lithographic definition and etching processes which are schematically represented in the figure 2.2.

A 400 nm silicon nitride ($SiN_x$) mask is deposited on top of the InP capping layer, see figure 2.2(a), by using a plasma enhanced chemical vapor deposition tool (Oxford Plasma-PECVD). The $SiN_x$ is formed by depositing silane ($SiH_4$) and ammonia ($NH_3$) at the temperature of 300 °C with the gas flows of 17 sccm and 13 sccm, respectively. After the deposition, the sample is placed in a spinner for a resist coating. A positive resist ZEP 520-A is preferred because it
Fabrication process and characterization of the cavities

Figure 2.2: The schematic representation of the fabrication process of the PhC structures. The sample after (a) the 400 nm SiN deposition, (b) the 400 nm ZEP 520-A spin coating, (c) the electron beam lithography and the resist development, (d) the reactive ion etching process, (e) the inductively coupled plasma etching and (f) anisotropic wet chemical etching.
has high resolution, high sensitivity and high resistance to dry etching process compared to the other resists. The thickness of the resist is determined by the spinning rate and the spinning time. By setting the rate at 4500 rpm and the time as 60 seconds, an approximately 400 nm thick resist is spin-coated on the sample as shown in figure 2.2(b). After the spin-coating, the sample is post-baked at 200 °C for 2 minutes.

2.2.1 Electron beam lithography

The electron beam lithography (EBL) is the first step in fabricating the sub-micron PhC structures with a beam of a few nanometer diameter. The device resolution is determined by the resist thickness. Ultimate hole diameters in the range one-third to one-half the resist thickness can be made. The system focuses a beam of electrons and scans the beam across the sample surface. In this work, a Raith-150 EBL system is used to define the PhC pattern in the resist. The computer controlled EBL system consists of a nanometer resolution mechanical stage to accurately position the sample, a scanning electron microscope (Leo-SEM) to make sample alignment in real time, an electron gun to supply electrons, and column to focus and to deflect the electron beam.

The hexagonal array photonic crystal structures having radius-to-lattice spacing ratio of 0.3 are defined in the EBL by using an acceleration voltage of 30 keV, see figure 2.2(c). For a successful EBL, the accurate determination of the charge dose value for the structures is essential. If the dose for the holes is too low, then the PhC holes will not be fully defined. If the dose factor is too high, then the radii of the holes will be larger than the designed one. The discrepancy in the radii of the designed and obtained values is caused by the back scattered electrons, which induce an additional exposure of areas surrounding the area where the electron beam is incident. This is known as proximity effect. Figure 2.3 shows the scanning electron microscope (SEM) images from a dose test sample where the dose values of (a) 40 Coulomb/cm², (b) 50 Coulomb/cm², (c) 60 Coulomb/cm², and (d) 70 Coulomb/cm² are used. The PhC holes are designed to have a radius of 75 nm. Figure 2.3(a) and (b) show that the dose factors of 40 Coulomb/cm² and 50 Coulomb/cm² cannot fully open the PhC holes while the dose values of 60 Coulomb/cm² and 70 Coulomb/cm² can fully open the holes, as shown in figure 2.3(c) and (d). The proximity effect is visible in figure 2.3(c) and (d) where the radii of the holes are enlarged by more than 10%. In practice, a dose somewhat larger than needed to open the resist is used, but with a designed hole size that is smaller than the size of the holes in the final device. After the EBL, the resist is developed by using n-amyl acetate for 60 seconds and is rinsed in a solution of methyl isobutyl ketone (MIBK) in isopropyl alcohol (IPA) for 45 seconds at room temperature.
2.2.2 Dry etching

The ZEP layer is not suitable as a mask for the InP etching because of its high etch rate and its deformations at high temperatures. For this reason, the pattern is first transferred to the SiN$_x$ layer and then to the semiconductor layer. To do this, the sample undergoes reactive ion etching (RIE) and inductively coupled plasma RIE etching for the hard mask and the semiconductor, respectively. The recipes of the etching processes are developed and optimized for the selectivity between the mask and etch layer.

The most traditional dry etching technique is the reactive ion etching which is an anisotropic etching process; here the anisotropy means that the etch is uni-directional, i.e. the sidewalls are vertical at the edge of the mask. The chemically reactive species for etching are supplied by a plasma that is generated above the sample in a cylindrical vacuum chamber by applying a strong RF (radio frequency) electromagnetic field, typically 13.56 megahertz at a few hundred watts, to the bottom electrode plate which is electrically isolated from the rest of the grounded chamber. The gas enters into the chamber by inlets at the top and the oscillating electric field ionizes and dissociates the gas molecules by stripping them of electrons. The electrons in the chamber are electrically accelerated and become more mobile compared to the more massive ions, which give a little response to the RF field. The electrons absorbed by
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Figure 2.4: The cross sectional SEM images of the PhC holes etched into the SiNₓ hard mask layer. The radii of the holes are (a) 70 nm, (b) 95 nm and (c) 135 nm.

The bottom electrode build up a negative voltage, DC bias voltage $V_{\text{bias}}$ which is typically in the order of a few hundred volts. The plasma has a higher concentration of positive ions compared to the free electrons due to the loss of the electrons. The $V_{\text{bias}}$ accelerates the positive ions towards the sample, where they collide and etch the sample.

The reactive ion etching is widely employed for etching SiNₓ or SiOₓ hard masks because it can be run at room temperature which prevents the deformation of the ZEP. The RIE of the SiNₓ is done in a RIE-Oxford Instruments Plasma Lab, etches represented in figure 2.2(d). The resist functions as an etching mask during the RIE process. The etching proceeds for 20 minutes under a chamber pressure of 2.0 Pa with a gas flow of tri-fluor-methane ($\text{CHF}_3$) at 60 sccm at 50 W RF power and the induced $V_{\text{bias}} = -(250 - 350) \text{V}$. The etching rate of the hard mask process is determined as 20 nm/min for the hard mask and 10 nm/min for the ZEP 520-A. The etching rate of the hard mask becomes smaller for smaller hole radius, an effect which is known as RIE lag. Therefore, the smaller holes will be more difficult to etch. Figure 2.4 shows the result of the RIE lag where the PhC holes having radius of 70 nm are not fully opened, see figure 2.4(a), while the holes having radii of 95 nm and 135 nm are fully opened in the mask layer, see the figure 2.4(b) and (c). After the pattern transfer to the hard mask, the remaining ZEP is removed by a 30 minute oxygen plasma.

The sample with patterned hard mask is then subjected to the inductively
Fabrication process and characterization of the cavities

Figure 2.5: (a) The cross sectional SEM image of the PhC holes etched into the InP after ICP-RIE. The top layer is SiN$_x$ mask. The nominal hole radius is 135nm, (b) The SEM image of the underetched PhC. The SiN$_x$ layer is suspended in air.

coupled plasma tool (ICP-Oxford Instruments Plasma Lab) to etch the InGaAsP layer and a part of the InP buffer layer, see figure 2.2(e). The ICP-RIE process has a higher etching rate due to the high ion density generated. The SiN$_x$ layer serves as an etching mask; however, it is also etched by the plasma process. Therefore, the process chemistry is optimized to obtain a high selectivity of InP/InGaAsP/InP layers and the SiN$_x$ mask. The process parameters are the gas flows of Cl$_2$/Ar/H$_2$ with the flow rates of 7/4/12 sccm, respectively, ICP power of 1000 W, RF power of 394 W at a pressure of 1.4mTorr. The etching proceeds at the temperature of 200$^\circ$C for 75 seconds. After the ICP etch, the remaining hard mask is removed by rinsing it in a solution of hydrogenfluoride (HF) in water.

2.2.3 Wet etching

The final step is a wet chemical etching of InP to release the InGaAsP membrane using a solution of HCl : H$_2$O = 4 : 1 for 10 minutes. The solution etches the InP layer faster than the InGaAsP layer, which is hardly attacked. To control the etching speed and to obtain uniform sidewalls, the solution is cooled down to 2$^\circ$C. The etching is an anisotropic process which removes the InP cladding layer and part of the InP buffer layer, see figure 2.2(e) and forms V-grooves under the holes [62]. The origin of the anisotropy is the various etch speeds in different crystallographic directions and the speed is practically zero normal to the (0, -1,-1) and the (0,1,-1) planes [63]. Care must be given to the r/a ratio to avoid the etch stop planes. If the ratio is high enough, the stop planes meet and break each other and the underetching proceeds. Figure 2.5(b) shows the cross sectional SEM image of an undercut region of the suspended mem-
brane. The V-groove and the finer structure in figure 2.5(b) are a result of the anisotropic etching and the etch stop planes.

Figure 2.6 shows the SEM pictures of the fabricated InGaAsP PhC membrane devices, (a) one air hole missing (simple H1), (b) seven air holes missing (simple H2), (c) two adjacent holes modified (modified H0), (d) surrounding six holes modified (modified H1), (e) three holes missing cavity (modified L3) and (f) one air row missing waveguide (W1).

2.3 Numerical calculations

The optical behavior of the PhC structures is completely described by the Maxwell’s equation; however, analytical solutions are not possible. Therefore, numerical calculation tools are employed to solve the Maxwell’s equation in the time domain and frequency domain.

Since the initial work of Yee [64], the finite difference time domain (FDTD) method has been widely used to solve the Maxwell equations. The method relies on the spatial and temporal discretization of Maxwell’s equations in a rectangular cell. Electric and magnetic fields are determined at every point in space, and each electric (magnetic) field component is surrounded by four magnetic (electric) field components as it is illustrated in figure 2.7(a). The computation region is divided into these cells where the material properties are specified. The fields are calculated at successive time steps with very small time increments.

For this work, a commercially available software package, CrystalWave by Photon Design, has been used to determine the lithographic parameters of the PhC structures and to analyze the experimental measurement. In the calculation, the structure consists of a 220 nm thick semiconductor layer, lying in the x-y plane with a refractive index of 3.4 which corresponds to the refractive index of the InGaAsP at 1.5 µm. Two air layers with a thickness of 500 nm are placed on top and bottom of the semiconductor layer. The three dimensional FDTD simulation is performed to calculate the cavity resonances by placing a point dipole source (x polarized) at a cavity’s off-center position as shown in figure 2.7(b). A (sinusoidal) pulse in time which has a Gaussian frequency distribution, is generated from the dipole source with a central wavelength of 1.5 µm and a bandwidth of 0.5 µm. A special care is needed for determining the value of the grid spacing (lattice spacing divided by the number of the grid cells) since it is the key parameter to minimize computational artifacts and to obtain the most accurate result. However, a decrease of the grid spacing, i.e. increasing the number of the grid cells, requires a quadratic increase in available memory. To obtain an accurate result with the available memory, the device is discretized in square grid cells to have 16 grid cells for each lattice
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Figure 2.6: SEM pictures of (a) simple H1 cavity, (b) simple H2 cavity, (c) modified H0 cavity, (d) modified H1 cavity, (e) modified L3 cavity and (f) PhC waveguide.
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Figure 2.7: (a) A schematic representation of the distribution of the electric and magnetic fields in the Yee cell which is used for the finite difference time domain calculations. (b) A typical simulation layout for calculation of the spectral response of a cavity (In this case one air hole missing cavity). The layout shows the cuboid (box) sensor (in red) and the dipole excitor (in yellow).

constant. Perfectly matched layers\(^1\) with a thickness of 8 gridcells are inserted in the computation regions to prevent the reflection of the field.

The spectral response of the system is obtained by taking the Fourier transform of the transient response captured by the sensors. The resonant frequencies and the quality factors of the cavities are retrieved by using a cuboid sensor (box sensor) which surrounds the cavity. Since all fields are polarized in the plane (\(TE\)), the magnetic field has only one component perpendicular to the membrane (\(H_z\)). Therefore, the intensity of the magnetic field (\(H_z\)) is plotted as a function of the wavelength extracted from the sensor. The spatial profile of the resonances is simulated by narrowing the width of the Gaussian pulse of the excitor and by recording the field evolution for each time step. After a certain time step, the exciter dies out and the mode profile is obtained. The quality factor calculation from the obtained spectrum does not provide a reliable result because the program terminates before the cavity response is fully evolved. Therefore, the \(Q\) factor of the resonances is obtained by using the Pade approximation method \([65, 66]\) which is available in the software package.

2.4 Characterization of the cavities

For the experimental characterization of the fabricated structures, a custom-modified room temperature photoluminescence (PL) set-up was built in a com-

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\(^1\)Perfectly matched layers are artificial absorbing layers that provide open boundaries to prevent reflection of the electromagnetic fields.
Fabrication process and characterization of the cavities

commercially available near-field scanning optical microscope set-up (Nanonics Multiview 4000). This set-up allows conventional far-field and near-field-scanning optical microscopy (NSOM), Atomic Force Microscopy (AFM), and lateral lensed-fiber light injection and extraction which provide various PL characterization methods in the set-up.

Figure 2.8 shows the schematic representation of the set-up. The sample is placed on an x-y-z stage where the positioning of the sample is determined by a piezoelectric controller. Among the various PL characterization techniques available on the set-up, the conventional method, the objective excitation and collection, is commonly used in the thesis to characterize the structures. A continuous wave laser (\(\lambda = 632 \text{ nm} \) or \(\lambda = 660 \text{ nm} \)) is used to excite the PhC devices. The excitation of the cavities and the collection of the PL signal are done by a high numerical aperture microscope objective (50X or 100X, N.A.=0.5). After dispersing the signal in a 50 cm spectrometer (Princeton Instruments Acton 2500i), the signal is detected by a liquid nitrogen cooled InGaAs array. The recorded PL signal conveys the information about the resonant wavelengths and their quality factors. Two gratings, 300 g/mm and 600 g/mm, are installed in the spectrometer with the spectral resolution of 0.7 nm and 0.4 nm respectively, for the wavelength of 1.5 \(\mu\text{m} \). Therefore, experimental \( Q \) values higher than 3500 will be limited by the spectrometer resolution. Unless indicated, the represented optical signals in this thesis are resolved by using the 300 g/mm grating where the \( Q \) higher than 2200 will be under the resolution limit.

In some parts of chapter 6 and the appendix A, the experiment is conducted by scanning near field optical microscopy (SNOM/NSOM) technique which was simultaneously developed by two different research groups of D. W. Pohl [67] and A. Lewis [68] after the proposal of Synge [69]. It is a unique technique because it provides both scanning probe and optical microscopy. The technique goes beyond the diffraction limit by scanning the sample with a dielectric probe which is positioned at a few nanometers away from the sample. The distance between the sample surface and the probe is controlled by a feedback mechanism; our set-up has a shear-force feedback mechanism [70]. Among various operation modes, our system operates in so called \textit{tapping mode} where the oscillation of the tip is perpendicular to the sample.

In the experiment, the excitation of the cavities is done by the objective and the collection of the PL signal is obtained by a 500 nm aperture diameter SNOM probe. In this case, the topography image of the cavity is first obtained by atomic force microscopy (AFM) scanning via the SNOM probe. After the scanning, the probe can be placed on a specific position on the cavity with a high resolution where the PL signal can be collected and transferred to the spectrometer via a single mode fiber. The use of SNOM probe in this experiment also allows a near field imaging of the cavity modes when an InGaAs avalanche photodiode detector (APD) is used. In the APD imaging configuration, the collected light is not spectrally resolved. All the experiments repre-
sent in this thesis are performed at room temperature.

2.4.1 Point defect cavities

The fabricated point defect PhC structures are characterized by using the conventional PL set-up under an excitation power of $10\mu W$ and a signal collection time of 1 second. The diameter of the laser spot is determined as 3$\mu m$. The spot is scanned over the defect area to optimize the signal for the highest intensity. Figure 2.9(a) shows the collected PL emission from InAs QDs from an unprocessed area. The inhomogeneously broadened emission is due to the size fluctuation of the QD’s. The maximum emission intensity is collected around 1500 nm. The decrease in emission intensity after 1575 nm is due to the decrease in the detector efficiency which is negligible beyond 1600 nm. The emission of the InGaAsP layer around 1250 nm is not fully present in the spectrum; however, the tail of it can be recognized around 1350 nm. The absence of the InGaAsP emission in the spectrum is due to the presence of the low pass filter in the setup which filters out the wavelengths below 1350 nm.

Figure 2.9(b) shows the PL spectrum of a simple H1 cavity with a lattice spacing $(a)$ of 533 nm. The peak at 1520 nm is the doubly degenerate dipole mode having a $Q^2$ factor around 100.

Seven air holes removed simple H2 cavities were also investigated. The $Q$ factor is calculated by dividing the resonance wavelength ($\lambda$) by the resonance linewidth ($\Delta\lambda$), so $Q = \lambda / \Delta\lambda$.\(^2\)
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Figure 2.9: PL signal from (a) InAs QDs, (b) simple H1 cavity in a photonic crystal having a lattice spacing of 533 nm, (c) simple H2 cavity in a photonic crystal having a lattice spacing of 533 nm.

Large size brought many modes into the bandgap since the number of modes increases rapidly with the cavity size. Figure 2.9(c) shows the resonance modes collected from a simple H2 cavity with lattice spacing 533 nm. Detailed analysis of mode types for such cavities can be found in Ref. [71]. We considered only high intensity modes which are easy to track. The resonant wavelengths occurring between 1400 nm and 1500 nm are called low-Q modes having values around 100. The other modes are called high-Q modes and have Q values up to 1500. Since the Q factors are naturally higher for larger cavities, the Q factors of the modes in the H2 cavity are larger than for the H1 cavity.

H1 cavities with a modification of the innermost holes are simulated, fabricated and tested. Figure 2.10(a) shows the 3D FDTD simulation result for a modified H1 cavity obtained in a photonic crystal having a lattice spacing of 511 nm and radius of 0.33a. The innermost holes are reduced to r/a = 0.25 and shifted 23 nm outwards (The geometric values are determined from the corresponding SEM image of the cavity.). Three peaks are labeled as M1 (λ=1655 nm), M2 (λ=1551 nm), and M3 (λ=1500 nm). Figure 2.10(b) shows the collected emission from the fabricated modified H1 cavity. The M1 peak is located at a wavelength higher than 1600 nm where the detector has the cut-off. The M1 peak corresponds to the dipole mode as shown in figure 2.10(c). The peak at 1511 nm (M2) having a resolution limited Q value up to 3000 corresponds to the non-degenerate hexapole mode (H-mode), see figure 2.10(d). The dou-
ble peaks occurring around 1497 nm 1495 nm ($M3$ and $M4$) having resolution limited $Q$ factors up to 2500 correspond to degenerate first order quadrupole modes ($Q1$ and $Q2$) as shown in figure 2.10(e) and (f). The modes in the lower wavelength region are second order quadrupole modes occurring at 1430 and 1427 nm. They have lower-$Q$ factor than the first order quadrupole modes, their mode profiles are not simulated since these modes are out of the scope of the thesis. The real $Q$ values of the $H,Q1$ and $Q2$ modes are limited by our spectrometer resolution. In ideal structures, the quadrupole modes are degenerate, i.e. two modes have the same frequency; however, these modes are very sensitive to the fabrication imperfections. The split in degeneracy by 2 nm in the first order quadrupole mode is a direct evidence of the disorder. The dipole mode, figure 2.10(a), is not present in the optical spectrum. Since the cavity size is enlarged by the modifications, the resonant wavelength of the dipole mode is in the wavelength region where the detector efficiency is negligible.

Figure 2.11(a) shows the 3D FDTD simulation result for a modified H0 cavity obtained in a photonic crystal having the same lattice spacing as the photonic crystal having the H1 cavity. The two adjacent holes are both reduced ($r'/a = 0.24$) and shifted about 13 nm. These adjustments create the smallest possible cavity which can host only very small number of modes [16]. Figure 2.11(a) shows two peaks that are labeled as $M1$ ($\lambda=1520$ nm) and $M2$ ($\lambda=1456$ nm). Figure 2.11(b) displays the spectrum of the modified H0 having the same lithographic parameters as used in the calculation. The mode occurring at 1463 nm has a $Q$ value 2000 and is identified as monopole mode and the other modes occurring at 1432 and 1423 nm having $Q$ values 1000 and 800 respectively are identified as degenerate dipole modes, as shown in figure 2.11(c) and (d).

For both the modified H1 and the modified H0 cavities, the $Q$ values are at least an order of magnitude larger than those of the simple H1 cavities. The higher $Q$ factors are due to the gentle spatial decay of the modal electric field pattern at the edge of the modified holes which reduces the out of plane loss, i.e. the number of field components with a wavevector above the light line is reduced [15].

The calculated optical spectrum of a modified L3 cavity is represented in figure 2.12(a). The photonic crystal having the L3 cavity has a lattice spacing of 470 nm. The two end holes of the cavity are slightly shifted by 70 nm which provides a good confinement of the fundamental mode. Six peaks are observed in the spectrum and labeled as $M1$, $M2$, $M3$, $M4$, $M5$, and $M6$. Figure 2.12(b) shows the PL emission from a fabricated modified L3 cavity built in a photonic crystal having the same design parameters as used in the calculation. The fundamental mode, $M1$ as shown in 2.12(c), is located at 1573nm having a $Q$ value of 2500 which is limited by the spectrometer resolution. The higher order modes, $M2$ (1477nm), $M3$ (1463nm), $M4$ (1451nm), $M6$ (1357 nm), have lower $Q$ values below 500. Their mode profiles are presented in figures 2.12(d), (e), (f), (g), and (h) respectively. The mode $M5$, figure 2.12(g) is not present in the
spectrum because it is more sensitive to the structural disorder [72]. The spectral distance and the identifications of the modes are also in good agreement with Ref. [72] where the \textit{M5} mode is expected to have a higher wavelength than that of \textit{M6}.

The modes represented in the calculated spectra have almost 3% higher wavelengths than those in the PL spectra. The first reason for the discrepancy is the discretization issue in the calculations. The circular shape of photonic crystal holes is not accurately represented by the square grid cells; therefore, some cells are located at the hole/semiconductor boundary where their refractive index is different. Decreasing the grid spacing will lower the discretization errors but it will require a large amount of memory and calculation time. The second reason is the fabrication imperfections. Even though the calculated parameters are obtained from the corresponding SEM images, fluctuations in the hole sizes and deformations of the hole shape result a shift in the resonance wavelength.
Figure 2.10: (a) The calculated optical spectrum of the modified H1 cavity in a photonic crystal having a lattice spacing of 511 nm. The innermost holes are reduced to 0.25\(a\) and shifted 23 nm radially outwards. (b) The PL signal collected from a fabricated modified H1 cavity in a photonic crystal nominally having the same lithographic parameters as provided for the simulation. The magnetic field distribution (\(\mathbf{H}_z\)) of (c) the dipole, (d) the hexapole, (e) and (f) the quadrupole modes. The dipole mode is located at the higher wavelength which is not observed in the spectrum due to the cut-off of the detector.
Fabrication process and characterization of the cavities

Figure 2.11: (a) The calculated optical spectrum of the modified H0 cavity obtained in a photonic crystal structure having a lattice spacing of 511 nm. The two adjacent holes are reduced to 0.24a and shifted by 13 nm. (b) The PL emission collected from a fabricated H0 cavity in a photonic crystal having the same design parameters as used in the calculation. The magnetic field distribution ($Hz$) of (c) the monopole, (d) the dipole modes.
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Figure 2.12: (a) The calculated optical spectrum of the modified L3 cavity built in a photonic crystal having a lattice spacing of 470 nm. The two end holes are shifted by 70 nm. (b) The PL spectrum collected from the fabricated L3 cavity in a photonic crystal having the same design parameters as used in the calculation. The magnetic field distribution (Hz) of the M1-M6 modes are represented in (c)-(h). Note that the M5 mode is not present in the spectrum.
Chapter 3

Lithographic and photothermal control of the nanocavities

3.1 Abstract

Hexagonal symmetry InGaAsP membrane type cavities with embedded InAs quantum dots as active emitters were investigated by room temperature photoluminescence experiments at wavelengths near 1.50 \( \mu m \). Cavities consisting of simple defects of just removing one or seven air holes were studied as well as modified cavities with additional holes decreased in size and shifted in position. The latter include the H0 cavity, in which only two adjacent holes in one or two directions, \( \Gamma K \) and \( \Gamma M \), were modified, but none removed. Low-Q cavity modes were observed for the simple cavities while high-Q modes were observed after modification of the surrounding holes. The resonant frequencies were varied over a large range of lithographic parameters both by changing the lattice spacing or the size of the modified holes. More than 15 nm reversible optical tuning of the resonance modes was observed by changing the applied laser power up to 500 \( \mu W \) on the sample. For thermo-optic tuning, this corresponds to a heating of up to 150 °C.

3.2 Introduction

Tunable nanocavities are important to realize compact and active photonic devices. So far various tuning methods have been demonstrated relying on a change in the dimension or in the effective refractive index of the cavities [73–79]. The optical path length can be varied by modifying the geometrical parameters of the cavity or by modulating the refractive index through a perturbation
of an intrinsic property of the semiconductor material. In both methods, a large and a controllable tuning can be obtained.

Solid and liquid microcavities have been studied extensively in different geometric configurations for a large scale of photonic applications [80–82]. Various methods have been employed to alter the spectral properties of the cavities, among them varying the geometrical parameters. It has been shown that tuning of a single solid cavity relying on its size or shape change is extremely hard and so far upto 1 nm tuning has been obtained in a fused silica microsphere by stretching it [83]. Therefore, the tuning of the solid cavities by changing their geometric parameters is fixed during the fabrication process. On the other hand, liquid microdroplets offer more flexibility on the modulation of the shape or size by employing the evaporation and condensation kinetics [84] or by applying electric field [85].

Free carrier, Kerr and thermal effects have been widely employed to change the refractive index of the semiconductor in which the cavity is made [45, 46, 86–91]. To modify the refractive index, modulating the free carrier density by electromagnetic fields has been demonstrated for the photonic crystal structures [92]. Free carriers directly contribute to the refractive index by increasing the plasma frequency and lead to an effective decrease of the refractive index which results in a blueshift of the resonance frequencies [46, 93, 94]. The free carrier effect also changes the absorption of the material via bandfilling, bandgap shrinkage and carrier absorption [86]. The change in absorption modulates the imaginary part of the refractive index of the semiconductor which changes the real part of it as governed by the Kramers-Kronig relation. This effect alters the refractive index on a nanosecond time scale and shifts the resonances to lower wavelengths [88, 89]. The Kerr effect results from the third order component of the electric susceptibility which leads to an intensity dependent refractive index. The change in the index occurs faster than that from the free carrier effect at a terahertz rate [91] and results in a redshift of the cavity modes. However, the tuning process by the Kerr effect is counteracted by the free carrier generation via two photon absorption as the optical pump power increases [89] unless a pump energy below the half of the gap is used [95]. The thermal effect relies on the change in the refractive index of the semiconductor by heating it [53, 96]. Compared to the free carrier and Kerr effect, the thermal tuning is much slower, in the order of microseconds, and the modes shift to higher wavelengths as the temperature increases.

The inherent geometrical flexibility of a planar photonic crystal structure offers a full control on the spectral properties of the cavities during its fabrication process. Any modification in the PhC hole size or lattice spacing yields a shift of the mode frequency with a variation of its quality factor (Q). The geometrical changes engender various types of modes with different spatial extensions and spectral characteristics situated in the photonic bandgap, enabling a defect mode engineering.
In this part of the thesis, a lithographic tuning of various types of cavities will be investigated, see sections 3.3.1-3.3.4. The tuning is obtained by changing the lattice spacing of the PhC structures or the size of the surrounding holes of the cavities. The purpose is to assess the reproducibility of the fabrication process and to establish the electron beam lithography and plasma etching process parameters. The lithographic parameters are not the same as the obtained values; therefore, the hole sizes have to be obtained after calibrations. Next, the single cavity tuning is studied by thermally or photothermally changing the refractive index, see section 3.4 and 3.5. The thermal tuning is obtained by varying the temperature of the sample using a heating stage whereas the photothermal tuning is obtained by varying the excitation laser intensity.


### 3.3 Lithographic tuning of the point defect nanocavities

Photonic crystal cavities offer a great advantage of controlling the wavelength, emission direction, polarization, and quality factor ($Q$) of the cavity modes by varying their geometric parameters; hole radius ($r$), lattice spacing ($a$), and thickness ($d$) [97–101]. Thanks to the geometrical flexibility, a large number of photonic crystal lasers operating at different wavelengths can be monolithically fabricated on the same chip where their lasing wavelengths can be changed by varying either their lattice constant or hole radii during the fabrication process [97]. Additionally, the add/drop filters with tailored frequencies can be made as an array of PhC cavities. Lithographic tuning can also be used to realize spectrally encoded photonic crystal nanocavities for biosensing [100]. The change in the parameters also modulates the $Q$ factors. Therefore, the lithographic control of the cavities is also necessary to control the $Q$ factors.

Owing to the scaling property of the Maxwell’s equations, the geometrical parameters are normalized to the lattice spacing for the sake of simplicity. Therefore, the wavelength tuning can be obtained by changing the lattice spacing for fixed $r/a$ and $d/a$ ratios. Since the slab thickness is constant, the $d/a$ ratio will vary as the lattice spacing is varied which brings a sublinear change in the resonant wavelength [97]. In the case of the radius change, the change in the filling fraction of the dielectric material will shift the resonances.
3.3.1 H1 type of cavities

A simple H1 cavity is obtained by leaving one air hole in the array unetched. The cavity supports two degenerate, linearly polarized dipole modes. The modes are derived from the air band and therefore are called donor modes. The dipole mode has a strong electric field at the cavity center without any preferred direction; however, its polarization is sensitive to the cavity symmetry, and if the symmetry is broken, the x and the y polarized modes become distinct with polarizations in perpendicular direction, see figure 3.1. A typical optical spectrum of a simple H1 cavity obtained in a photonic crystal structure which has a lattice spacing of 496 nm is represented in figure 3.1(a). The doubly degenerate dipole mode is located at the wavelength of 1434 nm with a Q factor of 60. The PL spectrum also shows additional peaks towards higher wavelength located near the dielectric band edge. These modes located at 1564 nm, 1570 nm, and 1589 nm are the non-localized shallow acceptor modes having a Q factor around 1000 and are determined by a gradient in hole size due to the fabrication error [102]. Figure 3.1(b) shows that the degeneracy of the dipole mode of another H1 cavity in a photonic crystal having a lattice spacing of 533 nm is lifted due to an intentionally introduced asymmetry in the cavity region by increasing the size of two innermost holes. A 20 nm splitting is induced due to a 30 nm size difference in the radii of the two innermost holes. The modes located at 1500 nm and 1520 nm are the orthogonally polarized, x-polarized, see the magnetic field profile (Hz) in figure 3.1(c), and y-polarized, see figure 3.1(d), dipole modes. Both have low Q values ∼100 which is characteristic for this cavity [26].

In order to investigate the tuning effect, a series of simple H1 cavities are fabricated by varying the lattice spacing a while keeping the r/a nominally at 0.3. In this way, the resonant modes can be tuned throughout the emission range of the InAs QDs. We fabricated a large series of simple H1 cavities that are obtained in photonic crystals having a lattice spacing which varies from 422 nm to 544 nm with 3 nm increments. Figure 3.2(a) shows the shift of the dipole mode with four simple H1 cavities. As the lattice constant a is increased from 492 nm to 540 nm, the dipole mode (labeled as mode A) is redshifted by 80 nm due to the increase in the effective cavity length. The cavities in PhCs with the lattice spacings of 492 nm and 508 nm show a split dipole mode while at others the split is hardly observed. The split is caused by the variations in the innermost hole sizes which are induced during the fabrication process. The modes B and C correspond to the bandedge modes and they are also redshifted with the increase in the lattice spacing.

To see how accurately the resonance modes can be controlled by this method, data from several resonances in many simple cavities are compiled in figure 3.2(b). The resonances scale very well with a as expected [97]. The scatter from the straight line fits is the largest for the shallow acceptor modes in the H1 cavities. These modes are derived from fabrication imperfections.
Figure 3.1: (a) The collected photoluminescence emission from a simple H1 cavity in a PhC with a lattice spacing of 496 nm. The spectrum shows the degenerate dipole mode and the bandedge modes. (b) The PL emission from another H1 cavity in a PhC with a lattice spacing of 533 nm. The degeneracy is lifted and almost 20 nm distance is obtained between the x and y polarized dipole modes. (c) and (d) the calculated magnetic field mode profile ($H_z$) of the $x$ and $y$ polarized dipole modes in (b). One innermost hole is intentionally made smaller in diameter to break the cavity symmetry in order to simulate the split dipole modes.
Figure 3.2: (a) The photoluminescence spectra obtained from four different simple H1 cavities realized in photonic crystals having different lattice spacings. The mode $A$ is the dipole mode and it has a small split induced at the lattice spacings of 492 nm and 508 nm. The modes $B$ and $C$ are the shallow acceptor modes. (b) Resonant wavelength tuning vs lattice spacing for the simple H1 cavities.

caused by both the EBL and the dry etching process. These modes will not be considered in the rest of this thesis because they have large mode volumes. It should be noted however, that they can be easily made to lase because of their high-$Q$ [103]. The scatter for the other modes in the H1 is typically 10 nm. This result was obtained without any attempt to optimize the control over the lithographic tuning. The positions of the H1 resonances agree well with calculations when the $r/a$ is used as a fit parameter in the range of $0.3 \leq r/a \leq 0.35$.

Higher $Q$ values and different cavity resonances are obtained when the holes around the H1 cavities are modified [104, 105]. Reducing the size ($r'$) and/or shifting the center of the holes ($s$) radially outward enlarges the size of the simple H1 cavity. The modifications yield an increase in the $Q$ value of the dipole mode due to a better photon confinement inside the cavity. Moreover, the larger size shifts the wavelength of the dipole modes and pulls different modes from the air band into the photonic bandgap. These modes are named according to their symmetries: the degenerate quadrupole mode and non-degenerate hexapole and monopole modes. Figure 3.3(a) represents the 3D FDTD calculation result for the normalized frequency ($a/\lambda$) dependence of each mode as a function of the modified radii of the innermost holes keeping their positions fixed. The simulated modified H1 is realized in a photonic crystal with a lattice spacing of 500 nm. The radii of the holes except the innermost holes are set to
0.3a and the radii of the six innermost holes are varied in size. The thickness of
the slab is taken as 0.44a. The dashed line represents the calculated air
band for the system. Without hole modifications, \((r'/a=r/a=0.3)\), only the de-
generate dipole mode exists in the bandgap with a calculated \(Q\) value of 200.
As the radii decrease, the other modes, the hexapole, the quadrupole and the
monopole modes, are pulled into the bandgap. The calculations represented
in figure 3.3(a) are in good agreement with those of Ref.[104]. Figure 3.3(b)
shows the PL emission collected from a modified H1 cavity in a PhC with a
lattice spacing of 511 nm. Here, not only the innermost holes of the cavity
are modified by setting the radii as 0.18a but the positions are also shifted by
0.1a nm radially outward. Therefore, the wavelength of the peaks cannot be
directly compared to the calculation result\(^1\). The dipole mode (labeled by \(D\)) is
located at 1617 nm and has a \(Q\) value of 800. The non-degenerate hexapole
\((H)\) and monopole \((M)\) modes are located at 1457 nm and 1367 nm and they
have \(Q\) value of 2000 and 1000 respectively. The split degenerate quadrupole
modes \((Q_1\) and \(Q_2)\) are at 1451 nm and 1446 nm with \(Q\) values of 2200 and
2000 respectively. The calculated \(Q\) values of the same cavity are 1500 for the
dipole, 7000 for the hexapole, and 6000 for the quadrupole modes. Similar to
the dipole mode, the quadrupole mode is also sensitive to the asymmetries in
the cavity region and splits due to the fabrication imperfections. The modes
occurring at lower wavelength than the monopole mode are the second order
dipole and quadrupole modes.

A further defect mode engineering by means of the lithographic control is
also feasible. The number of modes or the type of modes in the bandgap can
be controlled. Introducing a fractional edge dislocation, for instance, affects
the dipole mode which can be tuned by modifying the hole sizes [106]. The
monopole mode, for example, is attractive for its good confinement inside the
semiconductor and can exhibit an ultralow threshold lasing operation when only
the innermost holes of the cavity are made elliptically shaped [104].

As can be seen in the calculations shown in figure 3.3(a), a fine tuning of
the cavity modes can be obtained while the radius \((r')\) of the innermost holes
is varied without introducing any change in the lattice spacing. Figure 3.4(a)
shows five different spectra obtained from the modified H1 cavities in a PhC
with \(a\) of 480 nm and different \(r'\). An increase in \(r'/a\) from 0.22 to 0.26 shifts the
dipole (1586 nm), hexapole (1444 nm), and quadrupole (1436 and 1426 nm)
modes to the lower wavelengths and at the highest \(r'/a\) only the dipole mode is
present in our measurement range. The \(r'/a\) dependent resonant wavelength
shift is plotted in figure 3.4(b). The figure suggests that the modes are almost
linearly blueshifted by more than 35 nm, 90 nm, and 60 nm for the \(D\), \(H\) and \(Q\)

\(^1\)Only a limited number of cavity-types has been simulated as a guide for design and iden-
tification. The long calculation times prevented a detailed calculation of all designs prior to the
fabrications. Due to the long calculation times, it was also difficult to calculate the theoretical \(Q\)
values of the cavities.
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Figure 3.3: (a) The 3D FDTD calculation result for the resonant modes of a modified H1 cavity as a function of the modified radius of the six innermost holes. Their positions are not changed. The photonic crystal has a lattice spacing of 500 nm and a \( r/a \) of 0.3. The dashed line represents the airband where at \( r'/a=r/a=0.3 \) only the dipole mode is present. (b) The PL emission from a modified H1 cavity in a PhC with a lattice spacing of 511 nm. The modes are identified as the dipole (D), the hexapole (H), the quadrupoles (Q_1) and (Q_2) and the monopole (M). The modes at lower wavelength than the monopole mode are the second order modes.

modes, respectively\(^2\). The slope of the linear fit line for each mode is different as a result of the different sensitivities of the modes to the hole size change. It shows that the \( D, H \) and \( Q \) modes have a tuning rate of 1.75 nm, 4.5 nm and 3 nm, respectively, in wavelength shift per 1 nm change in the radius. Therefore, the \( H \) mode is the most sensitive mode to any lithographic change of the cavity. The experimental data presented in figure 3.4 are in a good agreement with the simulation results represented in figure 3.3(a) where the \( r' \) ranges from 0.22 to 0.26. In this interval, the modes are almost linearly shifted and a 1% deviation occurred in the normalized frequencies of the dipole and the quadrupole modes in the experimental and the simulation data, whereas almost a 3% deviation occurred for the hexapole mode. The discrepancies are induced due to the uncertainties in the fabricated structure’s hole sizes. The high discrepancy is expected for the hexapole mode because of its high sensitivity to the uncertainties.

3.3.2 H0 type of cavities

The smallest possible cavity can be obtained by modifying two adjacent holes in the hole array in size and/or position without removal of any holes. The two holes either in the \( x \), in the \( y \) or in both directions are shown in the SEM pictures displayed in figure 3.5. This type of cavity is called "H0" which exhibits

\(^2\)Only one quadrupole mode is considered.
Lithographic and photothermal control of the nanocavities

Figure 3.4: (a) The photoluminescence spectra collected from five different cavities having the same lattice spacing of 480 nm but different radii of the innermost holes. The blueshift of the modes is observed for the dipole ($D$), the hexapole ($H$) and the quadrupole ($Q$) modes as the size of the modified holes get bigger. (b) The resonant wavelength dependence as a function of the radius modification. The straight line is the best fit of the data.

An ultrasmall mode volume of $0.25(\lambda/2n)^3$ [16]. The cavity supports a monopole and a degenerate dipole mode having theoretical $Q$ values in excess of $6 \times 10^4$ [16].

The data in figure 3.6(a) are collected from an H0 type cavity obtained in a photonic crystal with a lattice spacing of 511 nm. The two adjacent holes in both directions are modified by reducing their radii to $0.22a$. The two holes in the $x$ direction are laterally shifted by $0.12a$ and the two vertical holes in the $y$ direction are shifted by $0.06a$. The monopole ($M$, $\lambda=1540$ nm) and dipole ($D$, $\lambda=1508$ nm) modes are found in the bandgap. The $M$ and $D$ modes have the $Q$ factors about 3000 which is limited by the spectrometer resolution. The modes at the lower wavelengths are the second order dipole modes which are out of interest.

A series of H0 cavities are fabricated in order to investigate the lithographic effect on the resonant wavelengths. Only two adjacent holes in the $x$ direction are reduced in their size. Figure 3.6(b) shows the collected PL emissions from six H0 cavities in PhCs having the same lattice spacing ($a=530$) and radius to lattice spacing ratio ($r/a=0.3$). The radii of the two adjacent holes are changed from $0.22a$ to $0.27a$ and the holes are not displaced. When $r/a = 0.22$ the modes $M$, $D_1$ and $D_2$ which are occurring at 1551, 1525 and 1515 nm respectively, are apparent. Slight increase in $r'$ moves the resonant modes to lower
wavelengths and finally when $r'/a = 0.26$ is reached, the cavity does not host any mode anymore. Figure 3.6(c) shows the change in the resonant wavelengths as a function of the modified radius. The straight lines represent the best fit line where their slopes suggest that the monopole mode has a larger tuning rate than the dipole modes to the hole size changes.

### 3.3.3 H2 type of cavities

Seven air holes unetched PhC nanocavities (H2) are also fabricated to investigate the lithographic effect on the resonant wavelength change. Contrary to the H1 and H0 types of cavities, no modification on the innermost holes is introduced for the H2 cavities; nevertheless, due to the size of the H2 cavity, many modes are found in the bandgap with high $Q$ values. Figure 3.7(a) shows the PL signal collected from a H2 cavity in a PhC with a lattice spacing of 494 nm and the hole radii of $0.3a$. The modes labeled as M1, M2, and M3 have high $Q$ factors ($HQ$ modes) around 1000 whereas the modes labeled as M4, M5 M6 have lower $Q$ values ($LQ$ modes) less than 500. Figure 3.7(b) shows that as the lattice spacing of the photonic crystals hosting four H2 cavities is increased from 486 nm to 533 nm, the cavity modes are redshifted due to the increase in the effective cavity length. The $HQ$ modes ($M1$, $M2$, $M3$) are redshifted by more than 100 nm after the $a$ is increased by 58 nm. The $LQ$ modes ($M4$, $M5$, $M6$) are redshifted by more than 20 nm when the lattice spacing is increased by 24 nm. In order to analyze the tuning rate of the modes, the wavelength positions of the high intensity peaks are plotted in figure 3.7(c) as a function of the lattice spacing. The best fit lines of the data show that the $HQ$ modes
Figure 3.6: (a) The photoluminescence signal obtained from a H0 cavity in a PhC with a lattice spacing of 511 nm. The two adjacent holes in the $x$ direction are modified by setting their radii as $0.22a$ and shifting them by $0.12a$. (b) The photoluminescence spectra of six different H1 cavities in PhCs having the same lattice spacing but different hole modification. (c) The resonance wavelength shift of the modified H1 cavities as a function of the hole modification, as derived from (b). The straight lines are the best fit of the data.
have a high mode tuning rate of 1.75 (nm/nm) (1.75 nm wavelength shift in 1 nm lattice spacing change). The LQ mode, on the other hand, has a lower tuning rate of 1 nm/nm. The scattering for both LQ and HQ modes are less than those obtained in simple H1 cavities, typically 6 nm. The smaller scatter value attests that the modes in the wider cavities are less sensitive to the fabrication imperfections.

### 3.3.4 Comparison between the cavities and lithographic control of the $Q$ factors

The lithographic control of the cavities’ geometry offers a powerful tool to manipulate their spectral properties. The point defect cavities exhibit a number of well defined modes. The number of the modes increases with the cavity size. The lithographic tuning rate of the same type of mode varies with the cavity type. The dipole mode which exists in both the H1 and H0 types of cavities has a higher tuning rate in the H0 type of cavities as the radii of the two adjacent holes are changed in size. Consistently, the tuning rates of the H2 cavity modes have the smallest values as compared to the other modes in the H0 and H1 cavities. Therefore, the H2 cavity has the advantage of being less sensitive to the fabrication errors, see the figure 3.7(c). The hexapole mode in the modified H1 cavities has the largest tuning rate with the change in the radii of the innermost holes. This is expected since the in-plane electric field of the modes largely exists inside the holes as shown in figure 3.8(a) and (b). As a consequence, the wavelength of this mode will be most sensitive to the fabrication fluctuations.

The lithographic control of the PhC structures also determines the $Q$ factor of the resonant modes. In order to obtain a high $Q$ mode, the horizontal and the vertical confinement of the mode should have minimum light leakage. The total $Q$ factor is given by $Q = Q_\perp + Q_\parallel$ where $Q_\perp$ is the vertical $Q$ factor and $Q_\parallel$ is the horizontal $Q$ factor. The horizontal quality factor ($Q_\parallel$) depends on the number of the holes surrounding the cavity and can be maximized with a sufficient number of the holes. A 2D FDTD calculation is performed to investigate the dependence of the $Q_\parallel$ factor to the number of the surrounding holes. The $Q_\parallel$ factor of the dipole mode from a simple H1 cavity with an effective refractive index of 2.65 for 1.5 $\mu$m [11] built in a PhC with a lattice spacing of 500 nm and the PhC hole radius of 0.3$a$ was calculated for different number of the surrounding holes. Figure 3.9 shows the calculation result where a monotonic increase on the $Q_\parallel$ has been observed as the number of the air holes reaches four. After adding one more hole, the $Q_\parallel$ factor suddenly increases by a factor of two and then saturates with the increase in the number of the holes.

The $Q$ values obtained in figure 3.9 are determined by the Pade approximation [65, 66]. Since there is no loss introduced in the 2D calculations, the low values of the $Q$ are not realistic and the values are limited by the Pade
Figure 3.7: (a) The signal collected from the H2 cavity in a photonic crystal with a lattice spacing of 494 nm. Six modes are observed in the spectrum which are HQ \( (M1, M2, M3) \) and LQ \( (M4, M5, M6) \) modes. (b) Four spectra obtained from H2 cavities in photonic crystals with different lattice spacings. (c) The resonant wavelength shift as a function of the lattice parameter.

Figure 3.8: The simulated electric field mode profile of the hexapole mode, (a) \( E_x \) and (b) \( E_y \).
The 2D simulation result of the dependence of the horizontal $Q$ factor ($Q_\parallel$) of a dipole mode to the number of the surrounding air holes. The saturation in the $Q$ values is unexpected and considered as a computation artefact since in a lossless medium, the $Q$ should increase as the number of the holes increases. However, the result gives an indication on the minimum number of the holes that is necessary to surround the defect in order obtain $Q$ value around $10^3$.

The vertical $Q$ factor $Q_\perp$ is determined by the total internal reflection and can be optimized if the electric field distribution of the mode varies smoothly at the edge of the cavity. Therefore, a geometrical modification of the holes will modify the $Q_\perp$ and may suppress the light leakage from the cavity. If the $Q_\parallel$ factor is maximized, then the maximum $Q$ factor is reached when the $Q_\perp$ factor is optimized. In the experiments, more than ten holes surrounding the cavity are etched. Therefore the $Q$ factors of the modified H1 and H0 cavities are determined by the hole modifications. This effect has already been observed in the previous figures 3.4(a) and 3.6(b). Figure 3.10 shows the variation of the $Q$ factor of each mode as determined from those figures as the modification is introduced. The $Q$ factor of the dipole mode from the modified H1 cavity in figure 3.10(a) rapidly increases when the radii of the innermost holes are reduced from 0.27$a$ to 0.22$a$. The $Q$ factor has the same value as in the simple H1 cavity when the modified hole radii are close to the unmodified value, i.e. 0.27$a$. A similar trend has been observed for the hexapole and quadrupole modes where the modifications nonlinearly decreases the $Q$ factors as the radii of the innermost holes increase.

The $Q$ factors of the H0 cavities do not exhibit a clear trend within the range of the parameters shown in the figure 3.4(c). The monopole mode has its maximum value when the $r'=0.25a$. The dipole modes (Dipole 1 and Dipole 2) show no significant change in the $Q$ factor with the radius changes.
The obtained quality factor for the H1 and H0 cavities as a function of the hole size changes. The dependence of the $Q$ factor of the (a) dipole and (b) hexapole and quadrupole modes collected from the modified H1 cavities as the innermost holes are changed in radius. (c) The dependence of the $Q$ factor of the monopole and dipole modes to the hole changes of the H0 cavities.

In the above discussion, we only considered intrinsic losses for ideal cavities. In practice, significant losses exist due to scattering as a result of fabrication imperfections such as irregular positioning of the holes, hole shape deviations, hole side roughness etc. In addition, the samples contain QD's that absorb and scatter the excited light in unpumped parts of the sample. The intrinsic effects are expected to lead to $Q$'s of up to a few times $10^4$ for our cavities. The QD absorption is estimated to be insignificant for $Q$ up to $10^3 - 10^4$ [107].

### 3.4 Thermal tuning

The lithographically defined parameters provide a control on the resonance frequencies and the $Q$ factors of the cavities; however, due to the fabrication tolerances, there will be deviations between the desired and the obtained wavelengths. Therefore, a post-processing cavity tuning method is required to fine
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Tune the resonant wavelengths. Also, the active tuning is required for many applications. In this part, the thermal tuning of the optical properties of the point defect cavities is investigated. The tuning relies on the change in the refractive index of the semiconductor due to its temperature dependence.

A temperature tuning will result in principle from thermal expansion. A rough estimate yields \( \Delta \lambda / \lambda \approx \Delta l / l = \alpha \Delta T \), so that \( \Delta \lambda / \Delta T \approx \alpha \lambda \). With \( \alpha \sim 5 \times 10^{-6} K^{-1} \) for InGaAsP and \( \lambda \sim 1.5 \times 10^3 \), this gives a tuning of \( (\Delta \lambda / \Delta T) \sim 6 \times 10^{-3} \text{nm/K} \). Therefore, the thermal tuning of the modes originates from the change in the refractive index of the material due to the change in the optical excitonic bandgap [51, 108].

The thermal control of the cavities is accomplished by using a current controlled heating stage where the samples are mounted on. The figure 3.11(a) shows the photoluminescence spectrum collected from a modified H1 cavity exhibiting four modes, the dipole (\( D, \lambda = 1592 \text{ nm}, Q=600 \)), the hexapole (\( H, \lambda = 1453 \text{ nm}, Q=1200 \)) and the split degenerate quadrupole modes (\( Q_1, \lambda = 1438 \text{ nm}, Q=600 \), and \( Q_2, \lambda = 1430 \text{ nm}, Q=1000 \)). The lattice spacing of the photonic crystal hosting the cavity is 480 nm and the innermost holes are modified only in the size (\( r' = 0.22 \)) without displacement. To tune the cavity modes, the temperature of the stage is increased up to 70 °C. Figure 3.11(b) shows the six spectra collected from the cavity at six different temperatures. As the temperature is increased from 20 °C to 64 °C, the modes, \( D, H, Q_1 \) and \( Q_2 \), redshift up to 6 nm. In order to investigate the tuning of each cavity mode, the resonant wavelength shift as a function of the temperature is plotted in the figure 3.11(c)-(f). The tuning of all modes shows a strong linear dependence on the temperature change where a tuning ratio, \( d\lambda /dT \), of 0.1 nm/°C is obtained which is in good agreement with the literature value [50]. The temperature tuning is a reversible and no hysteresis is observed. this tuning is much larger than the tuning rate estimated for thermal expansion.

The temperature effect on the mode tuning is slightly different for the different modes because of their different spatial electric field distributions. Therefore, the modes will experience different refractive indices. However, the tuning rate deduced from the slopes of the best fits in the figures 3.11(c)-(f) is nearly the same for all modes; the slopes are 0.112 nm/°C, 0.115 nm/°C, 0.105 nm/°C and 0.106 nm/°C for the \( D, H, Q_1 \) and \( Q_2 \) modes, respectively.

3.5 Photothermal tuning

Photothermal tuning of a cavity by irradiating it with a focused laser beam is a convenient tuning mechanism to obtain the desired wavelength. The temperature changes due to the absorption of the laser power. Figure 3.12(a) shows three different PL spectra obtained from a modified H1 cavity (\( a = 511 \text{ nm}, r'/a = 0.23, s = 26 \text{ nm} \)) as the power of the CW pump laser (\( \lambda = 660 \text{ nm} \)) increases.
Figure 3.11: (a) The PL emission of the modified H1 cavity. (b) Six PL spectra collected at six different temperatures, (c)-(f) the thermal tuning of the individual modes.
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Figure 3.12: (a) The photoluminescence spectra collected from the modified H1 cavity at three different excitation powers and (b) the resonance wavelength tuning vs. applied excitation power.

The high-$Q$ modes, $H$, $Q_1$ and $Q_2$ clearly redshift as the excitation power increases from 100 $\mu$W to 500 $\mu$W on the sample. Significant decrease in both the $Q$ values and the intensity is observed as the pump power increases as a consequence of the free carrier generation. Figure 3.12(b) shows the laser power dependent wavelength shifts from the same cavity. The modes are redshifted more than 15 nm as the applied power is increased to 500 $\mu$W. The redshift of the modes is attributed to the change in the refractive index of the cavity due to cavity temperature increase. The increase is estimated to be more than 150 $^\circ$C by considering the value found in the previous section. The large temperature increase explains the reduced cavity emission at the higher values, related to increased nonradiative recombination from the QD’s. The large temperature increase results from the poor cooling of the free standing membrane. The tuning is reversible and no hysteresis has been observed. The photothermal tuning completely dominates the other optical tuning effects such as the free carrier effect under continuous wave conditions. The photothermal tuning is a simple and convenient way of all-optical tuning. Applying the optical tuning method to lithographically defined cavities, one can have full control of obtaining the desired wavelength from a cavity since the accuracy of lithographic tuning is 10 nm whereas optical tuning has a range of 15 nm.

3.6 Conclusion

In this chapter, the lithographic control of the various cavities has been demonstrated. By changing the cavities’ geometry during the fabrication, the reso-
nant wavelengths of the H1, H0 and H2 were tuned throughout the InAs QDs emission line. The lithographic parameters also modify the $Q$ factors of the resonances by changes of the innermost hole diameters or the number of the holes surrounding the defect.

The thermal and photothermal tuning methods were demonstrated for controlling single cavity resonances. The methods rely on the change in the cavity’s effective refractive index due to the induced temperature. The temperature is varied either by using a heating stage or a focused laser beam. In both cases, a large and reversible tuning of the cavity resonances was obtained.
Chapter 4

Optofluidic control of InGaAsP point defect photonic crystal nanocavities

4.1 Abstract

The optofluidic control of InGaAsP photonic crystal nanocavities is investigated by immersing the nanocavities in various liquids. A large tuning of the band edges and cavity resonances is obtained as the cavities effective refractive index is changed due to the infiltration. The sensitivities, the magnitude of wavelength shift divided by the refractive index difference, of various types of modes from different cavities were analyzed. Systematic trends of the variation of the sensitivity with increase of the overlap of the modes with the PhC holes are observed for varying cavity types as well as for a given mode within a cavity type. A maximum sensitivity of 300 nm/RIU (refractive index unit) is observed, corresponding to ~25% mode overlap with the holes and complete infiltration of the aqueous solution used. The experimental results are confirmed with the three-dimensional finite difference time domain calculations. The findings presented in this chapter can be used for realizing tunable, reconfigurable microphotonic devices and (bio)chemical sensing.

4.2 Introduction

Recently, microfluidics has been successfully integrated in optics to synergetically create highly functional devices [38, 39]. In the telecommunication and op-
toelectronics areas, the integration has been exploited to control microphotonic devices to obtain largely tunable, reconfigurable optical devices. In biology and chemistry, the fluids consist of an analyte which contains (bio)chemical substances. The fluids are transferred to a specific area in the chip via patterned microchannels [109]. In all applications, the spectral changes when the liquid is introduced are monitored.

The fusion of microfluidics with photonic crystal structures provides hybrid structures that offer tunable, reconfigurable and rewritable devices [43, 44, 110, 111]. By infiltrating the liquids into the photonic crystal voids, the band edges and resonances of the photonic crystal structures can be tuned. The tuning relies on the change in the cavity’s effective refractive index and the index change provided by the infiltration, in the order of $10^{-1}$, is higher than those provided by the thermal or photothermal effects, in the order of $10^{-2}$.

The fluidic integration of photonic crystal structures is particularly attractive because it may offer a local modification of structures. A fine control of the spectral characteristics of a single photonic crystal cavity or a coupled array can be controlled by local infiltration of water and by removing of infill with the microevaporation technique [43, 44, 110, 111].

Photonic devices are very attractive for (bio) chemical sensing since they are easily incorporated in fluid cells containing the analyte. The surface of light guiding structures can be functionalized with target-specific binding layers. The sensing is based on the change in refractive index experienced by the electromagnetic field near the surface with the presence of the target molecules, so that the target does not require any fluorescent labeling. Label-free sensors are important, not only because they avoid expensive and laborious labeling steps, but also because the labels may affect the biochemical recognition. So far, various label-free (bio) chemical sensors have been demonstrated, capable of measuring the refractive index change of the environment with high resolution [39, 81, 112–116]. The most developed sensors are the Surface Plasmon Resonance [115] and Mach-Zehnder interferometer [112, 116] based devices, that require a large sensing area (mm$^2$) which is one of the main limitations for integrating these sensors in optical chips.

Miniaturization of label-free optical sensors is of particular interest for realizing ultra compact lab-on-a-chip applications with dense arrays of functionalized spots for multiplexed sensing, that may lead to portable, low cost and low power devices [117]. Many efforts exist to realize small devices and among them are photonic crystal (PhC) fibers [118], microrings [114, 119] and PhC cavities [39, 42, 120–127]. The smallest possible sensors are the ones based on PhC cavities as their size is of the order of the wavelength, determined by the diffraction limit. Silicon based PhC microcavities have been used to detect (bio) chemical complexes [120–122, 127]. Sensors based on III-V semiconductors have been demonstrated as well [42, 123, 125]. These latter sensors are attractive as they potentially offer the full on-chip integration with sources.
and detectors, or may be operated as lasers [123] to decrease the detection level. In addition, they can be employed using remote readout, not requiring the delicate attachment of optical fibers or electrical wiring. The principle of array operation for multiplexed sensing was recently shown both for the Si [124] as well as for the InGaAsP III-V system [123].

In this chapter, the optofluidic control of InGaAsP photonic crystal nanocavities is demonstrated by infiltrating various liquids into the photonic crystal holes. The control is provided by the change of the cavity’s effective refractive index as a result of the infiltration\(^1\). The magnitude of the tuning is determined by the electric field distribution of the modes and a large tuning is obtained if a large fraction of electric field overlaps with the liquid. The frequency of each mode is tuned across the PhC bandgap by lithographically varying the parameters of many cavities. The systematic increase of the sensitivity of the dipole mode with decrease of the size of the cavity is demonstrated. For a given mode, the sensitivity smoothly increases when the resonance frequency increases towards the upper band edge of the PhC bandgap, irrespective of the detailed design details. Furthermore, the inverse correlation between sensitivity and quality factor \(Q\) is observed.

The section 4.3 shows simulation results to analyze the change in the band edges and the cavity resonances as the refractive index of the environment increases. The theory of the sensitivity is also provided in this section together with the formulation of the detection limit. A description of the geometry of the used cavities, the infiltration process and a chemical treatment of the surfaces to make them hydrophillic will be explained in the section 4.4. The effect of the infiltration of two different liquids, water and isopropyl alcohol, on the spectral properties of the resonances is discussed in the section 4.5. The section 4.6 covers the sensitivities of the point defect cavities.


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\(^1\)The effective refractive index of the cavity is changed with successive infiltrations; a continuous change in the index with a single infiltration will be explained in the chapter 5.
4.3 Theoretical considerations

Many photonic crystal devices have been fabricated in the form of freely suspended membranes in the air. However, in some applications, the air is replaced by different materials for use in a variety of applications. Therefore, it is interesting to analyze the effect of the infiltration on the band edges and on the modes since they have a different electromagnetic field distribution over the semiconductor and the holes. Consequently, the band-edges as well as every mode have their own specific tuning rate with hole refractive index variation. To investigate this effect, a series of simulations has been performed.

Near the band edge frequencies of a photonic crystal the electromagnetic fields are strongly localized either in the holes (for the air band) or in the semiconductor (for the dielectric band). Figure 4.1(a) shows the 2D calculation result of the variation of the air and the dielectric band edges of a planar photonic crystal having a lattice spacing of 500 nm and a hole radius of 150 nm \((r/a=0.3)\) as the index of the environment\(^2\) increases. The band edges experience redshifts of different magnitudes when the refractive index of the environment is varied. The air band moves to lower frequencies faster than the dielectric band because the air band mode has a larger spatial overlap with the holes. Figure 4.1(a) also shows that as the background refractive index increases, the width of the bandgap decreases and the bandgap will close when the refractive index of the environment \((n_{env})\) is approximately 2. The shifting of the edges is represented in the following formula deduced from the fit line of the data in figure 4.1(a).

\[
\frac{a}{\lambda}_{dielectric} = 0.24822 - 0.0098n_{env} \tag{4.1}
\]

\[
\frac{a}{\lambda}_{air} = 0.4593 - 0.1136n_{env} \tag{4.2}
\]

Since air band modes are strongly localized in photonic crystal holes, the tuning rate of the air band edge to \(n_{env}\) will be determined by the radii of the holes. Therefore, several simulations have been performed to investigate the influence of the hole radii. Figure 4.1(b) shows the shift of three air band edges of photonic crystal structures having the same lattice constant but different hole radii, \(r=0.25a\), \(r=0.3a\), and \(r=0.35a\). The air band edge of the PhC having an \(r/a=0.35\) shows a bigger shift than the the air band edge of the PhC having an \(r/a=0.25\). This implies that the bigger the size of the air hole is the larger the shift in the air band edge. Figure 4.1(b) can be formulated with the following equation deduced from the fitting lines of the data. For the \(r/a=0.25\);

\[
\frac{a}{\lambda}_{air} = 0.3645 - 0.070n_{env} \tag{4.3}
\]

and for \(r/a=0.35\);

\[
\frac{a}{\lambda}_{air} = 0.60948 - 0.1925n_{env} \tag{4.4}
\]

\(^2\)With the environment is meant the holes as well as the spaces below and above the membrane.
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Figure 4.1: (a) The change in the band edges as a function of the environment refractive index. The data are obtained by using a 2D planewave expansion (PWE) simulation for the photonic crystal structure having a lattice spacing of 500 nm and radius of 0.3a. The slab has the effective refractive index of 2.65. The bandgap is closed when $n_{e_{\text{env}}} \approx 2$. (b) The 2D PWE simulation results that show the change in the normalized frequency of the air band for three different photonic crystal hole radii as a function of the $n_{e_{\text{env}}}$.

The sensitivity ($S$) is a crucial parameter for the characterization of photonic crystal sensors. It is defined as the magnitude in the shift of the resonant wavelengths divided by the change in the refractive index of the environment. The shift in the wavelength is proportional to the fraction ($\kappa$) of the intensity distribution overlap of the mode with the analyte. Therefore, the $\kappa$ has to be maximized in order to obtain a high sensitivity. The sensitivity of the resonance is calculated as [128]:

$$S = \frac{\Delta \lambda}{\Delta n} = \kappa \frac{\lambda}{n_{e_{\text{env}}}}$$

(4.5)

where $\kappa$ has a value of $0 \leq \kappa \leq 1$. $\lambda$ is the resonant wavelength, $\Delta \lambda$ is the wavelength shift and $\Delta n$ is the change in the refractive index. The theoretical maximum sensitivity is obtained when all the mode intensity would be inside in the environment, i.e. $\kappa = 1$.

The resonances should exhibit a wavelength shift that can be resolved precisely and accurately. The minimum spectral shift that can be accurately measured defines the sensor resolution ($R$) [129] and together with the sensitivity, it determines the detection limit ($DL$) of the system. The detection limit is defined as the smallest change in the refractive index that can be detected accurately and the DL is given by [129]:

$$DL = \frac{R}{S}$$

(4.6)

The sensor resolution ($R$) is related to the linewidth ($\Delta \lambda_{FWHM}$) of the reso-
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nance. Depending on the noise level, accurate fitting procedures may determine the shift of a resonance with a resolution better than the linewidth. The experimental parameters which determine the resolution of the sensor are the signal-to-noise ratio, temperature uncertainties and the resolution limit of the experimental set-up. In the experiments conducted in this chapter, the latter two are small enough to be neglected. From an error analysis of a resonance line fit, White and Fan [129] arrived in the following expression for the resolution;

$$ R = \frac{3\lambda_{FWHM}}{4.5(SNR)^{0.25}} $$

where the SNR is the signal-to-noise ratio. Since $\Delta \lambda_{FWHM} = \lambda/Q$, the Eqn.4.6 can be rewritten as;

$$ DL = \frac{3\lambda}{4.5 \cdot (SNR)^{0.25} \cdot Q \cdot S} $$

Therefore, to have a minimum detection limit, the sensitivity, the SNR and the quality factor have to be maximized. Since a maximum sensitivity can be obtained by a high value of ($\kappa$), a figure of merit ($M$) for a good sensor can be defined as $M = \kappa \cdot Q$ [130].

It is important to note that the $R$ and the $Q$ are not independent. A high intensity overlap of the mode in the holes (large $\kappa$) leads to a high sensitivity, but also to out of plane scattering losses of the light into the cladding (low-$Q$). In addition, if the hole is filled with an absorptive material, the $Q$ will decrease due to the absorption.

The cavity resonances are expected to have different spectral shifts as the environment refractive index is increased because of the characteristic spatial distribution of their intensity pattern over the holes, i.e. $\kappa$ is different for different modes. Generally, the quality factors ($Q$) decrease after the infiltration because of the degradation in the vertical confinement and absorption by the presence of the analyte. To analyze the tuning of the various resonances as the $n_{env}$ increases, 3-D FDTD calculations are performed for two modified H1 cavities which are constructed on two photonic crystal structures having the same lattice spacing ($a=500$ nm) but different $r/a$. The radii of the innermost holes are set to $0.22a$ for both cavities without displacement. The results are depicted in figure 4.2(a) and (b) for the hole radii of $0.3a$ and $0.35a$.

Figure 4.2(a) and (b) show that all cavity resonances are linearly redshifted as the index of the environment is increased. The dipole mode ($D$ mode) shows a minimum tuning rate in both figures when the environment refractive index is varied, see Eqns.4.9 and 4.12 which are derived from the best fit line of figures 4.2(a) and (b), respectively. The small tuning rate is expected because a large fraction of the electric fields of the dipole mode exists in the semiconductor region. A larger tuning rate is obtained for the quadrupole modes in both figures, see Eqns.4.10 and 4.13. The hexapole mode ($H$ mode) shows the largest tun-
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Figure 4.2: The change in the normalized frequency of the modes, the dipole \((D)\), the hexapole \((H)\), and the quadrupole \((Q)\), as a function of the \(n_{\text{env}}\). The data are obtained from 3D FDTD calculations for two modified H1 type of cavities in two different photonic crystal structures having the same lattice spacing of 500 nm but different hole radii, (a) \(r=0.3a\) and for (b) \(r=0.35a\). The innermost holes have the same radii of 0.22\(a\).

All the H1 cavity modes are donor type modes, i.e. derived from the air band by a local increase of refractive index by leaving out and decreasing of the size of the number of the holes. By comparing Eqns.4.9-4.14 with Eqn.4.1-4.4, the tuning rates are (much) larger than those of the dielectric band edge, but smaller than those of the air band edge.

In order to analyze the fraction of the intensity overlap with the environment, \(\kappa\), Eqn.4.5 is used. The slope of the fits in figures 4.1 and 4.2 is related to the \(S\)
by $S = \left( \frac{\lambda^2}{a} \right) m$, where $m$ is the slope. Then from Eqn.4.5, we have $\kappa = \frac{\lambda}{a} n_{en} m$
where the $\lambda$ can be approximated by the gap center wavelength $\lambda \sim 3a$, so that $\kappa \sim 3n_{en} m$. For the simulations presented in figure 4.2(a), the values for the $\kappa$ when the radius of the PhC holes is set to $0.3a$ are 0.22, 0.24, 0.10 for the $Q$, $H$ and $D$ modes, respectively. Since these modes are derived from the air band edge, the tuning rate of the modes varies as the radius of the holes is changed, see figure 4.2(b) which attests the change in the spatial distribution of the electric fields. The $\kappa$ values from figure 4.2(b) are found as 0.4, 0.42, and 0.16 for the $Q$, $H$ and $D$ modes, respectively. Therefore, the shift in the resonance wavelength (i.e. the sensitivity) is heavily determined by the size of the holes.

### 4.4 Sample preparation

For H0 type of cavities, independent modifications were made to the two adjacent holes in the $\Gamma K$-direction ($x$) and/or in the $\Gamma M$ direction ($y$). To distinguish different H0 cavities, they are represented by $r_i$, $s$, $r'_i$ and $s'_i$, as sketched in figure 4.3(a). The six inner holes of the H1 defect cavities were reduced in radius (labeled by $r'$) and/or had their center position shifted radially outward (labeled by $s$). For a given cavity type, the parameter sets ($r'_i$, $s_i$) were varied to tune the resonant wavelength for each mode within the bandgap. Figures 4.3(b) and (c) show the scanning electron microscope images of the fabricated H0 and H1 cavities. Due to the fabrication tolerances, the fabricated nanocavities have $r/a$ ratio of 0.32 instead of the intended 0.30, as determined from the scanning electron microscope (SEM) images.

The fabricated InGaAsP point defect cavities exhibit a hydrophobic surface which can prevent a successful infiltration of the liquid. The hydrophobicity of the surface lowers the real sensitivity of the device since the holes are partially infiltrated [131]. The liquid infiltration inside the holes is governed by the capillary pressure, which is proportional to the surface tension ($\gamma$) and the contact angle ($\theta$) and inversely proportional to the hole radius ($r$). The capillary pressure ($p_c$) is given by;

$$p_c = \frac{2\gamma \cos(\theta)}{r} \quad (4.15)$$

Since the infiltration is governed by the capillary forces of the holes, a good wetting is essential which results in a low contact angle. The fabricated structures underwent several processes to ensure a good wetting. The sample was cleaned by an $O_2$ plasma which removes any organic residue on the sample. Next, the sample was rinsed in a 10% solution of phosphoric acid in water to remove the deposited thin layer of oxide. Finally, the sample was rinsed with isopropanol. The contact angle of a millimeter size droplet is measured before and after the process, and a contact angle decrease from $30^\circ$ to $6^\circ$ was observed.
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Figure 4.3: (a) Schematic representation of hole modifications; SEM images of fabricated (b) H0(\(r'_x, s_x; r'_y, s_y\)) and (c) H1(\(r', s\)) type of InGaAsP nanocavities. The fabricated structures has a \(r/a\) of 0.32 which is determined from the SEM images.

The infiltration of the liquids was performed at room temperature under the ambient pressure by placing a drop of liquid at the top of the sample. The ideal infiltration where all surroundings of the cavity are filled requires \(\sim\) femtoliter volume of the analyte. The excess liquid at the top of the sample forms a curvature at the air/liquid boundary which deteriorates both the excitation of the cavities and the collection of the photoluminescence signal. A cover glass having a thickness between 60 \(\mu\text{m}\) and 130 \(\mu\text{m}\) is placed on the top of the drop to prevent the forming of the curvature. The cover glass was pushed down to reduce the thickness of the liquid layer at the top to minimize the absorption losses caused by the thick layer of the liquid [132].

4.5 Liquid infiltration

To analyze the effect of the infiltration on the cavity resonances, various types of liquids were infiltrated into the PhC holes. Figure 4.4(a) is the photoluminescence emission collected from a modified H1 type cavity (\(r'=0.24a; s=0.03a\)) having a lattice spacing of 511 nm and radius of 0.33a which are determined from the corresponding scanning electron microscope image. Figure 4.4(a) shows the PL emission when the PhC structure is suspended in the air. The
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modes are identified by comparing with the 3D FDTD calculation considering the real geometric parameters. The split quadrupoles ($Q_2$ and $Q_1$) and hexapole ($H$) modes are located at 1487 nm, 1490 nm and 1500 nm with quality factors of 1200, 1000, and 1600 respectively. When the cavity is immersed in water, $n_{\text{water}}=1.33$, these modes are redshifted, as shown in figure 4.4(b), due to the increase in the cavity's effective refractive index. Because of the different spatial electric field distribution of the modes, the magnitude of the shift is different for the modes. The quadrupole modes are redshifted by $\sim 70$ nm, whereas the $H$ mode is redshifted by $\sim 80$ nm.

When the water is replaced with the isopropyl alcohol (IPA) which has a higher refractive index than water, $n_{\text{IPA}}=1.377$, the cavity modes exhibit an extra redshift as shown in figure 4.4(c). The magnitude of the redshift obtained is $\sim 10$ nm for the quadrupole modes and $\sim 12$ nm for the $H$ mode.

The sensitivity is determined by dividing the $\lambda_{\text{IPA}} - \lambda_{\text{water}}$ by the $n_{\text{IPA}} - n_{\text{water}}$. The sensitivity for the quadrupole mode is found as $\Delta \lambda = 210 \Delta n_{\text{env}}$ in nanometers. The $H$ mode has a higher sensitivity of $\Delta \lambda = 242 \Delta n_{\text{env}}$ in nanometers. Considering the minimum resolvable wavelength shift is the one linewidth of the resonance, the calculated minimum resolvable detectable change in the refractive index is found as $5.8 \times 10^{-3}$ and $3.8 \times 10^{-3}$ for the quadrupole and the hexapole modes respectively.

Figure 4.4(d) and (e) show the experimental and the simulation results of the dependence of the normalized frequency on the refractive index change as a result of the infiltration, respectively. The split degeneracy in the quadrupole mode is not observed in the simulations since the splitting is induced by the fabrication errors. The change in the normalized frequencies is described by the fit line of each data and is represented as:

\begin{equation}
(a/\lambda)_{H-\text{mode}} = 0.3929 - 0.05224n_{\text{env}}
\end{equation}

\begin{equation}
(a/\lambda)_{Q-\text{mode}} = 0.3894 - 0.04646n_{\text{env}}
\end{equation}

And the simulation result is represented as

\begin{equation}
(a/\lambda)_{H-\text{mode}} = 0.4052 - 0.059n_{\text{env}}
\end{equation}

\begin{equation}
(a/\lambda)_{Q-\text{mode}} = 0.4098 - 0.051n_{\text{env}}
\end{equation}

The experimental $\kappa$ values for the modes are obtained by considering the slope of the each fit as described before. For the $H$ mode the $\kappa$ value corresponds 0.24 whereas for the quadrupole modes it corresponds 0.21. The calculated $\kappa$ values are 0.26 and 0.23 for the hexapole and the quadrupole modes which shows that the error between the experimental result and the calculation result is almost 8% for both the hexapole and the quadrupole modes. The discrepancy is due to the fluctuation in the hole sizes in the fabricated structure and possible incomplete filling of some individual holes. The detection limit
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Figure 4.4: (a) The photoluminescence emission collected from the modified H1 cavity suspended in the air. The photonic crystal has a lattice spacing of 511 nm and radius of 0.33a as determined from the corresponding SEM image. The innermost holes have a radius of 0.24a and are shifted by 0.03a. The peaks correspond to the split quadrupole, $Q_1$ and $Q_2$, and the hexapole (H) modes. The PL spectrum when the cavity is backfilled with (b) water, $n_{water} = 1.33$ and (c) IPA, $n_{IPA} = 1.377$. (d) The change in the normalized frequency when the cavity is backfilled with water and IPA. (e) 3D FDTD simulation result for each infiltration.
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Table 4.1: The refractive indices for different concentration of sugar/water solutions. The indices are taken from [133].

<table>
<thead>
<tr>
<th>Sugar concentration (% weight/weight)</th>
<th>Refractive index</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.333</td>
</tr>
<tr>
<td>2.6</td>
<td>1.3367</td>
</tr>
<tr>
<td>6.0</td>
<td>1.3417</td>
</tr>
<tr>
<td>9.3</td>
<td>1.3467</td>
</tr>
<tr>
<td>12.5</td>
<td>1.3517</td>
</tr>
<tr>
<td>15.6</td>
<td>1.3567</td>
</tr>
<tr>
<td>18.7</td>
<td>1.3617</td>
</tr>
</tbody>
</table>

for this cavity is calculated by using Eqn. 4.8 and found $\sim 10^{-3}$. However, the detection limit can be further improved by increasing the quality factor or increasing the SNR. Even though the surface plasmon resonance sensors have lower detection limits, the photonic crystal devices are beneficial to integrate in lab-on-a-chip devices since the sensing is established with a femtoliter liquid, limited by the mode volume.

The intensity of the photoluminescence emission significantly decreases after each infiltration. When the sample is immersed in liquids, the intensity decreases more than a factor of ten for the hexapole mode and factor of two for the quadrupole modes even though the excitation laser powers are the same for all cases. The large decrease in intensity for all modes is due to the change in the collection efficiency.

4.6 Sensitivities of the point defect cavities

Tuning of the resonances with various liquids with the smallest refractive index difference of 0.047 was demonstrated in the previous section. However, to have a deep understanding on the sensitivity and the detection limit of the resonances, liquids having smaller refractive indices are needed to be introduced in the PhC.

Sugar-water solutions with different sugar concentrations with known refractive indices [133] as shown in Table 4.1 have been infiltrated into the two types of InGaAsP PhC nanocavities in order to investigate the sensitivity of the cavities. After each infiltration, the cavities were cleaned with deionized water and blown with dry nitrogen. After each cleaning, the sample was characterized by PL again. No frequency shifts were detected after the cleaning compared to the unfilled cavity. Figure 4.5(a) shows the typical spectral response of an H1(r’s), having a nominal lattice spacing of 511 nm with nominal values of r’
= 105 nm, and \( s = 15 \) nm, to seven different sugar-water concentrations. The resonance peak at 1475 nm (\( a/\lambda = 0.34 \)) was identified as a hexapole mode by using 3D finite difference time domain (FDTD) calculations (CrystalWave). The normalized frequency of the mode suggests that the hole size of the fabricated device is bigger than that of designed ones because of the fabrication tolerances; see figure 4.2 (a) and (b). After pure water is infiltrated, the hexapole mode redshifts more than 70 nm due to the increase in the ambient refractive index from 1 to 1.33. As the sugar concentration increases, the cavity mode redshifts further. From the slope of the best fit near \( n = 1.33 \), the sensitivity, \( S = \Delta \lambda / \Delta n \), is determined. For this particular cavity, the sensitivity is 280 nm/RIU (refractive index unit). Incomplete filling of the small PhC holes with the analyte is frequently reported [125, 127]. The sensitivity depends on how effective the analyte is infiltrated into the holes and the region underneath the holes. This filling is determined by the wetting and governed by capillary forces inside the holes. Therefore, we simulated three different conditions: (1) total filling, (2) surface coverage and filling of the holes, and (3) surface coverage only, by using 3D FDTD. Figure 4.5(b) shows the 3D FDTD simulation results of the resonant wavelength shift dependence on the refractive index change for three different liquid infiltration conditions as shown in the inset. Sensitivities of 75 nm/RIU, 230 nm/RIU and 285 nm/RIU have been obtained for the surface coverage, surface coverage and hole filling and total filling respectively. Absolute values of calculated and measured resonant wavelengths differ typically by 3% and are caused by fabrication tolerances in the unmodified and modified holes sizes in the cavity. Our experimental result is in good agreement with the calculation; it shows that with a proper treatment of the surface to make it hydrophilic, both the holes in the membrane and the area underneath the membrane can be completely filled. Incomplete, or solution-dependent filling may lead to unpredictable effective sensitivities [125, 127].

4.6.1 Sensitivity dependence on the normalized mode frequency

The resonance modes have different sensitivities to the change in the environment refractive index because of their different \( \kappa \) values. For a given mode, we can tune its \( \kappa \) by varying its resonance frequency within the bandgap. The same type of mode will exhibit a higher sensitivity when it is located close to the air band edge. In this part, the relation between the sensitivity of a given mode and its position inside the bandgap was investigated. This position was varied by lithographically varying the innermost holes in the \((r', s)\) parameters. Figures 4.6(a) and (b) show the sensitivity of the dipole and the monopole modes respectively, obtained from different \( H_0(r'_1, s_1; r'_2, s_2) \) cavities as a function of the normalized mode frequency \( (a/\lambda) \) for the cavities in PhC’s with three different lattice spacings, 480, 499, 511 nm. Also indicated in the figure are
the PhC dielectric band edge near $a/\lambda = 0.29$ and the air band edge near $a/\lambda = 0.37$. The $r/a$ can be estimated from figure 4.1(a) which suggest that the $r/a$ is approximately 0.32. The sensitivities increase when the cavity modes are lithographically tuned from the dielectric band to the air band. The same trend has been also obtained for the H1($r',0$) type of cavities as follows from figure 4.6(c), which shows that the sensitivity of all supported cavity modes, the dipole ($D$), the hexapole ($H$) and the split quadrupole ($Q_1$ and $Q_2$) increases when the resonance gets closer to the air band edge. Qualitatively, this behavior is expected since the closer the cavity mode frequencies to the air band edge, the larger the mode overlap with the holes, and thus the higher the sensitivity [130]. The smooth behavior in figure 4.6 suggests that the position within the bandgap mainly determines the sensitivity, irrespective of the details of the cavity design, i.e. in our case the ($r',s$) sets. The data in figure 4.6 are obtained from measurements with and without water, so that the wavelength shifts are large. Therefore there are no data near the dielectric band edge as these resonances would fall inside the dielectric band after infiltration. From figure 4.6(c) there are data even at or slightly above the air band edge. This is believed to be a real effect as some (rather broad) resonances exist above the band edge, but in the frequency interval between the stopbands in the $\Gamma M$ and $\Gamma K$ directions.

Since the Figure of Merit for a sensor is $M = S \times Q$ [130], which should be maximized, we experimentally investigated the correlation between the sensitivity and the $Q$ factor. Figure 4.7(a) shows the PL signal collected from an unfilled H0($r'_x,s_x,r'_y,s_y$) cavity where $a = 511$nm, $r'_x = r'_y = 0.2a$, $s_x = 0.14a$ and
Figure 4.6: The sensitivity dependence on the modes’ position in the bandgap before infiltration for (a) dipole and (b) monopole mode in $H_0(r', s; r'_y, s_y)$ and (c) all cavity modes of $H_1(r', 0)$ cavities. The data are collected from three different lattice parameters with different modification parameters introduced to the innermost holes.
Figure 4.7: (a) The photoluminescence signal collected from a H0($r'_x, s_x; r'_y, s_y$) type of cavity built in a photonic crystal structure having a lattice spacing of 511 nm. The modification parameters are $r'_x = r'_y = 0.2a$, $s_x = 0.14a$ and $s_y = 0.1a$. The peaks correspond to a monopole ($M_4$), a dipole ($M_3$) and second order modes ($M_2$ and $M_1$). (b) The sensitivity correlation with $Q$ factor of all the modes from all H0 type of cavities. The $M_1$ ($\lambda = 1396$ nm) and the $M_2$ ($\lambda = 1469$ nm) are the higher order modes; the $M_3$ ($\lambda = 1546$ nm) and the $M_4$ ($\lambda = 1582$ nm) are dipole and monopole modes [123]. Figure 4.7(b) shows the measured quality factor plotted against the sensitivity for the four modes of the H0 cavity for varying ($r'_x, s_x; r'_y, s_y$) parameters. Although there is no clear functional dependence, the expected inverse correlation between $S$ and $Q$ is clearly present [130]. The high $Q$ modes ($M_3$ and $M_4$) are strongly confined inside the dielectric material and have lower sensitivity, whereas the low $Q$ modes ($M_1$ and $M_2$) are less confined inside the dielectric and have a higher sensitivity. Figure 4.7 suggests that for sensitivities near $\sim 150$ nm/RIU the $Q$-factor can be made very large.

4.6.2 Sensitivity dependence on mode and cavity type

Since sensitivities depend on the position of the mode resonance inside the bandgap, it is not straightforward how to compare sensitivities of different cavity-types. For each cavity-type and mode, we have taken the sensitivity as averaged for many H1($r'_x, s$) and H0($r'_x, s_x; r'_y, s_y$) configurations, at least ten per cavity-mode type, with frequencies somewhat uniformly spread over the bandgap as in figure 4.6. The results are collected in Table 4.2. Although the precise values may be arbitrary, as they depend on the exact cavities taken for averaging, some clear trends are observed from Table 4.2. For a specific cavity, e.g. H1($r'_x, 0$) cavity, the sensitivity is larger for the modes that are more confined to the perimeter of the cavity such as the hexapole and quadrupole modes. These modes have higher electric field overlap with the holes as compared to the modes which are more localized near the center of the cavity inside the
dielectric, e.g. the dipole. The sensitivity of a specific type of mode varies in a characteristic manner with the cavity type. The sensitivity of the dipole increases if the cavity size is reduced by modifying the surrounding holes, which corresponds to going from bottom to top in the table 4.2. On the other hand, the modes which are confined near the perimeter of the cavity, like the quadrupole and the hexapole modes, do not depend much on cavity size.

The maximum sensitivity values of the modes $S = \lambda / n_{\text{env}}$ are also displayed in Table 4.2 for different type of cavities. The ratio of the average sensitivity divided by the maximum $S$ is given in the last column of Table 4.2. It shows that the sensitivities are within 30% of the maximum value.

To optimize the sensitivity, special designs have been reported to maximize the overlap of the resonant mode with the holes where the analyte is. Loncar et al. obtained a sensitivity of 245nm/RIU from InGaAsP PhC membrane cavities having fractional edge dislocations [42], and with a central hole to increase the overlap. Very recently, Falco et al. obtained a theoretical sensitivity of 585 nm/RIU from their slotted double-heterostructure PhC in Si [127]. Their experimental value was even three times higher, but this was attributed to an improved infiltration as the sugar concentration in the sample increased. Dorfner et al. compared two type of cavities, L3 (three missing holes in a row) and H1 with a large central hole in Si. The sensitivities were 63 and 155 nm/RIU respectively, with lower (L3) or comparable (H1) cavity Q-factors [122]. A sensitivity of 400nm/RIU has been obtained from InGaAsP cavities in a lasing mode, similar to our H0 cavities, by Kita et al. [123]. Kim et al. demonstrated a sensitivity of 247nm/RIU for a hexapole mode of a modified single air hole missing cavity [125]. They created a deformed hexapole mode cavity by enlarging two air-holes facing each other.

4.7 Summary and conclusion

The fusion of the fluids with photonic crystal devices provides a good opportunities for lab-on-a-chip applications that require label free biosensors. Since the tuning is determined by the spatial distribution of the electric field of the modes, to realize these devices, the cavity must support a mode having a high sensitivity. In this chapter we demonstrated the optofluidic control of InGaAsP photonic crystal nanocavities by infiltrating various liquids into the photonic crystal voids. The infiltration changes the cavity’s effective refractive index which induces a change in its spectral properties. The strength of the tuning of the band edges and the resonances are different because of their spatial electromagnetic field distributions.

The effect of the infiltration on the band edges and the cavity resonances was demonstrated by the simulations. The bottom of the air band showed a
Table 4.2: Average sensitivities, maximum sensitivities and filling fraction of different mode types with different cavities.

<table>
<thead>
<tr>
<th>Cavity Type</th>
<th>Mode</th>
<th>(S_{\text{ave}}) (nm/RIU)</th>
<th>(S_{\text{max}}) (nm/RIU)</th>
<th>(\kappa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(H_{0}(r', 0))</td>
<td>dipole</td>
<td>(3.1 \times 10^2)</td>
<td>(1.0 \times 10^3)</td>
<td>0.30</td>
</tr>
<tr>
<td></td>
<td>monopole</td>
<td>(2.6 \times 10^2)</td>
<td>(1.1 \times 10^3)</td>
<td>0.24</td>
</tr>
<tr>
<td>(H_{0}(r'_x, s_x; r'_y, s_y))</td>
<td>2nd order monopole</td>
<td>(2.0 \times 10^2)</td>
<td>(1.04 \times 10^3)</td>
<td>0.20</td>
</tr>
<tr>
<td>(H_{1}(r', 0))</td>
<td>2nd order dipole</td>
<td>(2.2 \times 10^2)</td>
<td>(1.15 \times 10^3)</td>
<td>0.21</td>
</tr>
<tr>
<td></td>
<td>monopole</td>
<td>(1.6 \times 10^2)</td>
<td>(1.1 \times 10^3)</td>
<td>0.15</td>
</tr>
<tr>
<td></td>
<td>dipole</td>
<td>(1.4 \times 10^2)</td>
<td>(1.12 \times 10^3)</td>
<td>0.13</td>
</tr>
<tr>
<td>(H_{1}(r', s))</td>
<td>dipole</td>
<td>(1.1 \times 10^2)</td>
<td>(1.12 \times 10^3)</td>
<td>0.10</td>
</tr>
<tr>
<td></td>
<td>hexapole</td>
<td>(2.6 \times 10^2)</td>
<td>(1.09 \times 10^3)</td>
<td>0.24</td>
</tr>
<tr>
<td></td>
<td>Quadrupole</td>
<td>(1.9 \times 10^2)</td>
<td>(1.09 \times 10^3)</td>
<td>0.18</td>
</tr>
<tr>
<td>(H_{1}(r', s))</td>
<td>dipole</td>
<td>(0.9 \times 10^2)</td>
<td>(1.06 \times 10^3)</td>
<td>0.08</td>
</tr>
<tr>
<td></td>
<td>hexapole</td>
<td>(2.8 \times 10^2)</td>
<td>(1.07 \times 10^3)</td>
<td>0.27</td>
</tr>
<tr>
<td></td>
<td>quadrupole</td>
<td>(1.9 \times 10^2)</td>
<td>(1.08 \times 10^3)</td>
<td>0.18</td>
</tr>
</tbody>
</table>
larger tuning rate than the dielectric band edge as the refractive index of the environment increases. The larger tuning of the air band is caused by its strong spatial overlap with the environment. A decrease in the width of the bandgap is observed as the index increases due to the reduction in the refractive index contrast.

The sample preparation is discussed in section 4.4. In order to obtain a good wetting, the sample underwent some processes. The surface treatment provided an ideal infiltration of the water and the IPA, the experimental results are in a good agreement with the calculation results. Nevertheless, a discrepancy is observed between the experimental and simulation data of both the quadrupole and the hexapole modes which is caused by the fluctuations in the hole sizes of the fabricated structure.

The sensitivities of the different types of modes from various types of cavities were determined by infiltrating different concentration of sugar-water solutions inside the holes. We demonstrated that the sensitivity has a simple relation to the cavity type and increases gradually when the mode frequency increases. Maximum sensitivity of $\sim 300\text{nm/RIU}$ is observed which corresponds to a $\kappa$ of 0.25. The present experimental data provide insight in the operation of PhC sensors and support theoretical expectations.
Chapter 5

Thermal and photothermal control of liquid crystal infiltrated InGaAsP point defect nanocavities

A liquid crystal (5CB), which is a birefringent material, is infiltrated into photonic crystal structures to investigate its contribution to the tuning of the resonant wavelength of several modified H1 cavities. A birefringence induced mode dependent tuning has been observed by changing the liquid crystal’s refractive index by heating the sample either directly or through the photothermal effect.

5.1 General introduction

The infiltration of various liquids into the photonic crystal holes could provide a passive tuning of the resonances, as was discussed in the chapter 4; however, for many applications of photonic crystal nanocavities, it is a primary requirement to obtain some degree of active tunability of the cavity resonances. The requirements of the active tuning are that the tuning is fast, large, reversible, reliable and reproducible. One way to obtain the active tuning of the resonant modes is to infiltrate electro-optically active materials into the photonic crystal holes which can change the cavity’s effective refractive index with an external control. As a class of electro-optical materials, a liquid crystal (LC) has attracted much attention as an infill source because of the possibility of refractive index modulation by a thermal or an electrical effect and because of its compatibility with the current electronic devices.

An extensive research has been done to modulate the optical properties of
the one-, two-, and three-dimensional photonic crystal structures by changing the refractive index of the infiltrated liquid crystal by thermally inducing a phase transition or electromagnetically rotating the director field of the liquid crystal [25, 134–144]. Busch and John [143] demonstrated theoretically that the bandgap of an inverse opal photonic crystal could be continuously tuned by infiltrating liquid crystals in the void regions and rotating the director field of the liquid crystal electromagnetically. Yoshino et al. [144] demonstrated experimentally that the photonic bandgap of the synthetic opal can be partially closed or opened by modulating the refractive index of the infiltrated liquid crystal thermally.

The liquid crystal infiltration has been also a primary focus of work in two dimensional photonic crystals. Leonard et al. [145] have demonstrated a continuous tuning of the photonic bandgap of a two dimensional liquid crystal infiltrated macroporous silicon photonic crystal by temperature tuning of the refractive index of the infill. They observed that after the infiltration the TM (electric field parallel to the hole axis) bandgap is shifted dramatically to higher wavelengths while the TE (electric field perpendicular to the hole axis) bandgap is completely collapsed [145]. The temperature tuning of the photonic bandgap of the liquid crystal infiltrated deeply etched InP/InGaAsP/InP material system has been also reported [138, 139, 146]. The tuning of the resonant modes of the nanocavities and waveguides has been also reported for the deeply etched photonic crystal systems [25, 138, 140]. A large redshift of the resonances after the liquid crystal infiltration has been observed and thus, the resonances can be further tuned thermally. Maune et al. demonstrated a tunable lasing from an InGaAsP photonic crystal membrane type nanocavity by electrically activating the infiltrated LC [137].

Although the liquid crystal has an anisotropy in its refractive index, none of these studies has demonstrated the influence of the anisotropy on the nanocavity resonances. The resonances have had only redshifting [25, 138, 140] or blueshifting [137]. Furthermore, in the temperature tuning experiments, the entire chip is heated which also affects the optical properties of other devices located on the chip. This may be unwanted for possible device applications; therefore, the cavities should be locally heated.

Addition to the active tunability, the LC brings some more advantages when it is infiltrated into the membrane cavities. One is that the backfilling with the LC makes the membrane less fragile which is important for the use in the real applications. Second advantage is that the infiltrated LC, similar to the other infiltrated liquids or organic materials, increases the heat transfer from the cavity to the host semiconductor [131], when the cavity is locally heated. To dissipate heat, usually membranes are bonded to different material such as sapphire [147] which requires extra processing of the sample.

In this work, we present the birefringence effect of the infiltrated LC on the resonant wavelength of the InGaAsP point defect nanocavities relying on
Thermal and photothermal control of liquid crystal infiltrated InGaAsP point defect nanocavities

the thermal and photothermal effect. We show frequency shifts in opposite directions with varying temperature of two nearly degenerate modes, which is attributed to the opposite temperature dependence of the ordinary and the extra-ordinary refractive index of the LC. Moreover, we demonstrate tuning of a LC-infiltrated PhC cavity by local heating with a focused laser spot. The heating is induced by the absorption of radiation in the semiconductor, but the tuning effects are dominated by the temperature dependence of the LC refractive index. The observed tuning rate $\frac{d\lambda}{dT}$ is large, reversible and has an opposite sign for the modes with different polarizations, which is a genuine property of the LC because of its anisotropic optical properties [141, 142].

The section 5.2 explains the properties of liquid crystals and their molecular alignment in a confined geometry. The birefringence induced mode dependent tuning is demonstrated in the section 5.3 relying on the thermal effect. The section 5.4 shows the local tuning of a modified H1 cavity by a laser heating. Finally, in the section 5.5, a comparison between the thermally and photothermally tuned cavity is given.


5.2 Liquid crystals

A liquid crystal is an intermediate phase of matter that has physical properties between those of ordinary solid crystals and liquids. It flows like a liquid, yet possesses some characteristics of crystals. Such intermediate phases that the materials exist are called mesophases and the materials having these phases are called mesogens. Depending on the concentration, substituents or the temperature, the liquid crystal exists in various mesophases such as smectic, nematic, cholesteric but only the nematic mesophase will be considered here.

The thermotropic liquid crystals which exhibit various crystalline phases as a function of temperature have been extensively studied and used in device applications. In general, those crystals exhibit a limited temperature range of the various phases. Three phases, crystalline, nematic and isotropic, will be discussed here. The liquid crystal has long cigar-shaped molecules. At low temperatures, the LC exhibits a crystalline phase, in which the molecules are ordered anisotropically as shown in figure 5.1(a). As the temperature is increased to the transition point, $T_{cr}$, a phase transition from the crystalline state
CHAPTER 5.

Figure 5.1: The phases of a nematic liquid crystal. (a) The crystalline phase of the liquid crystal when its temperature is below the crystalline temperature $T_{co}$. In the crystalline state, the molecules have both directional and spatial orders. In that phase, the liquid crystal mimics a solid crystal behavior. (b) The nematic phase of the liquid crystal where the temperature of the LC is above the $T_{co}$ and below the $T_c$ (clearing temperature). The molecules have an orientational order which is represented by director axis $\vec{n}$ which is centrosymmetric. However, the LC loses its spatial order. (c) The isotropic phase of the LC where its temperature is above the $T_c$. Neither the spatial order nor directional order remains. In the isotropic phase, the LC has an ordinary fluid behavior.
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Figure 5.2: The chemical structure of the 5CB (K15) LC used as an infill. Its full name is 4-Cyano-4'-n-pentylbiphenyl or 4'-Amyl-4-biphenylcarbonitrile and its molecular formula is $C_{18}H_{19}N$. It has a clearing temperature of $34.5^\circ C$. The molecule is about 2 nm long.

to nematic state occurs. In the nematic phase, the molecules have no positional order very much like liquids, but they self-align to have long-range directional order, which is defined by a unit vector $\vec{n}$ that is called director axis, with their long axes roughly parallel to each other as schematically represented in figure 5.1(b). The molecules in the nematic state are generally centrosymmetric which provides the same optical properties in the $+\vec{n}$ and $-\vec{n}$. For a further increase in the temperature to the clearing temperature, $T_c$, a phase transition from the nematic state to the isotropic state occurs and the directional order and spatial order of the molecules disappear, see figure 5.1(c). The LC having this disordered or isotropic phase behaves very much like the ordinary fluids of anisotropic molecules.

There are many ways to modify the physical properties of the liquid crystals. The temperature range of the mesophases of a liquid crystal, anisotropies, molecular sizes can be modified by substituting various chemical bonds into a particular class of liquid crystal. The cyanobiphenyl homologous series $n$CB ($n=1,2,3,...$) is an example. For the $n$CB liquid crystals with $n \leq 4$, the liquid crystal does not have a nematic phase; for $n=5-7$, the LC exhibits a nematic phase within a proper temperature range. For the LCs having $n>8$, the smectic phase, which means that the molecules have a positional order, appears [148, 149]. Another way to change the physical properties is to mix different types of liquid crystals. The optical properties of the final mixture is completely different than those of the individual mixture constitutes. The liquid crystal E7 is a good example of this class of the liquid crystals [150].

In our experiments, a commercially available liquid crystal K15 (5CB) from Merck has been used. The chemical name of the liquid crystal is 4-Cyano-4'-n-pentylbiphenyl and its chemical structure is displayed in figure 5.2 [151]. Its transition temperature from the crystalline phase to nematic phase is $T_{cn}$ of $23^\circ C$ and from the nematic phase to isotropic phase is $34.5^\circ C$ [151]. Since $n=5$, the LC does not exhibit a smectic phase.
5.2.1 Physical properties of the LC

The degree of the orientational order of the LC molecules is described in terms of the scalar order parameter $S$ which is given as [150, 152]

$$S = \frac{1}{2} \langle 3 \cos^2 \theta - 1 \rangle \quad (5.1)$$

where the $\theta$ is the angle between the molecular axis and the director axis. Eqn.5.1 is a statistical average taken over the whole ensemble and provides a measure of a long or a short range order of the system. The short or long range order is described by the interaction of one molecule with another one in the short or long distance; in the crystalline phase a long range and in the isotropic phase a short range order is obtained. In the crystalline state, the magnitude of the $S$ is close or equal to unity, the system is in long range order. When the $S$ is equal to 1, since $\langle \cos^2 \theta \rangle = 1$, a perfectly ordered system as in solid crystals is achieved. If the LC molecules are in the nematic phase, the angle between the molecular axis and the director axis has large fluctuations and depending on the average angle fluctuations, the order parameter, $S$, will have a value between 0 and 1, $0 \leq S \leq 1$ which depends on the temperature. When the material is in the isotropic state, a perfectly random alignment of the LC molecules is observed, as in an ordinary liquid, where the $S=0$ since $\langle \cos^2 \theta \rangle = \frac{1}{3}$ [150]. Due to the negligible intermolecular interactions, the isotropic phase has a short range order [152].

One of the interesting properties of the LC molecules in the nematic state is the nature of the alignment of the molecules in a confined geometry such as in a small radius cylinder or a photonic crystal void. The orientation of the LC molecules defines the director axis $\hat{n}$. It is determined by the sidewall anchoring, the surface energy and the LC molecular elasticity. Depending on these effects, the optical and the nuclear magnetic resonance experiments [149, 153–156] showed mainly four LC molecular orientations inside small diameter voids with radii $R=0.05-0.4 \mu m$. These are a uniform axial, a planar polar, a planar radial and an escaped radial type of orientations, as sketched in figure 5.3 [157]. The uniform axial (UA) type of orientation occurs when the LC molecules have an anchoring parallel to the lateral surface as represented in figure 5.3(a). This type of configuration shows no singularities nor elastic deformation.

If the $\hat{n}$ is perpendicular to the lateral surface, the anchoring is of homeotropic type. The planar radial (PR) and the planar polar (PP) alignments exhibit this type of anchoring where the $\hat{n}$ has a two dimensional distortion as shown in figure 5.3(b) and (c). In the PR configuration a singularity exist in the center of the cylinder, see the figure 5.3(b) whereas in the PP configuration two singularities exist at the both side of the lateral surfaces, see figure 5.3(c). The escaped radial (ER) configuration possesses also homeotropic type of anchoring, but the molecules in this configuration have a three dimensional deformation; the sin-
Figure 5.3: A schematic representation of four possible configurations of a nematic LC confined to a cylindrical hole, i.e. photonic crystal hole. The small lines depict the orientation of the LC molecules. (a) A side view of the uniform axial configuration where the molecules are aligned parallel to the hole axis. The configuration has no singularities. A top/bottom view of the (b) planar radial and (c) planar polar configurations, two examples of the homeotropic anchoring where the LC molecules have two-dimensional distortions. One singularity is shown at the center of the cylinder for (b) and two singularities are observed in two lateral ends of the cylinder for (c). (d) A top/bottom and a side view of the escaped radial configuration a class of homeotropic anchoring where the LC molecules have three-dimensional distortions. No singularity exists. Adapted from the reference [157].
A liquid crystal is a birefringent material having two different refractive indices, the ordinary \( n_o \) and the extraordinary \( n_e \) refractive indices, in the nematic phase depending on the incident optical polarization as shown in figure 5.4. If the electric field polarization is perpendicular to the LC molecules then the light will be influenced by the ordinary refractive index, see figure 5.4(a), if the polarization is parallel then the light will be influenced by the extraordinary refractive index of the LC, see figure 5.4(b). In the case of a tilted LC molecule or an oblique polarization of the field as shown in figure 5.4(c), the light will experience a refractive index between \( n_o \) and \( n_e \), and the birefringence occurs. When the LC is in the isotropic state, the birefringence disappears due to the disordering and the isotropic refractive index, \( n_i \), can be approximated by:

\[
n_i = \sqrt[3]{\frac{1}{3}(2n_o^2 + n_e^2)}
\]

**5.2.2 Temperature effect on the LC refractive index**

The most notable property of the LC is the possibility to change its refractive index by the temperature or the electric field. The refractive indices, the \( n_o \) and \( n_e \)
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the \( n_e \), are determined mainly by the temperature, the material structure and the incident field's wavelength [158, 159]. As the temperature increases, the angle between the director axis and the molecular axis fluctuates more and the order parameter \( S \) changes. So, the temperature dependence of the \( S \) is given as [158]:

\[
S(T) = (1 - T/T_c)^\beta
\]  (5.3)

where \( T \) is the temperature, \( T_c \) is the critical temperature where the nematic to isotropic phase transition occurs, and the exponent \( \beta \) is a parameter which depends on the material structure.

In the nematic state, as the temperature increases, the \( n_o \) and the \( n_e \) changes oppositely and nonlinearly due to the change in the order parameter. The dependence of the \( n_o \) and the \( n_e \) on the temperature is approximated as [160];

\[
n_o(T) \approx n_i - \frac{G'}{2} S(T)
\]  (5.4)

and,

\[
n_e(T) \approx n_i + G' S(T)
\]  (5.5)

where \( n_i \) is the isotropic refractive index and \( G' \) is a fitting parameter which depends on the wavelength [160]. Therefore, the \( n_o \) and \( n_e \) are also determined by the optical wavelength.

As the temperature increases in the nematic state, the \( n_o \) increases while \( n_e \) decreases because of the decrease in the value of the \( S \) parameter, i.e. \( 0 < S < 1 \), which makes the \( S \) parameter a determining factor of the birefringence (\( \Delta n = n_e - n_o \)). When the temperature reaches the value of the clearing temperature, \( S(T) \) in Eqn.5.3 becomes zero, as it is also provided by Eqn.5.1, so both the \( n_o \) and the \( n_e \) have the same refractive index value which is the \( n_i \). Note, however that the Eqn.5.1 only holds in the nematic state. At \( T_c \), \( S \) has a discontinuous jump as nematic-isotropic transition is a first order transition. The \( n_i \) does not change strongly with the temperature since LC molecules are in the random state.

Figure 5.5 represents the change in the refractive indices as a function of the temperature for the 5CB LC at the wavelength of 1.55 \( \mu \)m calculated by using Eqns.5.4 and 5.5 and the parameters given in Ref.[159, 160]. The upper branch represents the \( n_o \) with an initial value of 1.683 at the temperature just above the crystalline temperature, \( T_{cn} \), whereas the lower branch represents the \( n_e \) with an initial of 1.516 at temperature just above the \( T_{cn} \). The figure shows that as the temperature increases from 23 °C to 35 °C, the ordinary refractive index increases and the extraordinary refractive index decreases. At the temperature of 35 °C, the LC experiences the phase transition and both refractive indices abruptly take on the isotropic refractive index. After the phase transition, the refractive index is nearly constant and only weakly depends on the temperature. The calculated isotropic refractive index, 1.572, is in good
agreement with the result of the Eqn.5.2, which is 1.571.

Figure 5.5: The temperature dependent refractive index of the 5CB LC for the wavelength of 1.55 \( \mu \text{m} \) calculated by using the parameters given in Ref.[159, 160]. The lower branch represents the ordinary refractive index value as a function of temperature, where the electric field is perpendicular to the LC molecules; the refractive index value is 1.516 just above the \( T_{cl} \). The upper branch represents the extraordinary refractive index as a function of temperature, where the electric field is parallel to the LC molecules. The refractive index is 1.683 just above the \( T_{cl} \). Both refractive indices exhibit a sudden change at \( T_c \) where the refractive index of the LC is isotropic, \( n_i = 1.572 \).

The tuning magnitude and direction of the resonant shift of the LC infiltrated photonic crystal structures are determined by the electric field polarization direction and the LC molecular orientation at a given temperature. In 2D deeply etched photonic crystal structures, the tuning is entirely determined by the refractive index change of the photonic crystal holes. Therefore the molecular alignment, as shown in figure 5.3, inside the voids completely controls the magnitude and the direction of the tuning. In the uniform axial configuration, two distinct refractive indices can be observed depending on the electric field polarization. If the field is TE polarized, i.e. electric field is in plane, then the resonant wavelength will be redshifted as the temperature increases since the effective refractive index is equal to the ordinary refractive index. For the TM polarized field, i.e. the electric field is parallel to the hole axis, the resonant wavelength will be blueshifted since the field will experience the extraordinary refractive index of the LC. At the clearing temperature, both polarized modes will exhibit a sudden change; for the TE-polarized mode a sudden redshift and for TM-polarized mode a sudden blueshift.

On the other hand, if the LC has a homeotropic anchoring resulting in the planar polar or planar radial configurations inside in the voids, the effective refractive index will be weighted by both \( n_o \) and \( n_e \) for the TE polarized mode.
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because of the two-dimensional orientation distribution of the LC molecules (the incident polarization will have an angle with the LC as represented in figure 5.4). So, the resonant wavelength will be either redshifted or blueshifted as the temperature increases. This kind of tuning has been observed by Schuller et. al. [139] where the wavelength of the TE polarized light is slightly blueshifted with the temperature. However, the TM polarized mode will have the $n_0$ since its polarization is perpendicular to the molecules which was also reported in Ref.[139]. At the clearing temperature, the TM-polarized mode will have a sudden redshift in its wavelength while the wavelength of the TE-polarized light is either redshifted or blueshifted depending on the contribution factor of the $n_0$ and the $n_e$. In the escaped radial configuration, the determination of the contribution of the LC refractive indices is more complex because of the three dimensional orientation distribution of the LC molecules. Therefore, the effective refractive index of the TE- and TM-polarized mode will be determined by the spatial distribution of the their electric field orientation with respect to the LC orientation distribution.

Analyzing the tuning behavior of the modes of the LC infiltrated membrane type of nanocavities is more complicated than that of 2D deeply etched structures. In the 2D deeply etched photonic crystals, the contribution of the LC orientation at the top/bottom surfaces to the tuning direction and magnitude is negligible; however, in the membrane type of photonic crystal nanocavities, the contribution of the surface is significant since the evanescent waves\(^1\) of a mode extends over the surface. To analyze the tuning effect of the LC in its isotropic phase\(^2\) where the LC has a single refractive index, 3D FDTD calculations have performed for three filling configurations; presence of the LC (i) at the top of the surface only, (ii) inside the holes only, and (iii) at the top of the surface, inside the holes and in the undercut region. Table 5.1 shows the calculation result for three modes, the dipole, the hexapole and the quadrupole, supported by a modified H1 cavity in a photonic crystal having a lattice spacing ($a$) of 500 nm, a radius of 0.35$a$, and innermost holes radius of 0.26$a$. The wavelength shift ($\Delta \lambda$) is calculated by subtracting the final resonant wavelength from the initial wavelength where the cavity is not filled. Table 5.1 suggests for the dipole mode that a 60% contribution on the tuning magnitude comes from the LC which is present at the top and bottom surfaces and a 40% contribution comes from the LC which is present inside the holes. For the hexapole mode, the contribution is almost 40% from the surfaces and 60% from the holes whereas for the quadrupole mode, it is approximately 45% from the surfaces and 55% from the holes. The findings here are fully consistent with the calculations in previous chapters where the hexapole mode is the most sensitive to the refractive index change of the holes and the dipole mode is the least.

\(^1\)An evanescent wave is a near field wave that has an exponential decay in its intensity as the distance is getting larger from the boundary where the wave is generated.

\(^2\)The isotropic refractive index is considered in order to prevent the birefringence effect on the mode tuning. Therefore, the modes in each polarization will experience the same refractive index.
Table 5.1: 3D FDTD calculation results to analyze the influence of the LC, which has the isotropic refractive index, on the tuning magnitude of three different cavity modes, the dipole, the hexapole and the quadrupole, of a modified H1 cavity. The LC is present either at the top surface, inside the holes, or at top/bottom surfaces and inside the holes. The magnitude of the resonant wavelength shift ($\Delta \lambda$) is determined by subtracting the resonant wavelength after the infiltration from the wavelength before the infiltration. The PhC hosting the cavity has a lattice spacing of 500 nm and a radius of 0.35\(a\). The radius of the innermost holes is 0.26\(a\).

<table>
<thead>
<tr>
<th>Mode Type</th>
<th>Contribution of the surface ($\Delta \lambda$ nm)</th>
<th>Contribution of the holes ($\Delta \lambda$ nm)</th>
<th>Contribution of total infil. ($\Delta \lambda$ nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dipole</td>
<td>30</td>
<td>44</td>
<td>104</td>
</tr>
<tr>
<td>Hexapole</td>
<td>32</td>
<td>83</td>
<td>145</td>
</tr>
<tr>
<td>Quadrupole</td>
<td>25</td>
<td>70</td>
<td>115</td>
</tr>
</tbody>
</table>

Maune et. al. [137] observed that a surface coverage of a LC material can introduce a considerable blueshift on the lasing mode of an InGaAsP photonic crystal slab nanocavity by activating it electrically. Recently, a numerical analysis has been reported by Wang et.al [142] concluding that the determination of the molecular alignment inside the photonic crystal holes from the optical data is not straightforward. Therefore, to evaluate the effect of the LC orientation on the spectral position of a mode requires a comparison of the optical data with advanced calculations which include both the spatial distribution of the electric field at every point on the top/bottom surfaces and inside the holes.

5.3 Liquid crystal infiltration

The LC 4-pentyl-4’cyanobiphenyl (5CB, Merck), which has the nematic-isotropic phase transition temperature, or clearing temperature, $T_c$ at 35 °C, is infiltrated under ambient pressure. This is carried out by putting a drop of LC on the sample, while the sample and the LC are heated above the $T_c$. The excess liquid is blown off the sample by dry nitrogen. The remaining LC thickness on the top of the sample is unknown. Since the hole infiltration is driven by capillary pressure effects, good wetting of the LC to the surface is essential. A good wetting is obtained after the treating the sample as was explained in section 4.5. Contact angles were inspected occasionally, and are typically below 15 °.
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Figure 5.6: Scanning electron microscope image of a fabricated modified H1 cavity. The photonic crystal has a lattice spacing of 480 nm and a nominal radius of 0.32a. The radius of the innermost holes is reduced by 35 nm and the holes are shifted by 15 nm.

5.4 Thermal tuning

Tuning of the liquid crystal infiltrated photonic crystal structures by temperature is of interest for future tunable optical devices. To investigate the temperature tuning, the LC infiltrated 220 nm thick InGaAsP photonic crystal membrane type nanocavities are placed on the sample in a heating stage made from an aluminium plate. A resistor and a thermocouple are attached on the stage by using a thermally conductive epoxy. The temperature is controlled by varying the current passing through the resistor and measured by using the thermocouple device.

Figure 5.7(a) shows the PL spectrum collected from a modified H1 nanocavity as shown in figure 5.6 before infiltration. The photonic crystal hosting the cavity has a lattice spacing of 480 nm, a radius of 0.32a and the innermost holes of the cavity are modified by reducing them in size about 35 nm and shifting them radially outward by 15 nm. The modes are identified by a 3D FDTD simulation. The peaks occurring at 1461 nm and 1468 nm are quadrupole modes, referred to as the $Q_1$ mode and the $Q_2$ mode respectively, having $Q$ values up to 1000. The $Q_1$ mode and the $Q_2$ mode are degenerate in ideal cavities, but in practice are split due to fabrication tolerances. The peak occurring at 1479 nm is the hexapole mode, referred as the $H$ mode, with a $Q$ value 900. Figure 5.7(b) shows the spectrum of the same cavity after the infiltration of the LC, which is done with the LC in the nematic state. All resonant modes are redshifted by more than 70 nm. The redshift is somewhat smaller than expected from simulations (~100 nm), so that the complete filling is not realized, see Table 5.1. Presumably, the space below the membrane is not filled as represented in figure 5.7(d). This may result in increased scattering, but the $Q$ is still high enough to clearly resolve the resonances. Figure 5.7(a) shows that
Figure 5.7: (a) The PL signal collected from the modified H1 cavity before the LC infiltration. The modes are identified as split degenerate quadrupole mode ($Q_1$ and $Q_2$), and the hexapole mode ($H$). (b) The PL emission collected from the same cavity after the LC infiltration at the nematic state. A schematic of a side view of an InGaAsP membrane (c) before and (d) after the LC infiltration. The corresponding 3D FDTD calculation suggest that the LC occupies the top surface and the PhC holes.

The $Q_1$ mode and the $Q_2$ mode are split by 7 nm before the infiltration. Figure 5.7(b) shows that the splitting is increased to 15 nm after the infiltration. The increase in the splitting shows that the two modes respond differently to the infill of the holes, which could be the result of different overlaps of the modes with the holes. The intensities and the $Q$ values of the resonant modes are significantly decreased after the infiltration due to the lower refractive index contrast between the semiconductor membrane and the surrounding medium.

To investigate the possible influence of the LC orientation on the nanocavity modes, the temperature is increased from 22°C to 44°C across the clearing temperature of $T_c = 35°C$. Figure 5.8(a) represents three PL spectra collected from the LC filled cavity at three different temperatures, one (22°C) is well below and two (32°C and 35°C) are near $T_c$. Figure 5.8(b) shows the temperature dependent wavelength shift of the three modes. As the temperature increases from 23°C to 34°C, the $Q_1$ mode and the $H$ mode, redshift by more than 3 nm and 2 nm, respectively. The redshift can be partly accounted for by the temperature dependence of the refractive index of the semiconductor, corresponding approximately to 0.1 nm/K [50] as also found in section 3.4. However, the $Q_2$-mode exhibits a small blueshift around 0.5 nm. Near $T_c$, the $Q_1$-mode and the $H$-mode show an abrupt redshift by more than 4 nm and 2 nm, respectively, while the $Q_2$-mode is abruptly blueshifted by more than 1.5 nm. Above the transition temperature, there is no significant shift in the modes observed because the refractive index of the LC does not change in the isotropic state.
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Figure 5.8: (a) The PL signal collected from the modified H1 cavity at three different temperatures; one well below the clearing temperature, 23°C and two near the $T_c$ 32°C and 35°C. The dashed lines represent the corresponding wavelengths of the LC filled cavity at 23°C. (b) The change in the resonant wavelengths when the temperature is increased from the 23°C to 44°C; the birefringence induced mode dependent tuning is observed where the $Q_1$ and $Q_2$ modes are redshifted and blueshifted respectively. At the clearing temperature, all the modes exhibit a sudden change.

Our experimental results can be explained if the $Q_2$-mode is dominated by the $n_e$, while the $Q_1$-mode and $H$-mode are dominated by the $n_o$. The electric field of the cavity mode is in the plane of the PhC (TE-polarization), perpendicular to the hole axis. This requires that at least a substantial fraction of the LC is aligned in the plane, i.e. perpendicular to the hole axis. Since different modes, including degenerate ones, have different E-field profiles, the relative contributions of $n_e$ and $n_o$ to the effective refractive index in the holes may vary between modes. Even though the change in the refractive index is larger for the $n_e$ than for the $n_o$, the data show that the observed blueshift for the $Q_2$-mode is smaller than the obtained redshift for the $Q_1$-mode and the $H$-mode. The reason is that even if the LC orientation is completely in-plane, there is still a distribution of orientations between the E-field and the LC orientation.

In order to investigate the persistence of the effect, the resonant frequency shifts at $T_c$ were investigated for different nanocavities; all fabricated on the same chip and thus subjected to the same processing conditions. The cavities are of the type shown in figure 5.6, and only differ by slight variations of the surrounding hole geometry. The tuning behavior of two different nanocavities, with the same $a$ and $r/a$ as the cavity in figure 5.6 are given in figures 5.9(a) and (b). In one cavity, the radii of the six surrounding holes are reduced by 33 nm and their center positions are displaced by 24 nm. For the other cavity, the radii are reduced by 20 nm, while the center positions are left unchanged. We refer
to these cavities as $C/c_{C,33}$ and $C/c_{C,20}$ respectively. Both cavities accommodate the same $Q_1$, $Q_2$, and $H$- modes as the cavity in figure 5.7(a). Figure 5.9(a) shows that all three modes of the cavity $C/c_{C,33}$ are redshifted by more than 2 nm, 8 nm, and 5 nm, respectively, including an abrupt increase at the clearing temperature. Below the clearing temperature, the $Q_1$-mode and the $Q_2$-mode accidentally appear at the same wavelength. At the clearing temperature, the near-degeneracy of the modes is lifted and they suddenly split by more than 5 nm. This might be caused by the orientational effects of the LC, but also by unequal filling of the holes. Figure 5.9(b) shows results from the cavity $C/c_{C,20}$. Here only the $Q_1$-mode redshifts by more than 6 nm at $T_c$. The $Q_2$-mode and the $H$-mode are blueshifted by more than 9 nm and 1.5 nm, respectively. All three modes show abrupt changes at the clearing temperature. The different behavior of the very similar cavities $C/c_{C,33}$ and $C/c_{C,20}$ show that the orientation of the LC inside the voids is not due to an intrinsic molecule-wall interaction, but may be randomly determined by varying surface properties of the etched holes. A variable LC orientation in the holes, depending on variations of the etched surface conditions, was also concluded on different grounds in previous work [146]. Since the orientation of the LC molecules inside the PhC holes is apparently varying, no model calculations have been undertaken to fit the frequency shifts. In addition, it should be noted that the optical properties of non-uniformly polarized LC’s in small geometries may be exceedingly complex [161].

5.5 Photothermal tuning

Of particular interest are optical tuning methods with an external laser beam, because they are contactless, do not require elaborate sample processing steps, are very local and are easily reconfigurable. The optical tuning of planar photonic crystals using the same LC has been demonstrated previously by infiltrating a photoresponsive mixture of this LC and azobenzene derivatives [162]. Upon irradiation with UV light, the azobenzene molecules isothermally induce a phase transition of the LC to the nematic state while the transition could be largely reversed by irradiation with visible light. The photonic crystal cavity resonance wavelength in the isotropic state was always redshifted with respect to that in the nematic state. To exploit the full reversibility of this tuning mechanism, two different light sources at UV and visible frequencies are required. In the present work, we demonstrate tuning of a LC-infiltrated PhC cavity in an InGaAsP membrane PhC by local heating with a focused laser spot. The heating is induced by the absorption of radiation in the semiconductor, but the tuning effects are dominated by the temperature dependence of the LC refractive index. The observed tuning rate $d\lambda/dT$ is large, reversible and has an opposite sign for the modes with different polarizations, which is a genuine property of
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Figure 5.9: Another evidence of the birefringence effect on the mode tuning of two different modified H1 cavities. (a) The resonant wavelength shift of the first modified H1 cavity, $C_{24}^f$, as the function of temperature. The degenerate quadrupole mode splits after the clearing temperature. (b) The resonant wavelength change of the second modified H1 cavity, $C_{20}^f$, as a function of the temperature where the quadrupole modes are split just above the clearing temperature and merged at the clearing temperature. All the modes in both cavities have the abrupt change at the clearing temperature.

As a reference, we first investigate the effect of the laser-induced heating for empty structures. Figure 5.10(a) shows the PL signal collected from the H1 cavity similar to the one shown in the figure 5.6 before the infiltration under a low excitation power. The photonic crystal has a lattice spacing of 470 nm and a hole radius of 0.35$a$ and the innermost holes of the cavity are both reduced to 0.3$a$ and shifted by 0.032$a$ outward as the parameters are determined from the corresponding scanning electron microscope image. The modes at 1455 nm and 1460 nm are split dipole modes, which we refer to as $DX$ and $DY$ respectively, and which are identified by comparing with the results of 3D finite difference time domain (FDTD) simulation (CrystalWave). The $DX$ and $DY$ modes are ideally degenerate but split in reality due to the imperfect fabrication. Figure 5.10(b) shows that the $DX$ and the $DY$ modes both redshift by more than 5 nm as the laser power on the cavity surface increases up to 410 $\mu$W. The power incident on the sample is estimated from a separate measurement with a power meter at the position of the sample\(^3\). The redshift of the modes is caused by the increase in the refractive index of the semiconductor due to the thermo-optic effect as described in the section 3.5. The tuning magnitude implies that

\[^3\]The obtained wavelength shift as a function of the laser power is different than that is found in section 3.5. The difference is caused by using two different two different experimental set-ups which introduce different laser power on the sample.
the observed shift corresponds to a local temperature increase of more than 50 °C. Such a large temperature increase with the modest laser power occurs due to the poor thermal coupling of the undercut slab to the semiconductor chip.

Figure 5.10: (a) The PL signal collected from the modified H1 cavity in a photonic crystal having a lattice spacing of 470 nm and a radius of 0.35a under the excitation laser power of 50 µW. The innermost holes are reduced to 0.3a and shifted by 0.032a nm radially outwards. The parameters are determined from the corresponding SEM image of the PhC. The cavity exhibits a split degenerate dipole mode (DX, DY) around the wavelength of 1455 nm. The peaks at higher wavelength are the band edge modes. (b) The resonant wavelength change as a function of incident laser power of the cavity where DX and DY are almost linearly redshifted.

Figure 5.11(a) shows the PL emission from the H1 cavity after the infiltration of the LC at the nematic state with the low laser power of 50 µW. The spectrum shows that the DX and DY modes are redshifted by 100 nm with an increased splitting of 15 nm. The redshift of the modes is caused by the change in the environment refractive index due to the LC. The 3D FDTD simulation confirms that in this experiment the LC occupies the undercut region, as shown in Table 5.1, the PhC holes and the surface. Figure 5.11(b) represents the PL signal collected from the infiltrated cavity under three different pump-powers. The peak positions of the two modes are plotted as a function of power in Figure 5.11(c). When the laser power is increased up to 250 µW, the DX mode redshifts by more than 3 nm while the DY mode gradually blueshifts by more than 5 nm. The wavelengths of the DX and the DY modes show a rapid change near 300 µW. Apparently, the Tc (35 °C) of the LC is reached at 300 µW. Given the temperature sensitivity of the resonance wavelengths of ~0.1 nm/K, and the 4 nm wavelength shift for 300 µW power observed for the empty cavity (figure 5.10(b)), this power is somewhat higher.
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than expected. This is reasonable because the LC will cause some additional cooling of the cavity [131]. In the isotropic state above 300 $\mu W$, the splitting of the two modes is not clearly observable within the experimental linewidth resolution. The infiltration increases the losses somewhat, so that the linewidths broaden. This implies that the observed splitting in the nematic LC state is dominated by the LC optical anisotropy and not by PhC fabrication imperfections. The fabrication-induced splitting as observed before infiltration (figure 5.10(a)) is not observed in the isotropic LC-filled case, presumably due to the decreased linewidth resolution. A maximum tuning rate with a blueshift of about 0.1 nm/ $\mu W$ is observed between 200 and 300 $\mu W$ with the LC, whereas from figure 5.10(b) a redshift tuning with a magnitude about an order of magnitude smaller is obtained for similar laser powers with the empty PhC. Increasing the excitation power above 300 $\mu W$ up to 500 $\mu W$, shows no significant change in the resonant wavelengths. Upon decreasing the laser power, it is found that the tuning is reversible and no hysteresis is observed. This shows that the LC is not evaporated under the high excitation power. In principle, there is no reason why the two resonant mode wavelengths would not cross as a function of the laser intensity, though it was not observed so far. The crossing would be very interesting as it would offer an accurate and tunable control of the mode degeneracy with possible applications in quantum optics.

The redshift and the blueshift of the two modes are attributed to the existence of the ordinary and the extraordinary refractive indices of the LC as it was analyzed in the case of a simple heating for the nearly degenerate quadrupole modes of the same cavity in the previous section and in Ref.[142]. The blueshift of the one quadrupole mode was much smaller than the redshift of the other, as opposed to the behavior for the nearly degenerate dipole modes investigated now. Since the modes are TE-polarized, the electric field is almost entirely in the plane of the PhC, i.e. perpendicular to the hole axis. This in-plane E-field pattern, calculated using 3D FDTD [163] for the two modes is given in figure 5.12(a) and (b)\(^4\). It is plotted for the center plane of the slab, but the pattern varies only weakly when we move from the center to the top or the bottom surface. Unlike the case for the quadrupole modes [142], there is no clear 90° polarization rotation inside the holes for the two modes. On the other hand, in the center of the cavity, the two modes have polarizations that are nearly orthogonal to each other. Therefore, we attribute the observed splitting to interactions of the modes with the LC on the top and bottom surfaces of the slab, assuming that the LC molecules tend to align parallel to the surface. The much larger effect observed here for the dipoles than observed with the temperature stage for the quadrupole is probably also the result of the more uniform polarization of the dipole. For practical reasons, the experiments for the dipole have not been repeated with the heating stage.

It is also important to note that at high laser powers the LC can be removed

\(^4\text{The simulation was done by Bowen Wang.}\)
Figure 5.11: (a) The PL signal collected from the modified H1 cavity after the LC infiltration where the splitting of the DX and the DY modes is now 15 nm. (b) Three PL emissions collected from the filled cavity at three different laser powers. (c) The resonant wavelength change of the DX (the lower branch) and the DY (upper branch) modes as the function of the incident pump power. At the power of 300 µW, the modes show an abrupt change due to the phase transition. The process is fully reversible and no hysteresis observed.
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Figure 5.12: The 3D FDTD calculation [163] result of the electric field vector of the dipole modes, (a) DX and (b) DY. The electric field direction of the DX and the DY modes at the center of the cavity is perpendicularly polarized each other.

away from the PhC structure due to the large temperature gradient increase around the cavity. In order to observe the possible removal of the LC, the image of the cavity is captured after increasing the laser power. Until the laser power of 425 $\mu W$, the increase in the temperature does not cause any liquid transport or liquid evaporation as shown in the image represented in figure 5.13(a), which was taken with a 50X microscope objective, and the lack of those effects was confirmed by the mode’s reversibility. However, a sudden blueshift ($\sim 20$ nm) is observed for the dipole mode when the laser power is increased to 650 $\mu W$ as shown in the figure 5.13(c). This sudden change is most likely related to the laser induced mass transport out of the cavity or evaporation of the LC [164] due to the temperature, as shown in figure 5.13(b). The further increase in the laser power causes a smaller blueshift and then saturation due to the transportation or evaporation of the little amount of the LC inside the pores. The resonant wavelength of the experimental dipole mode at the highest laser power differs by $\sim 80$ nm from that of the empty cavity. The calculated tuning magnitude of the dipole mode represented in Table 5.1 suggests that the LC on surface is almost totally removed but holes and space underneath the membrane is still filled. The tuning by removing of the LC is not reversible when the power is decreased. More laser power after that point could destroy the cavity.

5.6 Summary and conclusion

A LC is an intermediate state of matter which possesses either crystalline or liquid properties at different temperatures. Infiltrating the LC into photonic crystal holes offers an active tuning of resonances of photonic crystal nanocavities
CHAPTER 5.

Figure 5.13: The 50X optical microscope images of the modified H1 cavity after the LC infiltration, (a) taken after the laser power of 425 µW, (b) taken after the laser power of 650 µW which shows that the LC is either removed or evaporated due to the large thermal gradient. (c) The corresponding resonant wavelength change of the DX and the DY modes as a function of the laser power, where before 500 µW the reversible tuning and after 500 µW the irreversible blueshift is observed.

by changing the LC's refractive index via temperature. As the temperature increases in the nematic phase, where the LC molecules have a directional order, the ordinary refractive index increases while the extraordinary refractive index decreases. At the clearing temperature, where a phase transition from nematic to isotropic occurs, the two indices exhibit an abrupt change and have the same refractive index, which is called isotropic refractive index. The isotropic refractive index does not change with the temperature and in this phase, the LC has the same properties as an ordinary liquid has.

The PhC nanocavities are backfilled by the 5CB LC (Merck) to investigate the thermal effect on the mode tuning. As the temperature is increased from just above the crystalline temperature to the clearing temperature, a birefringent induced mode dependent tuning is observed for the split quadrupole modes of a modified H1 cavity. The wavelength of the modes show an abrupt
change at the clearing temperature. A further increase in the temperature does not change the resonant wavelengths since the isotropic refractive index does not depend on the temperature.

Heating the cavities by a laser source provides a control on the temperature of the individual devices on the chip. In order to benefit from the local control, the resonant modes of a LC infiltrated cavity are tuned by relying on the photothermal effect. Similar to the thermal tuning, the wavelengths of the degenerate dipole modes are oppositely shifted in the nematic phase as the excitation power is increased. The corresponding clearing temperature occurred at the excitation power of 300 $\mu W$ where the modes exhibited a sudden shift. A further increase in the power did not show any significant change; however, in the case of high excitation powers, the LC is either removed away from the cavity or evaporated because of the large temperature. Both the thermal and photothermal tuning (until the high laser power) are reversible and no hysteresis is observed.

The tuning of the LC infiltrated cavity resonances by temperature will be of interest for realizing optically tunable optoelectronic PhC devices. Although the tuning speed is very slow, in the order of millisecond, the LC infiltrated devices can be envisaged as an optical switch [136]. However, the response time can also be decreased by mixing with another organic material [150].
Chapter 6

Tunable coupled cavity systems

6.1 Abstract

An optical coupling between an L3 cavity and a photonic crystal waveguide is investigated when they are brought in a close proximity. The reported experiments will be limited to finite length waveguides, closed at both ends by photonic crystal holes. The waveguide thus is actually a large cavity with many Fabry-Perot like modes. Two different coupling configurations are analyzed where the L3 cavity is oriented either under 60° or parallel to the waveguide end. The coupling strength is varied both by the cavity orientation and number of the holes that separate the L3 cavity from the waveguide. The coupling results in splitting of the cavity modes as a result of the interacting cavities.

6.2 Introduction

In the previous chapters, the spectral properties and the tunability of single photonic crystal structures have been demonstrated for use in photonic devices. In this chapter, we will explore an application of the local photothermal tuning and present the preliminary results. Two cavities are coupled to a common waveguide, but are far separated by tens of microns. The goal is to demonstrate an on-chip spectrometer based on a tunable cavity that acts as a tunable filter. The second cavity serves as a narrow band on-chip source, the frequency of which is to be determined by the tunable filter. Because tuning is most conveniently done by the PL-generating pump beam, the practical configuration would be to tune the source and to keep the filter fixed. For the operation, the coupling of the cavity to the waveguide is important, and therefore, the coupling configurations have been varied. To better study this coupling, it was not only
investigated for open waveguides, but also for finite length waveguides closed at both ends by photonic crystals. Such closed waveguides, in fact, are also very large cavities. The coupling of a single tunable L3 cavity to such a large waveguide cavity showed a wealth of phenomena. Since the interaction between very dissimilar photonic crystal cavities has not been reported before, the chapter will be limited to this subject only.

In the previous chapters, the distance between each structure on the chip was large enough, so that their mutual electromagnetic influence can be neglected. However, when the distance between the structures is decreased, their mutual interaction cannot be neglected anymore and a new common-mode is formed with an electromagnetic field distribution over the entire coupled system.

A great deal of work exists in which a series of photonic devices is intentionally brought in a close proximity to enhance resonant coupling between the individual elements [165] to realize add/drop filters [166], optical spectrometers [167, 168], ultra fast lasers [169] and many other components for future photonic devices. A pair of coupled cavities has been denominated as a photonic molecule [170]. The system with identical structures is designated as a homoatomic photonic molecule, or with different structures, as a heteroatomic photonic molecule. The coupling of homoatomic photonic molecules has been theoretically reported and experimentally demonstrated in various cavity systems including Bragg mirror semiconductor cavities [170], microdisks [171], microrings [172], microspheres [173] and photonic crystals [174–176]. A famous example of a coupled cavity system is the coupled resonator optical waveguide (CROW) structure which consists of a linear chain of cavities [165]. The energy transfer along the chain is obtained by the evanescent coupling through the adjacent cavities. The CROW systems offer new ways of controlling the group velocity of light on the chip and have found many applications in delaying, storing and buffering of optical pulses [177]. The coupling of heteroatomic systems has been a challenging task to realize since it requires more advanced design to match the resonances both spatially and spectrally.

In photonic crystal homoatomic structures, two or more identical cavities are brought into close proximity to exploit their energy transfer. The distance between the structures is varied by changing the number of the hole barriers. Atlasov et. al [178] have demonstrated that the coupling of two L3 type point defect cavities results in a splitting of both mode wavelength and the modal loss and those are controlled via the number of the lateral hole barriers. The coupling of the L3 cavities with different orientation angles has been evaluated by Chalcraft et. al [179] theoretically and they demonstrated that 30° diagonal geometry offers the smoothest control of the mode splitting. Vignolini et. al. [111] have demonstrated a clear anticrossing of a homoatomic system based on two identical photonic crystal cavities. They employed a local tuning mechanism to control the coupling condition. They also investigated a heteroatomic
structure with identical cavities, but different modes of each cavity [180].

A cavity-waveguide coupled system is important for filtering out or inserting a signal in a line waveguide. Fan et. al. [13, 181] reported theoretically that by coupling two singly-degenerate resonators to two line waveguides (bus and drop), a particular frequency can be selectively dropped from the bus waveguide to the drop waveguide.

Smith et. al [182] have experimentally demonstrated a heteroatomic coupling scheme where an H7 type of cavity is brought near a channel waveguide with a distance between two and five hole barriers. They observed the coupled modes in the wavelength range of the waveguide ministopband due to the anticrossing mechanism. In this early experiment, the anticrossing was not directly demonstrated due to the lack of tuning.

Several groups have studied the optimization of the coupling cavities to waveguides, by positioning and orienting the cavity with respect to the waveguide [183, 184]. Kim et al. [183] studied the coupling of the hexapole mode of a modified H1 cavity to a W1 waveguide. They showed that the coupling efficiency strongly depends on the transverse overlap of the cavity mode and the waveguide mode. In their work, they showed that the best coupling to the end of a waveguide is obtained when the cavity is displaced over a few holes both with respect to the waveguide center position as well as with respect to the waveguide end. This is called a "shoulder position" of the cavity with respect to the waveguide end. Another theoretical and experimental work was conducted by Faraon et. al [184] for an L3 cavity-W1 waveguide coupling scheme where the long cavity axis is rotated by $60^\circ$ with respect to the waveguide axis to increase the coupling efficiency for the fundamental mode. This they also called shoulder coupling. A shoulder coupling of an H0 cavity has been studied by Nozaki et. al.[185] where they demonstrated an effective light extraction from the cavity via the waveguide. Therefore, both in the homoatomic and in the heteroatomic systems, care must be given to the orientation of the cavity to obtain an efficient energy transfer.

Another interesting application of the coupling of cavities to waveguides is to study coupled resonator induced transparency (CRIT) due to the coherent interference of the optical modes [186, 187]. The CRIT has an analogy with the phenomena of electromagnetically induced transparency (EIT) which is a result of the destructive quantum interference of spontaneous emission from two close energy states that reduces the light absorption [188, 189]. In a configuration with two L3 cavities coupled to a W1 waveguide, an all-optical analog of electromagnetically induced transparency is created [190].

When the individual cavities are brought close, they optically couple to each other with the evanescent field of the modes. The interaction gives rise to mode hybridization which results in an energy splitting [191]. This splitting is analogous to the splitting in the diatomic molecules where the Coulomb interaction between the atom cores and the electron splits the energy levels in a bonding
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and antibonding state. The mode coupling forms the delocalized *symmetric* and *antisymmetric* coupled modes [192] where the strength of the optical coupling between the modes of the cavities depends on the difference between their resonant frequencies. Furthermore, the quality factor of the modes also varies with the change of the inter-cavity coupling efficiency [178].

The coupled cavity system is generally described by considering two linearly coupled oscillators (the cavity modes in our case). The photonic splitting for the coupled cavity modes is given by [192]:

$$\Omega = \sqrt{\Delta^2 + 4g^2}$$

(6.1)

where $\Delta$ is the frequency difference of the cavities when they would be isolated, and $g$ is the coupling energy of the mode. The mode splitting ($\Omega$) can provide a direct determination of the coupling energy ($g$) if there is no detuning of the modes in isolated cavities, i.e. $\Delta = 0$. If there is a big spectral mismatch between the modes having the same spatial profile, i.e. $\Delta \gg g$, no coupling can be observed. In Ref. [192], the $\Delta$ of nominally identical cavities was caused by disorder.

In this work, we demonstrate the coupling of an L3 type of point defect cavity to a line defect waveguide cavity (closed ends) in two different coupling orientations. The coupling gives rise to coupled L3-FP modes in the spectral region of the L3 cavity modes which could result in mode hybridization. Our work differs from previous work in several respects. In previous work (with exception of Ref. [182]) nominally identical cavities were used. Here we use two genuinely different cavities of very different size, both with very well characterized and well defined modes. Even the study of heteroatomic mode coupling of Ref. [180] used nominally identical cavities. The coupling can be studied in great detail because we appreciably tune the small cavity mode with a much smaller tuning of the second large cavity. In the previous work [192], the mode interaction was studied by laser heating assisted tuning which was very local but also irreversible and occurring on the time scale of hours. In contrast, the present tuning method is fully reversible and occurs on the time scale of tens of microseconds, which is the estimated thermal relaxation time of the cavity.

In section 6.3, the spectral and spatial characteristics of an L3 cavity and W1 photonic crystal waveguide will be explained. In the section 6.3.1, different coupling orientations in which the experiments are conducted will be demonstrated. In sections 6.4 and 6.5, experimental results of the side coupling and the shoulder coupling configurations will be presented respectively.

### 6.3 Coupled cavity-waveguide systems

The L3 type of point defect cavity, where three air holes are unetched as shown in figure 6.1(a), is a good candidate to realize cavity-waveguide coupling
Figure 6.1: (a) Scanning electron microscope image of a fabricated L3 cavity. (b) A typical photoluminescence spectrum obtained from an L3 cavity where five cavity modes are observed. The modes are labeled as $M_1$, $M_2$, $M_3$, $M_4$, and $M_6$ from high wavelength to low wavelength. (c) The corresponding magnetic field profiles of the cavity modes. Note that $M_5$ peak is not observed in the spectrum.

scheme because it provides a good overlap between the cavity and waveguide field patterns. The cavity supports many modes; a typical photoluminescence spectrum is shown in figure 6.1 (b) where the modes are labeled as $M_1$, $M_2$, ..., $M_6$. Those modes have different symmetries with respect to the $x$- and $y$-axes, as their magnetic field profiles ($H_z$) are shown in figures 6.1(c)-(h).

When another photonic crystal structure is introduced near the L3 cavity, an energy flow from the cavity to the structure is induced. Since the overlap of the resonant modes is one of the prerequisites for the optical coupling, a W1 type (one air row missing in the $\Gamma K$ direction) photonic crystal waveguide, as shown in figure 6.2(a), is chosen because it has a similar mode symmetry and frequency as the L3 cavity.

Since the spectral overlap is another key factor to obtain the optical coupling, the spectral properties of the W1 waveguide have to be analyzed. Therefore, we calculated the three-dimensional bandstructure of a W1 photonic crystal waveguide by using a 3D FDTD calculation [163]. Figure 6.2(b) shows two dispersion curves that exist in the photonic bandgap region which correspond to an even mode with a frequency of 0.29 at $k_x = \pi / a$ and an odd mode with a frequency of 0.315 at $k_x = \pi / a$. The parities are defined with respect to the $}\ldots$
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Figure 6.2: (a) Scanning electron microscope image of a photonic crystal waveguide where a single row of air holes is unetched in the $\Gamma K$ ($x$-) direction (W1 waveguide). (b) The 3D bandstructure of a W1 waveguide. The two lines in the bandgap correspond to the even and odd parity modes of the waveguide. The thin straight lines correspond to the frequency of the L3 cavity modes where the lithographic parameters of the photonic crystal hosting the both structures are the same. The magnetic field profile of the even (c) and the odd (d) parity modes of the waveguide with respect to the symmetry on the $x$- and $y$-axes respectively. The calculations correspond to the nominal parameters of a fabricated sample. The calculated frequencies for the L3 cavity modes are without modifications of the end holes.

$H$-field symmetry in relation to the center of the waveguide as shown in the figure 6.2(c) and (d) respectively. Both parities have a nearly flat dispersion near the band edge where the group velocity goes to zero. The frequencies of the L3 cavity modes, $M1$, $M2$, $M3$, and $M4$, are represented with straight lines that cross either even or the odd parity modes.

Figure 6.2(b) also indicates that the $M1$ mode of the L3 cavity promises an efficient coupling because the $M1$ (and the $M2$) derive from the even mode of the waveguide. Another important feature of the $M1$ mode is that its frequency is close to the flat region of the dispersion curve where the cavity can be strongly coupled to the waveguide modes [193]. The $M2$ mode crosses the
even mode just above the light line in that geometry; however, in our experiments the $M2$ mode is generally observed as rather sharp due to modifications of the two end holes of the L3 cavity which shifts the $M2$ mode to lower frequencies below the light line. In some cases, where the modification is not introduced, we also observe the $M2$ mode with a low $Q$ factor; apparently it lies above the light line. Both the $M1$ and $M2$ modes exhibit a strong optical coupling [179, 184]; therefore, they will be of interest in this chapter.

In order to optically characterize the fabricated (closed) waveguides, two different photoluminescence experiments are conducted. One is the conventional one that is using the same objective for excitation and collection and the other one is using the objective for excitation and a SNOM tip for collection. In this way, we can separate the position for excitation and detection. In this case, no L3 cavity was coupled to the waveguide. The figure 6.3 (a) shows the photoluminescence spectrum collected from a photonic crystal waveguide where the objective is used for both excitation and collection. The broad peak around 1450 nm ($\lambda$) originates from the $\Gamma$ point of the odd mode which lies above the light line, see 6.2(b), hence it is a leaky mode. It has a large intensity because since $k=0$ it strongly radiates perpendicular from the wafer. This mode leads to the $M4$ mode in the L3 cavity. The peak located at 1560 nm ($B$) corresponds to the slow light mode that lies on the flat region of the even mode dispersion of the waveguide from which the $M1$ mode derives.

Another photoluminescence experiment is conducted for a similar W1 photonic crystal waveguide by exciting the structure via the objective and collecting the emitted signal via the SNOM tip at almost 20 $\mu$m away from the excitation spot. The SNOM tip has a 500 nm diameter and no cladding. Large diameter tips are used since a high spatial resolution is not required, while a large signal is very useful. The figure 6.3(b) shows many peaks in the spectrum. The modes are nearly equally spaced and correspond to Fabry-Perot (FP) peaks. They get closer together as the frequency approaches the band edge. The FP resonances have very low losses, and therefore are hardly observed in the objective experiment. Only when excitation and detection is done at the ends of the waveguide, enough scattering occurs to weakly see the FP in the PL. When detecting with the SNOM, the signal is obtained from the evanescent field, independent of out of plane radiation and scattering.

The peak $A$ occurring near the wavelength of 1450 nm, in figure 6.3(b), is associated with the $A$ peak of the waveguide as observed with the objective, see figure 6.3(a). Despite the strong out of plane scattering and slow group velocity near $k=0$, it apparently propagates at least tens of microns along the waveguide.
Figure 6.3: (a) The photoluminescence spectrum of a W1 PhC waveguide which is obtained by exciting and collecting the signal by the microscope objective. The broad peak (A mode) located near the wavelength around 1450 nm is an odd mode which originates from the Γ point. The sharp peak (B) mode located at the wavelength of 1565 nm is the slow light mode. (b) The PL spectrum from a similar waveguide cavity where the cavity is excited by the microscope objective but the emitted signal is collected by a 500 nm aperture SNOM probe which is positioned by 20 µm away from the excitation spot. The sharp peaks at the higher wavelengths are the Fabry-Perot peaks and they are equally spaced in the linear region of the dispersion line and get closer at the flat region of the line. The data for (a) and (b) were taken on different waveguides, therefore the B peak and the onset of the FP resonances occur at different wavelengths. For the same reason, the A peaks are not at the same position.
6.3.1 Fabricated coupling configurations

To investigate the coupling of the L3 cavity modes, different coupling configurations are designed and fabricated similar to those reported in Refs. [183, 184]. Among the various configurations, side and shoulder coupling configurations will be analyzed here. Figure 6.4 (a) is a scanning electron microscope image of a side coupling configuration as a representative example. The side coupling consists of one L3 cavity which has the same orientation as the L60 (the W1 waveguide) cavity with a one hole offset. The distance between the L3 cavity and the W1 waveguide is determined by the number of the holes between the end of the cavity and the closer end of the waveguide. For instance, for the configuration in figure 6.4 (a), the number the hole separations is one. The shoulder configuration consists of an L3 cavity oriented along $60^\circ$ rotated $\Gamma K$ direction to one end of L60 (closed waveguide) Fabry-Perot cavity. Similar to the side coupling case, the distance between the L3 and the L60 cavity is determined by the number of the holes between the end of the L3 and the closer end of the L60.

The PL experiment is conducted by exciting the cavity and collecting the signal by the same objective. In order to prevent the direct excitation of the waveguide, the laser spot is placed at the left(-upper) part of the L3 cavity.

6.4 Side coupling

First, we investigated the coupling of the L3 modes to the L60 cavity in side coupling configurations. This kind of coupling configuration has been studied before as a channel drop filter [194–196]. In contrast to the configurations presented in the Refs.[194–196], our configuration consists of a closed waveguide (L60 type Fabry-Perot cavity) where the L3 cavity is placed in a close proximity to one end of the waveguide. Both structures are oriented in the $\Gamma K$ direction as shown in the SEM image 6.4 (a) and the L3 cavity is located one hole above the waveguide’s lateral direction.

Figure 6.5 (a) shows a set of PL emissions at different excitation powers which are collected from the L60 cavity via a 500 nm diameter SNOM probe, which is positioned at the other end of the waveguide, when the side coupled L3 cavity is excited by the microscope objective. In this configuration, the photonic crystal has a nominal lattice spacing of 445 nm and a nominal radius of 0.3a. The two end holes of the L3 cavity are not shifted in position but reduced in size ($r'=0.22a$). When the laser power is 0.11 mW, the spectrum shows the Fabry-Perot peaks and the cavity mode (the $M1$) at the wavelength of 1531 nm. As the laser power increases, all the peaks redshift due to the refractive index change. At the laser power of 0.19 mW, the $M1$ mode and a FP mode

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1 The laser powers given in this chapter do not correspond to the laser powers on the sample. Therefore, they are different than those in the previous chapter.
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Figure 6.4: Two representative scanning electron microscope images of coupled L3-L60 (or closed W1 photonic crystal waveguide) cavity configurations. (a) The side coupling configuration where both the L3 and the L60 cavity are oriented in the same direction but the cavity is located one hole above from the waveguide. The image shows that the number of separation holes is one. (b) The shoulder coupling configuration where the L3 cavity is oriented along a $60^\circ$ rotated $\Gamma K$ direction at the end of the waveguide. In this image, the cavity is located at two holes distance from the end of the waveguide. L3-L60 systems with 2, 3, and 4 hole barriers for both the shoulder and side coupled configurations have been fabricated and investigated.
Figure 6.5: (a) PL spectra collected from the L60 cavity via a 500 nm diameter SNOM probe when it is coupled to the L3 cavity. The Fabry-Perot fringes are equidistant in the linear regime of the dispersion curve and get closer together at the higher wavelengths (>1530nm). The resonance wavelength tuning of (b) a FP peak which is located at the wavelength of 1530 nm and (c) the cavity mode (the $M1$) as a function of the laser power.

The spectra in the figure 6.5 (a) suggests that the $M1$ mode has a larger tuning range than the FP peaks which shows that the laser heating is very local, only heats the L3 and not the L60. In the 6.5 (b) and (c), we plot the resonant wavelength tuning of a FP peak ($\lambda = 1530$ nm) and the $M1$ mode as a function of the laser power respectively. Both peaks are almost linearly redshifted as the laser power is increased but with different tuning magnitudes due to the local heating of the L3 cavity. The tuning magnitude for the FP peak is found almost 1 nm ($d\lambda/dP = 6.25$ nm/mW) while the tuning magnitude of the $M1$ mode is found almost 8 nm ($d\lambda/dP = 50$ nm/mW) (At the laser power of 0.23 mW, the $M1$ and the FP peaks are not well resolved in the spectrum which resulted in a wavelength that is the same as when the laser power is 0.19 mW). This suggests that we almost independently tune largely the L3 cavity mode without significantly affecting the modes of the L60 cavity.

Figure 6.6 (a) shows five PL spectra collected from a side coupled L3 cavity. The cavity has three holes distance to the waveguide (L60 cavity). Both structures are obtained in a photonic crystal having a lattice spacing of 425 nm and a nominal radius of 0.3 $a$. The two end holes of the L3 cavity are shifted by 100 nm. Two split sets of peaks (labeled as B and A) are observed near the wavelength regions of 1450 nm and 1490 nm which correspond to the wave-
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Figure 6.6: (a) PL spectra collected from a side coupled L3 cavity having three holes away from the waveguide under five different laser powers. Two sets of split peaks near the wavelength region of 1450 nm (B) and 1490 nm (A) are observed which are the indication of the coupling of the $M_2$ and the $M_1$ modes with the even mode of the waveguide. (b) and (c) are the PL spectra of the set of split peaks of A and B at different laser powers respectively. The photonic crystal has a nominal lattice spacing of 425 nm and nominal radius of 0.3a. The two end holes of the cavity are shifted by 100 nm laterally outward.

lengths of $M_2$ and $M_1$ modes of an isolated L3 cavity with the same nominal parameters respectively. These peaks originate from the coupling of the $M_2$ and $M_1$ modes of the L3 cavity with the FP modes from the even parity dispersion curve of the waveguide. As the L3 modes are tuned when the laser power is increased from 0.1 mW to 0.3 mW, the splitting of A and B peaks is maintained. Figures 6.6 (b) and (c) show the stacked PL spectra of the A and B peaks under different excitation powers, respectively. Coupling of those modes is evident from a splitting of the peaks. These peaks are the coupled L3-FP peaks which are enhanced in the wavelength region of the $M_1$ mode.

When the number of separation holes is decreased to two, figure 6.7(a) shows that the $M_1$ mode is clearly present at the wavelength of 1495 nm whereas the $M_2$ mode is split in two peaks ($B_1$ and $B_2$) which shows that the $M_2$ mode is coupled to the waveguide mode whereas the $M_1$ mode does not. The split peaks are well maintained as the laser power is increased from 0.05 mW to 0.3 mW. Within the laser power range, the $M_1$ mode does not exhibit any splitting which shows that it does not couple to the waveguide mode at any power, in contrast to the coupling of the $M_1$ mode that has been observed in the previous case. In fact, the lack of coupling of the $M_1$ mode has also been observed in the other side-coupled configurations where the two end holes of
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Figure 6.7: (a) PL spectra collected from a side coupled L3 cavity located two holes away from the waveguide under six different laser powers. One set of split peaks near the wavelength region of 1450 nm (B) is observed as a result of the coupling of the $M_2$ mode. The $M_1$ mode does not exhibit any coupling since it is not split. (b) The stacked PL spectra of the B peaks as a function of the different laser powers. A clear node is observed between the peaks. (c) The resonance wavelength shift of the $M_1$ mode as the laser power increases.

6.5 Shoulder coupling

The $M_1$ mode promises a good coupling possibility due to its spatial and spectral characteristics. But the cavity orientation must be optimized to obtain larger overlap with the waveguide mode. The field profile of the $M_1$ mode suggests that the cavity must be rotated in order to have an efficient coupling. [179, 184].
Figure 6.8 shows the collected PL signal from two shoulder coupled L3 cavities with a different number of holes separating the L3 cavity from the closed W1 PhC waveguide (The waveguide is constructed by removing 60 air holes in the row, i.e. L60). The design parameters for the cavities are nominally the same and the cavities are obtained in a photonic crystal having a lattice spacing (a) of 445 nm and radius of 0.3a. The two end holes of the L3 cavities are both reduced in size, i.e. \( r' = 0.22a \), and shifted in position, i.e. 100 nm outward. Figure 6.8(a) shows the PL of the L3 cavity with a four-hole separation. The peaks correspond to the cavity modes and they are labeled as \( M_1 (\lambda = 1538\, nm) \), \( M_2 (\lambda = 1460\, nm) \), and \( M_3 (\lambda = 1427\, nm) \) modes; the corresponding field profiles are given in figure 6.1 (c), (d) and (e) respectively. Similarly, the L3 cavity with a three hole separation from the closest end of the W1 waveguide shows the same modes in the spectrum with the same resonance wavelength as shown in figure 6.8 (b). In both cases, there is no evidence for optical coupling observed in the spectrum. The spectra are the same as for isolated cavities. The possible reason could be a spectral mismatch with the closed waveguide modes. Therefore, the wavelength of the cavity modes are tuned photothermally to overcome possible spectral mismatch with the waveguide modes. As the laser power is increased from 0.05 mW to 0.3 mW, all the modes of both L3 cavities are redshifted due to increase in the refractive index which is induced by heating, see figures 6.8(c) and (d). Still, no spectral splitting has been observed as the modes are tuned hence no coupling is induced. Therefore, the cavities are not strongly coupled to the waveguide.

However, when the number of the barrier holes decreases to two, the \( M_1 \) mode splits whereas the \( M_2 \) and \( M_3 \) modes do not split, as shown in figure 6.9, within the limit of our spectral resolution. The existence of the split peaks in the spectrum is due to the coupling of the \( M_1 \) mode with the even parity mode of the waveguide. Note that the resonance wavelengths are slightly blueshifted as compared to those in the figure 6.8, this is due to the fabrication tolerances. As the laser power increases from 0.05 mW to 0.3 mW, the cavity modes are redshifted as expected from the refractive index change, see figure 6.9 (b). However, the characteristic multiplet of lines remains; the FP peaks are observed at each laser power. It is also important to note that the \( M_2 \) mode has a \( Q \) factor around 150 which suggests that the mode is located just above or very close to the light line as demonstrated in figure 6.2(b).

In order to further analyze the coupling of the \( M_1 \) mode with the even parity FP modes of the waveguide, the tuning is investigated in more detail. Figure 6.10 (a) shows six photoluminescence spectra collected from the coupled L3 cavity. The peaks in the spectra are the coupled L3-FP peaks and labeled by \( A \). Their tuning range as a function of the laser power is given in between the dash lines. At the laser power of 0.041 mW, the spectrum shows three coupled modes labeled as \( A_1, A_2 \) and \( A_3 \). As the excitation power is increased to 0.091 mW, all the peaks are redshifted due to the increase in the cavity’s refractive
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Figure 6.8: Photoluminescence spectra which are obtained from two shoulder coupled cavity configurations by exciting the cavity and collecting the signal via the same objective. (a),(b): The PL spectrum of the L3 cavity when the number of holes between the waveguide is four and three respectively. The peaks are the $M_1$ ($\lambda=1538$ nm), the $M_2$ ($\lambda=1460$ nm) and the $M_3$ ($\lambda=1427$ nm) modes. (c),(d): The pump power dependence of the resonant wavelengths of the cavity modes when the cavity has four three holes away from the waveguide. The optical coupling is not observed.
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Figure 6.9: (a) The PL spectrum of the shoulder coupled L3 cavity where the number of the separating holes is two. A multiplet of peaks is observed in the wavelength region of the $M_1$ mode which is the indication of the optical coupling of that mode. (b) The pump power dependence of the resonance wavelengths of the L3 cavity. The two end holes are not modified. The photonic crystal structure has a lattice spacing of 445 nm and radius of 0.3 $a$.

index; however, since the coupling is degraded due to the spectral mismatch, the $A_1$ mode is inhibited; on the other hand, another peak, $A_4$ mode, is now observed in the spectrum. Further increase in the laser power modulates the optical coupling where at the laser power of 0.136 mW, the $A_2$ peak is totally inhibited whereas the $A_5$ peak is enhanced. Figure 6.10 (a) suggests that despite a continuous tuning, a discrete set of wavelengths near the dashed lines is avoided. To have a better demonstration of the avoided wavelength ranges, all the spectra are collected in one figure as a function of the laser power in figure 6.10 (b). The coupled modes $A_1$, $A_2$, $A_3$, $A_4$, and $A_5$ are clearly distinguished and the avoided wavelengths are seen clearly. The figure 6.10 (c) is a three dimensional view of the evolution of the split peaks as they are tuned. At the high laser powers, the $A_4$ and the $A_5$ modes are enhanced whereas the $A_1$ and $A_2$ modes are inhibited. Figure 6.10 (d) shows the coupled L3-FP peaks’ wavelengths as a function of the laser power. The straight horizontal lines are the nodes of the individual peak. Figure 6.10 (d) suggests that the resonant wavelengths do not increase linearly as the laser power increases; as they are approaching the straight lines (nodes), they are inhibited.

When the two end holes of the L3 cavity are shifted by 100 nm outward, the $M_2$ mode shifts to a higher wavelength where it moves to below the light cone, close to the flat region of the even parity of the waveguide mode. Therefore, by introducing a W1 waveguide in a close proximity, it can couple to the even mode of the waveguide. Similar to the $M_1$ mode case above, figure 6.11 (a) shows the coupled L3-FP peaks in the wavelength region of the $M_2$ mode. The dash line represents the tuning range of the L3-FP peaks and all peaks are labeled as $B_1$, $B_5$. As the laser power is increased, the $B_1$ peak disappears and $B_5$ peak
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Figure 6.10: (a) Pump power dependence of the split $A$ peaks. The dash lines represent the node of the peaks. As the pump power increases, different split $A$ peaks are observed in between the lines. (b) The spectra of the peaks as a function of the pump power which clearly shows the nodes of the split peaks. (c) A three dimensional view of the evolution of the split peaks as a function of the laser power. (d) The resonance wavelength change as a function of the laser power for the split peaks where the redshifting of the peaks are avoided when they are close to the horizontal lines (nodes).
Figure 6.11: (a) The PL spectra of the shoulder coupled L3 cavity where two end holes of the cavity are shifted by 100 nm diagonally outward. The spectra show both the split peaks \((B)\) and the \(M1\) mode at each laser power. The dash lines represent the node of the split peaks. As the pump power increases, different split \(B\) peaks are observed between the lines. The \(M1\) mode is not coupled in this configuration since it almost linearly shifts as a function of the laser power. (b) The spectra of the peaks as a function of the pump power which clearly shows the nodes of the split peaks \((B)\) due to the coupling. (c) A three dimensional view of the evolution of the split peaks as a function of the laser power. (d) The resonance wavelength change as a function of the laser power for the split peaks.

appears in the spectrum while the other peaks remain. It is also interesting that the \(M1\) mode does not show any splitting within our resolution limit which is an indication of not coupling, most likely due to its spectral mismatch. In the enlarged L3 cavity, the \(M1\) mode is also redshifted and will be very close to the W1 waveguide edge. With increased power, it may be redshifted below the band edge of the W1 waveguide. Figure 6.11 (b) shows the stacked spectra obtained under different pump powers where the split \(B\) peaks are piled up. Their nodes are clearly seen and their resonant wavelengths exists in between the nodes.

Figure 6.11 (c) shows a closer look of the figure 6.11 (b) in a three dimensional window. As the laser power increases, the \(M2\) mode couples with different modes located on the even mode dispersion line which results in enhancement of different coupled peaks at different laser powers, i.e. similar to the coupled \(M1\) mode case. As the laser power is increased, the coupled peaks
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Figure 6.12: (a) The PL spectra collected from another shoulder coupled L3 cavity under different excitation powers where splitting of both the $M1$ and the $M2$ modes is found showing that both modes are coupled to the waveguide mode. Three dimensional views of the evolution of the split peaks (b) the $A$ peaks and (c) the $B$ peaks as a function of the laser power. The photonic crystal hosting both the L3 and the L60 (the waveguide) cavities has a nominal lattice spacing of 425 nm and a nominal radius of 0.3$a$. The number of the holes between the cavity and the waveguide is two. The two end holes of the cavity is shifted by 100 nm outward.

The spectrum shows two groups of split peaks located around the wavelength regions of 1450 nm and 1490 nm which correspond to the wavelength regions of the $M2$ and $M1$ modes respectively. As the laser power is increased, different split $A$ peaks and the split $B$ peaks are observed which are shown in the three dimensional window in figures 6.12 (a) and (b).

The coupling can be simply modeled by considering two coupled one dimensional Fabry-Perot resonators having different lengths, i.e. $L1<$L2 where $L1$ and $L2$ are the lengths of the resonators as sketched in figure 6.13(a). The resonators have a common plane parallel mirror ($D_3$) which has a lower reflectivity than the other plane parallel mirrors. In order to tune the Fabry-Perot modes of the small FP-cavity (C1) to obtain a spectral match with the resonances of the long FP-cavity (C2), the L1 is varied by moving the mirror D1
closer or further to the mirror $D_3$. One way to obtain the spectral characteristics of the system is to calculate the scattering transfer matrices ($S$-parameters) of each resonator [197]. Figure 6.13(b) shows the tuning of the coupled modes ($K$ modes) of the system as a function of the length of $C_1$. The level anticrossings of the $K$ modes are observed at different length of the $C_1$ which supports our experimental findings in figures 6.10(d) and 6.11(d).

We have not discussed the role of the second cavity at the other waveguide end. We believe it plays no role since it is mostly detuned from the other. All data are very similar when we use the other cavity for excitation and tuning.

### 6.6 Summary and conclusion

In this chapter, an optical coupling of two different cavity modes is demonstrated where the coupling is obtained when the mode of the cavity has both spectral match and spatial overlap with the mode of one other cavity. Two different coupling configurations have been fabricated and tested where an L3 cavity is either shoulder or side coupled in a close proximity an L60 Fabry-Perot cavity (60 air holes are removed in the $\Gamma K$ direction).

We investigated the coupling characteristics of the $M1$ and the $M2$ modes of the shoulder coupled L3 cavities to one end of the L60 cavity (the waveguide). When the number of separating holes is larger than three, the cavity modes do not couple to the waveguide mode hence their modes are linearly redshifted with the increase in the excitation laser power. However, when the cavity-waveguide has two hole separation, the modes can efficiently couple to
the even parity mode of the waveguide. Both the $M1$ and the $M2$ modes of
the laterally oriented L3 cavities (side coupling) exhibited different coupling be-
haviors. When the number of holes between the cavity and the waveguide is
three, two sets of split peaks have been observed in the resonance wavelength
of the cavity modes which is the indication of the coupling. However, when
the number of the separation holes is two, only the $M2$ mode is coupled to the
waveguide mode while the $M1$ mode is not.
Appendix A

Tunable photonic crystal devices by local infiltration and removal of liquids

A.1 Abstract

An exploratory research is undertaken to realize tunable microfluidic double heterostructures where liquid crystals and ordinary liquids (glycerol, oil) are used as the infill materials. Heterostructures consist of line defect waveguides but due to the local modulation in the refractive index, they can confine light with ultra-high $Q$ values, an order of magnitude larger than that of simple point defect cavities. The resonances of LC microfluidic cavities can be tuned by means of the photothermal effect which changes the temperature of the LC and removes the LC partially away from the cavity.

A.2 General introduction

An attractive way of controlling the spectral properties of the photonic crystal structure is to locally tune the cavity modes by selectively infiltrating liquids into the holes or selectively removing the infiltrated liquids from the holes. Such tuning is attractive to locally correct the fabrication deviations on the device when the device is fabricated with passive materials. Moreover, an active tuning can be obtained if the infill has the property that its refractive index can be changed by applying an electric field or by increasing the device temperature. For this purpose, the liquid crystal, as demonstrated in the previous chapter, is a promising candidate.

Recently various groups have demonstrated tunable, rewritable and reconfigurable photonic crystal structures based on local infiltration of liquids
Intonti et al. have infiltrated each photonic crystal pore with a solution of Rhodamine dye in water in order to demonstrate rewritable structures with a "pixel by pixel" approach. They used hollow submicron size pipettes to introduce the liquids into large diameter photonic crystal holes $\sim 1\mu m$. The proof of principle was demonstrated by measuring the PL signal from a locally infiltrated photonic crystal hole. Later, they introduced a controllable and continuous tuning of photonic crystal structures by removing the locally infiltrated water from one or a few photonic crystal holes. By increasing the excitation laser power, i.e. photothermally, they could remove the infiltrated water in a controllable manner which brings a fine tuning of the cavity resonances.

Infiltration of liquids into a part of the photonic crystal waveguide holes also creates a nanocavity due to the local increase of the refractive index. This liquid infiltration induced heterostructure cavity was first proposed by Tomljenovic-Hanic et al. Localization of the light relies on the mode-gap effect which is similar to the lattice shifted double-heterostructure cavities. Smith et al. constructed a microfluidic double heterostructure nanocavity by infiltrating a liquid into holes of a PhC having a line defect. They used a tapered glass micropipette to drag the liquid from a droplet near the structure to infiltrate the pores to create a double heterostructure nanocavity. A tapered curved fiber is used to conduct the transmission experiment via evanescent probing. The same infiltration technique was employed by Bog et al. to obtain high Q microfluidic cavity in silicon photonic crystal line waveguide. Bedoya et. al. have demonstrated a microfluidic double heterostructure cavity constructed after selectively infiltrating liquid crystal in to the silicon photonic crystal pores. They investigated the dynamics of the LC in the structure at different temperatures, and they explored the LC stability in the silicon pores due to the evaporation. They could demonstrate tunability of the resonances; however, the tuning was irreversible due to the evaporation.

Another way to tune resonances of photonic crystal structures is local infiltration of liquids into photonic crystal holes where the holes are selectively re-opened. Kicken et al. used a focused ion beam milling technique to re-open a masking layer which was deposited on the surface of the photonic crystal device. This novel technique enables them to independently re-open any photonic crystal hole and infiltrate it with the liquid to control the optical properties of the structure at precisely a single hole level. They showed that resonances of the H1 cavity were blueshifted due to the enlargement of the locally opened holes and redshifted after the local infiltration of the liquid crystal. Nevertheless, to accomplish the tuning requires more effort on the post-processing of the sample.

In this chapter, we demonstrate preliminary results from our ongoing work dedicated to tune resonant wavelengths of photonic crystal structures by locally
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infiltrating either active or passive liquids\(^1\). The infiltration is done by using a pulled glass fiber by drawing the liquid from a liquid drop close to the structure. In this way, we aim to construct a double heterostructure nanocavity where we can later tune its resonances by photothermal effect, which would go beyond the work of \[202, 203\]. Furthermore, we study on locally removing the liquids out of the cavity or the selectively infiltrated waveguide relying on the photothermal effect.

The ultimate goal of this work is to control the liquid infill status of PhC holes by light, either by controlled evaporation/condensation or by light induced liquid flow. This control is showed to be realized on a time scales (far) below a second, i.e. many orders of magnitude smaller than in the experiment of Ref. \[110\].

Section A.3 describes optical properties of photonic crystal waveguides. The construction of a double-heterostructure cavity by combining two photonic crystals having different lattice spacings will serve as a reference for the selective liquid infiltrated waveguides. The preliminary results obtained from a microfluidic double heterostructure will be demonstrated. Section A.4 explains an experimental result obtained from a modified H1 cavity where the infiltrated liquid crystal could be moved away from the cavity by a photothermal effect.

### A.3 Photonic crystal waveguides

When a line defect is introduced in a photonic crystal by leaving out one or more complete rows of air holes in a photonic crystal array that exhibits a bandgap, a waveguide may be created. Such a structure can guide light with minimal propagation losses particularly at sharp bends which allow the routing of optical signals between the devices. Therefore, it can be used to transmit electromagnetic waves between various photonic devices and components in an interconnected system. In addition to this, recently, many groups have reported ultra high \(Q\) photonic crystal cavities, an order magnitude higher than point defect cavities, constructed in the photonic crystal waveguides when some modifications are introduced in the surrounding holes of the waveguide. In this section, we will focus on the light confinement properties of the waveguides rather than light transmission.

The photonic crystal waveguides can be fabricated by omitting a single or multiple rows of air holes either in the \(\Gamma M\) or \(\Gamma K\) direction as shown in figure A.1 (a) and (b) respectively. The latter is generally used since the configuration reduces scattering and propagation losses; thus, in this chapter, the photonic crystal waveguides in the \(\Gamma K\) direction will be analyzed. The waveguide is usually denoted by their width as \(Wn\), where \(n\) determines the width of the

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\(^1\)We define that an active liquid has the property to change its refractive index under an external trigger while a passive liquid has always the same refractive index.
waveguide, $n(a\sqrt{3})$, i.e. if $n=0.9$, then the width of the waveguide is $0.9(a\sqrt{3})$, so W0.9.

In order to illustrate the light guiding property of the photonic crystal structure, a near field scanning microscopy experiment is conducted by using a 500 nm diameter near field probe. Figure A.2 (a) shows the topography image of the scanned W1 photonic crystal waveguide. Due to the large size of the probe, hole sizes look smaller than their real sizes and are deformed. Figure A.2 (b) shows the near field image of the photoluminescence generated in the waveguide when the excitation spot is placed almost ten micron away from the scanned area. The bright region corresponds to the waveguide region where both even and odd modes are guided by the waveguide.

Figure A.3 (a) shows the scanning electron microscope (SEM) image of a fabricated photonic crystal waveguide (W1) (one row of missing air holes) in $\Gamma K$ direction. The photonic crystal has a lattice spacing (a) of 445 nm and a radius of 0.33a as determined from the SEM image. The calculated band dia-
Figure A.3: (a) The SEM image of a fabricated W1 photonic crystal waveguide. (b) The 3D band structure of the W1 waveguide where the two TE-polarized even and odd parity modes of the waveguide are present in the bandgap region. (c) and (d) are the magnetic field ($H_z$) profiles of the even and odd symmetry modes respectively. The images are obtained from the center of the slab.
gram of the photonic crystal waveguide is given in figure A.3 (b). The structure has a bandgap in the normalized frequencies \((a/\lambda)\) between 0.28 and 0.365. The two curves in the bandgap correspond to the even and odd parity modes of the waveguide. The parities are defined in relation to the \(H\)-field symmetry with respect to the center of the waveguide as shown in figure A.3(c) and (d) respectively. The polarization of the even mode is found to be perpendicular while the polarization of the odd mode is found to be parallel to the waveguide [204]. Frequencies of the odd and even modes can be tuned lithographically by modifying the nearest photonic crystal holes either in size and/or in position. If the width of the W1 waveguide becomes smaller, the two lines shift to higher frequencies due to the decrease in the effective refractive index. Since the spectral width between the minimum of the even mode and the top of the dielectric band, there is not much room to engineer the cavities. For the liquid infiltration, it is useful to increase the edge of the W1 band by narrowing the waveguide. Therefore, heterostructure cavities are also studied for different waveguide widths.

Photoluminescence signals of a W1, a W0.9 and a W0.8 photonic crystal waveguides are obtained by using the same objective for both excitation of the cavity and collection of the signal and represented in figure A.4. The spectrum in figure A.4 (a) shows two important modes of the W1 PhC waveguide that correspond to an odd (the \(A_O\)) and an even (the \(A_E\)) parity modes of the waveguide. The odd mode is analogous to a Fabry-Perot mode bouncing back and forth between the PhC mirrors adjacent to the waveguide. The broad peak \((A_O)\) at the wavelength of 1426 nm (linewidth \(\sim 12\) nm) corresponds to an odd mode located above the light line where it originates from the \(\Gamma\) point of the photonic crystal lattice and is a photonic bandgap guided mode. Therefore, it is a leaky mode and strongly radiates perpendicular from the slab. The \(A_E\) mode which is located at the wavelength of 1555 nm is the slow light mode, having ideally a group velocity of zero at \(k = 0.5(2\pi/a)\). Figure A.4 (b) and (c) show the spectra collected from a W0.9 and W0.8 waveguides respectively. As the width of the waveguide decreases, the dispersion lines shift to the higher frequencies due to a decrease in the effective refractive index. Similar to the modes of the W1 waveguide, the spectra show clearly both the \(A_O\) and the \(A_E\) modes. Note that A.4 (a) and (b) also show the additional peaks which are derived from the odd mode dispersion line at \(k = 0.3(2\pi/a)\) and \(k = 0.5(2\pi/a)\) respectively where the odd dispersion line flattens, ie. the group velocity is ideally zero.

### A.3.1 Photonic crystal double heterostructures

Light confinement within a W1 waveguide is induced in the mode-gap region between the flat region of the even mode and dielectric band edge. The location of the mode-gap can be adjusted by changing the lithographic parameters of the waveguide. One way to achieve this is to locally changing the lattice
Figure A.4: The photoluminescence spectra collected from (a) a W1, (b) a W0.9 and (c) a W0.8 photonic crystal waveguides. The subscripts correspond to either odd (O) or even (E) parity modes.
parameter of a photonic crystal waveguide (inserting another photonic crystal waveguide with a different lattice spacing) where the effective refractive index is locally changed which shifts the mode-gap position locally. Song et. al. [23] have demonstrated for the first time ultra high-$Q$ factors from a double-heterostructure nanocavity in which two photonic crystals with different lattice spacings are joined, as shown in figure A.5(a). In such a structure, a part of PhC waveguide (PhC2) is placed between two adjacent waveguides (PhC1) [23, 205]. The lattice spacing of the PhC2 is slightly changed in the direction parallel to the waveguide only to locally change the effective refractive index. Such construction creates a confined mode which exists only below of the even and/or odd dispersion curve, if the $a_2$ of PhC2 is bigger than $a_1$. This mode has an exponentially decaying envelope at the edges leading to a well-confined $k$-space distribution and therefore small lose. The smooth exponential decay results in a theoretical $Q$ factor up to $2 \times 10^7$ [206] and an experimental $Q$ value of $6.5 \times 10^5$ [23]. Another way to change the location of the mode gap is to locally changing the width of the line waveguide by selectively shifting the holes. Kuramochi et. al. [207] have demonstrated an ultra-high nanocavity by locally modulating the width of a silicon W0.98 (the width of the waveguide is $0.98a_0\sqrt{3}$) waveguide by shifting selectively holes away from the line defect. They demonstrated an experimental $Q$ value up to $8 \times 10^5$. They also experimentally demonstrated that even shifting two opposite holes in the innermost rows in opposite direction, they could confine the light with a very high $Q$ factor up to $2.5 \times 10^5$.

Based on the design of Song et. al. [23], we constructed heterostructure cavities on W1, W0.9 and W0.8 waveguides. For the W1 waveguide, the lattice constants of PhC1 and PhC2 are 460 nm and 475 nm respectively. For the W0.9 and W0.8 waveguides, the PhC1 and PhC2 have lattice spacings of 510 nm and 525 nm respectively, see A.5(a). All the photonic crystals have radii of $0.3a_1$. The corresponding photoluminescence spectra are shown in figures A.5(b)-(d) for the W1, the W0.9 and the W0.8 respectively. The $A_O$ mode in all spectra corresponds to the odd mode of the waveguide and is located at $\Gamma$ point (It is the same mode, the $A_O$, in figure A.4). The sharp peak, the $M_O$ mode is a nanocavity mode which has a $Q$ value of $\sim 2500$ which is resolution limited. It is associated with the minimum of the odd mode. With only one peak present, it is not possible to distinguish between the bandedge mode of a bare waveguide as in A.3(b). The additional peaks, the $A_E$ and the $M_E$, in figure A.5 (d) are the slow light mode and the nanocavity mode respectively. These modes are not present in figures A.5(b) and (c) since they are located in high wavelength region where the detector efficiency is negligible. The $M_E$ mode has a resolution limited $Q$ value, $\sim 2500$, and is associated with the minimum of the even mode. Since the slow light bandedge mode and the nanocavity mode

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2A representative SEM image is not included since the lattice constant difference cannot be distinguished by the naked eye.
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Figure A.5: (a) Schematic of a double heterostructure cavity. Adapted from Ref. [23]. The photoluminescence spectra collected from double heterostructures built in (b) a W1, (c) a W0.9 and (d) a W0.8 photonic crystal waveguides. (e) Normalized frequencies of the nanocavity modes as a function of the lattice spacing ($\lambda/a$) which is obtained from W1, W0.9 and W0.8 heterostructure waveguides.
are very close together, and are located in different parts of the waveguide, they are not always seen simultaneously. Figure A.5(e) shows the change in the normalized frequency as a function of the lattice spacing \( a_1 \) for the nanocavity even \((M_E)\) and odd \((M_O)\) modes. The data are collected from a series W1, W0.9 and W0.8 photonic crystal heterostructure waveguides where the difference in the lattice spacings for each waveguide, i.e. \( a_2 - a_1 \), is nominally 10 nm. The nanocavities built in W1 and W0.9 waveguides show a single cavity mode \((M_E)\) at the smallest lattice spacing, however, the nanocavity built in W0.8 waveguide hosts both \((M_O\) and \(M_E)\). As the lattice spacing \((a_1)\) is increased, the frequency of the nanocavity modes almost linearly increases (The scatters are due to the fabrication imperfections.) which is caused by the constant slab thickness \((d)\) where \(d/a\) varies for each lattice spacing.

A.3.2 Microfluidic double heterostructures

Although double heterostructure constructions enable the confinement of light with an ultrahigh \(Q\) factor, these structures require a nanometer scale fabrication precision since the \(Q\) factor suffers from the fabrication disorders, surface roughness and even water adsorption by the surface [206, 208]. It is not straightforward to obtain a tunable device from these devices by means of microfluidic integration. An alternative solution is to construct a microfluidic double heterostructure by selectively infiltrating liquids into photonic crystal holes by a micropipette where the refractive index is locally changed [200–203, 209], thus the mode-gap position is locally introduced. This construction also offers rewritable, reconfigurable and tunable microfluidic double heterostructures by infiltrating various liquids and changing the length of the filled region. However, to realize such a device, additional infiltration processes are needed [209].

An exploratory research is undertaken in the tunable microfluidic double heterostructures where the active and passive liquids are used as the infill sources. In this way, the resonances can be largely tuned either thermally or photothermally. Furthermore, by employing a photothermal effect, the liquid can be removed from the infiltrated region due to the large thermal gradient of the excitation spot. To this end, experiments were conducted for both passive and active liquids where a tapered glass fiber is used to infiltrate the liquid selectively in photonic crystal pores as shown in figure A.6(a). While the method essentially must be local, a high resolution is not necessary. The width of the infiltrated region at least is two PhC periods or even considerably large. Small amount of liquid is drawn from the droplet which is close to the waveguide, in this case W0.9 waveguide, by a glass fiber having a diameter \(\sim 1 \mu m\), see figure A.6(a). When the fiber is passing through the photonic crystal region, due to the strong capillary force of the holes, the liquid is infiltrated, see figure A.6(b) where the W0.9 is partially filled.

Figure A.7 shows our preliminary photoluminescence result of selective in-
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Figure A.6: Microscope images (50X microscope objective) of a selective infiltration technique where a fiber is used to drag the liquid through the photonic crystal holes. (a) and (b) correspond to before and after the infiltration process respectively. The dashed area is the infiltrated region where we believe that a region of almost 5 $\mu$m is filled. The letter-characters are used to identify the waveguide.

Figure A.7: Photoluminescence spectra collected form a W0.9 photonic crystal waveguide (a) before and (b) after the selective infiltration of glycerol. The microscope objective is used for both excitation and collection where the laser spot is located on the middle of the waveguide before the infiltration and on the infiltrated region.
filtration with a passive liquid, oil. Figure A.7(a) is the PL signal collected from an uninfiltred W0.9 photonic crystal waveguide which is in the photonic crystal having a lattice spacing of 425 nm and a nominal radius of 0.3a. The microscope objective is used for both excitation and collection where the spot is located at the middle of the waveguide. The spectrum shows two peaks the $A_O$ ($\lambda = 1320$ nm) and the $A_E$ ($\lambda = 1510$ nm). When oil is selectively infiltrated by dragging the liquid with the tapered fiber, both the $A_O$ and $A_E$ peaks red-shift by 60 nm and 30 nm respectively due to the local increase of the effective refractive index, see figure A.7(b) where the excitation spot is located on the infiltrated region. Even though the demonstration of the microfluidic double heterostructure is not currently accomplished, the shifts in the resonances indicate the success of the infiltration technique. The selective infiltration is also confirmed by moving the excitation spot slightly away from the infiltrated area where we observe the same PL signal as in figure A.7(a).

Figure A.8 (a) shows the PL spectrum collected from a W1 waveguide from another sample before the infiltration (the lattice spacing of this photonic crystal is 425 nm). The odd mode, $A_O$, is located at $\lambda = 1385$ nm and the even mode, $A_E$, is located at $\lambda = 1505$ nm. The oil is infiltrated in the middle of the cavity by using a 500 nm glass fiber; the result of infiltration is shown in the inset of figure A.8 (b). Figure A.8 (b) shows the PL spectrum collected from the infiltrated region where the $A_O$ is shifted to 1425 nm as a result of the infiltration. Two peaks, $M_1$ and $M_2$, (maybe an additional one, $M_3$) appear at wavelength of 1525 nm and 1520 nm, respectively. These peaks, which have resolution limited $Q$-factors (>2500), are associated with the liquid-induced heterostructure cavity.
Bibliography


Optofluidic and photothermal control of InGaAsP photonic crystal nanocavities

A photonic crystal (PhC), which is an artificial material with a periodic modulation of the refractive index, provides an ultimate miniaturization of photonic devices since it can influence the flow of light on the optical wavelength scale. A particular useful device is the PhC cavity. It can be used to realize ultrasmall nanolasers, add/drop filters, and optical switches in the integrated circuits. But once photonic crystal cavities are fabricated, their spectral properties are fixed. Therefore, these structures are limited in their functionality due to the lack of active tuning of the resonances. Mechanisms providing an active tuning of the cavity resonances should be explored which is the main topic in this thesis.

The combination of fluidics with photonics provides large tuning capabilities of the cavity resonances due to the change in the effective refractive index of the cavity after liquid infiltration. This combination also offers flexible, rewritable and reconfigurable photonic devices. A largely tunable photonic device can also be obtained by relying on thermal and photothermal effects, since the refractive index of the cavity is dependent on the temperature. Furthermore, the combination of the optofluidic and the (photo)thermal effect brings more control on the cavity resonances. In this thesis, we demonstrate and investigate several tuning mechanisms based on fluidic, thermal and photothermal effects.

In chapter 2, the fabrication process and characterization method of the photonic crystal structures used for this thesis are described. 220 nm thick InGaAsP photonic crystal membranes having a hexagonal array of air holes were fabricated by using state of the art nanofabrication techniques. The membranes had epitaxially grown InAs quantum dots (QD’s) incorporated for luminescence emission in the telecommunication wavelength range near 1.55 micron. The fabrication process parameters for the electron beam lithography, dry plasma etching and wet chemical etching steps were determined and optimized. Cavity designs in a hexagonal photonic crystal structure were obtained by finite difference time domain simulations. Different type of photonic crystal structures were fabricated by removing one (simple H1), three (L3), seven (H2) or a row (W1) of air holes. The smallest possible cavity is also obtained by
modifying two adjacent air holes in their size and/or their position (H0).

For the characterization of the fabricated structures, a custom-modified photoluminescence set-up was realized, which integrated conventional far-field and near-field-scanning optical microscopy (NSOM/SNOM), and Atomic Force Microscopy, and which allowed for in situ local liquid infiltration of the samples. Room temperature micro-photoluminescence (PL) measurements were conducted to investigate the optical properties of the nanocavities. The samples were mounted on an X-Y-Z stage. A continuous wave power tunable diode laser ($\lambda = 660 \text{ nm}$) is focused through high numerical aperture microscope objective (50x, N.A = 0.5). The laser spot has a spot size around 3 $\mu$m in diameter on the sample. Two different PL techniques were used to characterize the cavities. One is the conventional PL technique where the excitation of the cavities and the collection of PL emission are done by the same objective. For the second PL technique, only the excitation of the cavities is done by using the microscope objective. For the collection of the signal, an uncoated or a metal coated glass SNOM probe having an apex of 500 nm diameter is used. The collected PL was then dispersed in a monochromator and detected by a liquid nitrogen cooled InGaAs array. The use of a SNOM probe in this experiment also allows a near-field imaging of the waveguide when an InGaAs avalanche photodiode detector (APD) is used.

In chapter 3, the lithographic and photothermal control of the nanocavities are demonstrated. The lithographic tuning of the cavity modes is obtained by varying the geometric parameters of the photonic crystal such as lattice spacing and modified hole radius. A single cavity tuning is demonstrated by employing thermal and photothermal effects. The thermal tuning is obtained by varying the temperature of the cavities using a heating stage. The tuning rate is found to be 0.1 nm/$\degree$C. The photothermal tuning is obtained by varying the excitation laser intensity where we obtained a 15 nm redshift of the resonances which corresponds to a temperature increase of 150 $\degree$C.

In chapter 4, the optofluidic control of the cavities is demonstrated by immersing the cavities into various liquids. The spatial intensity distribution of the resonant modes was studied experimentally by infiltration of the PhC holes with fluids of varying refractive index, consisting of water-sugar solutions. The shift of the resonance frequency with variation of the refractive index of the holes, is a direct measure of the overlap of the mode with the holes. By systematically varying the lithographically defined parameters of a given cavity type, the mode intensity distributions for different cavity types were obtained. These results can be applied for the design of PhC cavity sensors. A maximum sensitivity of 300 nm/RIU (refractive index unit) is observed which corresponds to $\sim$25% mode overlap with the holes.

Chapter 5 demonstrates the thermal and photothermal control of liquid crystal infiltrated nanocavities. A liquid crystal (LC) is a very suitable fluid for infiltration into the holes of the PhC to obtain tuning, since its refractive index can
be tuned over a large range. The LC is a birefringent material, with an opposite temperature dependence of the extra-ordinary and ordinary refractive index, including an opposite jump at the LC phase transition temperature. We investigated the infiltration with the LC 5CB, which has a convenient clearing temperature $T_c$ of 35°C. Mode-dependent shifts of the resonant frequencies of the cavities were experimentally observed when the temperature was varied across the $T_c$. The genuine property of the birefringence of a LC was observed from the frequency shifts in opposite directions for differently polarized modes of the cavity. Apart from the applications, these observations were important for obtaining information on the orientation of the LC molecules.

A tunable coupled cavity system is demonstrated in chapter 6. Two dissimilar photonic crystal cavities, an L3 and L60 type of cavities, are brought in a close proximity to investigate their coupling properties. Two coupling configurations, side and shoulder couplings, are analyzed by exciting the L3 cavity. A strong optical coupling is observed in the shoulder configuration for the fundamental mode of the L3 cavity. The coupling gives rise to hybridized modes in the spectral region of the L3 cavity mode. As the cavity is tuned by the photothermal effect, the hybrid modes are redshifted and level anticrossings are observed.

Appendix A describes an exploratory research on tunable photonic crystal devices by local infiltration and removal of liquids. To this end, PhC waveguides of different widths were studied for implementing a selective infiltration process to create a fluidic cavity. Spatially resolved photoluminescence signatures of the waveguide cut-off frequencies revealed the properties of the infiltrated and empty parts.
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List of Publications

Publications part of the thesis:


**Publications not part of the thesis:**


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