Digital Etching in Coupled L3 Photonic Crystal Cavities

A Dissertation submitted in partial satisfaction of the requirements for the degree Bachelor of Science in Physics

by

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Abstract

Photonic crystal cavities offer vast possibilities in the field of nanophotonics. By utilizing the properties of photonic band gaps in structures with varying refractive indices one can introduce defects, which break the periodic structure of the photonic crystal, in order to confine modes of light in small volumes. This project examines how the coupling between two cavities is affected by their distance from one another, as well as how modes can be tuned by digital etching. Using samples consisting of semiconductor quantum dots within GaAs photonic crystals, a blue shifting of the modes was observed due to digital etching; and a strong correlation was observed between the splitting of the modes and the spacing between two cavities. Furthermore, the optical profile of the photonic crystal cavities changed distinctly when the modes were shifted outside the photonic band gap. Simulation software and photoluminescence data were employed in order to examine and understand these effects.

Acknowledgements

I would like to thank Evelyn Hu for giving me the opportunity to study these intensely fascinating devices. Thank you for your guidance and patience through these exciting times. I would also like to thank Ridah Sabouni and all the group members for helping me get settled in the group and showing me all the tricks of the trade, including half price sandwiches at the Nano Cafe. I especially like to thank my family for their endless love and support, which without I could never have been able to complete this thesis. Finally I would like to dedicate this work to my Grandmother and Grandfather, Dave and Evelyn Kunz, I love you both very much.
To my Grandparents,
David and Evelyn Kunz
Contents

1 Introduction ................................................................. 7
2 Photoluminescence measurements ............................................. 10
   I Overview ............................................................................. 10
   II Spectroscopy Mode ............................................................. 13
   III Imaging Mode ................................................................. 17
3 Finite Difference Time Domain (FDTD) Simulations ...................... 23
   I Theory and Advantages ....................................................... 23
   II Implementation ............................................................... 24
4 Digital Etching of Photonic Crystal Cavities ............................. 26
   I Introduction to Digital Etching .............................................. 26
   II Effects of Coupling Between Cavities on Their Confined Modes .... 27
   III Digital Etching of Coupled Cavities .................................... 30
   IV Data Collection and Analysis .............................................. 32
5 Effects of Shifting Modes Out of the Photonic Band Gap .............. 37
6 Conclusion ............................................................................ 46
   Bibliography ......................................................................... 47
List of Figures

Figure A...........................................................................................................9
Figure B...........................................................................................................10
Figure C...........................................................................................................11
Figure 1...........................................................................................................14
Figure 2...........................................................................................................15
Figure 3...........................................................................................................16
Figure 4...........................................................................................................16
Figure 5...........................................................................................................18
Figure 6...........................................................................................................20
Figure 7...........................................................................................................21
Figure 8...........................................................................................................22
Figure 9...........................................................................................................22
Figure 10.........................................................................................................25
Figure 11.........................................................................................................25
Figure 12.........................................................................................................28
Figure 13.........................................................................................................28
Figure 14.........................................................................................................28
Figure 15.........................................................................................................29
Figure 16.........................................................................................................29
Figure 17.........................................................................................................31
Figure 18.........................................................................................................31
Figure 19.........................................................................................................32
Figure 20.........................................................................................................33
Figure 21.........................................................................................................35
Figure 22.........................................................................................................36
Figure 23.........................................................................................................37
Figure 24.........................................................................................................39
Figure 25.........................................................................................................40
Figure 26.........................................................................................................41
Figure 27.........................................................................................................42
Figure 28.........................................................................................................43
Figure 29.........................................................................................................44
Figure 30.........................................................................................................45

List of Tables

Table 1..................................................................................................................8
Introduction

Photonic crystals cavities offer a promising new frontier in the field of optics; with a broad range of applications including low threshold lasers, optical switches and the investigation of cavity quantum electrodynamics [1]. Understanding how photonic crystals control and manipulate light on the nanometer scale will be essential to the design and implementation of such devices. Photonic crystals are periodic structures with varying refractive indices, whose presence of a photonic band gap prohibits specific wavelengths of light from propagating in certain directions. In order to investigate precisely how light will behave in photonic crystals it is natural to start with the Maxwell equations, which describe all of electromagnetism.

\[
\begin{align*}
\nabla \cdot \mathbf{B} & = 0 \\
\nabla \times \mathbf{E} + \frac{\partial \mathbf{B}}{\partial t} & = 0 \\
\nabla \cdot \mathbf{D} & = \rho \\
\n\nabla \times \mathbf{H} - \frac{\partial \mathbf{D}}{\partial t} & = \mathbf{J}
\end{align*}
\]

Where \( \mathbf{B} \) is the magnetic field, \( \mathbf{E} \) is the electric field, \( \mathbf{J} \) is the current density, \( \rho \) is the charge density, and \( \mathbf{D} \) is the electric displacement field. By restricting ourselves to the propagation of light in a mixed linear dielectric medium and assuming that the dielectric medium is lossless, one can arrive at the following modified Maxwell equations, where \( \varepsilon(\mathbf{r}) \) is the value of the dielectric as a function of position inside the medium.

\[
\begin{align*}
\nabla \cdot \mathbf{H}(\mathbf{r}, t) & = 0 \\
\n\nabla \times \mathbf{E}(\mathbf{r}, t) + j_0 \frac{\partial \mathbf{H}(\mathbf{r}, t)}{\partial t} & = 0 \\
\n\nabla \cdot [\varepsilon(\mathbf{r})\mathbf{E}(\mathbf{r}, t)] & = 0 \\
\n\n\nabla \times \mathbf{H}(\mathbf{r}, t) - \varepsilon_0 \varepsilon(\mathbf{r}) \frac{\partial \mathbf{E}(\mathbf{r}, t)}{\partial t} & = 0.
\end{align*}
\]

Maxwell's equations in a linear and lossless dielectric medium

By decoupling these equations we arrive at what is known as the master equation.
\[ \nabla \times \left( \frac{1}{\varepsilon(r)} \nabla \times \mathbf{H}(r) \right) = \left( \frac{\omega}{c} \right)^2 \mathbf{H}(r). \]

**Master Equation**

While this equation appears rather daunting, one in theory could solve for \( \mathbf{H} \) and therefore obtain the electric and magnetic fields inside the photonic crystal. One fascinating property of the master equation is that it is clearly an eigenvalue equation; with the operator being quite analogous to that in the Schrödinger equation used in quantum mechanics. Table 1 displays the similarities between the operator, eigenvalue equation, and time dependent field between electrodynamics and quantum mechanics. One can find a more complete discussion of the similarities in Joannopoulos, Johnson, Winn, and Meade, 2008.

<table>
<thead>
<tr>
<th>Field</th>
<th>Quantum Mechanics</th>
<th>Electrodynamics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field</td>
<td>( \Psi(r, t) = \Psi(r)e^{-iE_t/t\hbar} )</td>
<td>( \mathbf{H}(r, t) = \mathbf{H}(r)e^{-i\omega t} )</td>
</tr>
<tr>
<td>Eigenvalue problem</td>
<td>( \hat{\mathbf{H}} \Psi = E \Psi )</td>
<td>( \hat{\mathbf{H}} = \left( \frac{\omega}{c} \right)^2 \mathbf{H} )</td>
</tr>
<tr>
<td>Hermitian operator</td>
<td>( \hat{\mathbf{H}} = -\frac{\hbar^2}{2m} \nabla^2 + V(r) )</td>
<td>( \nabla \times \frac{1}{\varepsilon(r)} \nabla \times )</td>
</tr>
</tbody>
</table>

Table 1: Similarities between the equations governing quantum mechanics and electrodynamics. (Joannopoulos, Johnson, Winn, and Meade, 2008)

Observing the close resemblance between quantum mechanics and electrodynamics, it is reasonable to assume that light will behave in a photonic crystal similarly to a quantum mechanical particle in a finite potential. Therefore we should expect light to propagate in modes within the structure and exist in discrete energy levels. Furthermore we should expect light to be prohibited from a certain energy range just as semiconductors and insulators exhibit a band gap between the valance and conduction bands, in which no electron state exists. In photonics, this is known as the photonic band...
gap and its presence prevents photons with specific energies, or wavelengths, from propagating in certain directions. This is because the number of possible modes per unit frequency is zero for the frequencies in the band gap. The presence of a band gap in photonic crystals is essential to the control of light because one can utilize its properties to guide or confine light within the structure. One way to utilize the band gap in photonic crystals is by introducing a defect to the periodic structure; which creates a single mode whose frequency is within the band gap. This confines the light in the defect because its frequency is in the photonic band gap, and therefore the mode cannot exist in the areas outside the cavity [2]. Figure 1a displays a cavity in a photonic crystal and the band structure for a triangular lattice photonic crystal; with the band gap denoted in yellow and the defect mode denoted by the broken line.

Figure A: an SEM image of a photonic crystal cavity and a simulated band structure with the band gap denoted in yellow and the defect mode denoted by black line. (Joannopoulos, Johnson, Winn, and Meade, 2008)

The photonic crystals used in this experiment consisted of a 226 nm thick GaAs layer with embedded InAs quantum dots. The air holes in the structure were defined by electron-beam lithography, dry anisotropic etching, and an HF selective wet etch. A triangular lattice structure was used, with a lattice constant of 265 nm and hole radius of
approximately 74 nanometers. The defect was created by removing three air holes; devices of this nature are called L3 photonic crystal cavities. Figure 1b displays a cross section of a coupled L3 photonic crystal structure. I would like to thank Dr. Fabian Rol for creating this illustration for me.

![Figure B](image.jpg)

**Figure B**: a perspective view of a photonic crystal.

The control and manipulation of light in photonic crystal cavities relies heavily on the mode of the cavity being in resonance with the quantum dot emitters embedded in the sample. Matching the frequency of the light emitted from the quantum dots to the modes of the cavity allows for the efficient storage and exchange of energy in the cavity [3]. This is due to the fact that light is re-absorbed by quantum dots in resonance with the mode, allowing for altered photon lifetimes in the cavity. Achieving resonance between a mode and a quantum dot can prove difficult because the frequency of light emitted from a quantum dot depends on its size and dimensions. Furthermore, because the embedded quantum dots are self assembled via strained layer epitaxy, one does not have precise control over their dimensions and subsequently their emission frequency. This experiment investigates a method known as digital etching which allows one to tune the mode into resonance with the quantum dot emission in order to optimize the light-matter interaction in the cavity. Specifically, by altering the dimensions of the photonic crystal
one can incrementally shift the frequency of the confined mode into resonance with the quantum dot. Figure 1c displays an illustration of a mode in resonance with a quantum dot.

The shifting of modes via digital etching has been realized in single cavity photonic crystals, and has proved to be an effective post fabrication method for achieving resonance between a mode and a quantum dot emitter [4]. This project looks to examine the effects of coupling between two modes on the digital etching process. In addition improvements were also made to the micro-photoluminescence setup used to measure the spectrum of photonic crystal cavity devices.

**Photoluminescence Measurements**

1. **Overview**

In order to analyze the optical properties of photonic crystals one must perform a photoluminescence measurement on the device. Photoluminescence measurements rely on the sample's ability to absorb and re-radiate photons. Specifically, by using a laser one can excite a sample to a higher energy state. When the electrons return to their lower energy state they emit photons; which are then collected by a spectrometer. The optical characteristics of the sample can be determined by analyzing the data collected by the
spectrometer. One commonly measured property is the proportion of reflected to transmitted light by the sample over a range of wavelengths. Due to the fact that photonic crystal cavities in question are so small, on the order of 1 micron, one must perform a micro-photoluminescence measurement in order to determine the optical properties of the specific cavity. This is necessary because ordinary pl can only access sizes on the scale of several tens or hundreds of microns because the beam size is on the order of those sizes. Micro-photoluminescence measurements use a focused laser beam with a spot size of a few microns so that one can investigate the properties of a specific cavity instead of the whole sample. Such properties include the intensity and wavelength of the confined modes in the cavity, as well as the quality factor of those modes. For the purposes of this experiment, the laser excites the InAs quantum dots embedded in the sample which form excitons and bi-excitons which subsequently radiatively decay, releasing photons [5]. Some of these photons are then confined in the cavity for a period of time, parameterized by the quality factor, and then released. The quality factor is most generally defined by $Q = \text{Energy Stored/ Power Loss}$, or for photonics $Q = \frac{\lambda_0}{\Delta \lambda}$ where $\lambda$ is the wavelength of the confined mode and $\Delta \lambda$ is the full width at half maximum. Higher quality factors signify lower losses from the cavity and better confinement of light in the cavity over time. As with regular photoluminescence measurements these photons are then sent to a spectrometer, which uses a prism and a CCD camera to determine the wavelengths and intensity of the emitted light.

While micro photoluminescence does offer the advantage of being able to obtain spectroscopy data on scales of a few microns, the overall experimental setup is more elaborate than a regular photoluminescence setup. This is due to the fact that in order to
obtain a spot size of a few microns one must couple the laser to a single mode optical fiber with a diameter of two or three microns, which requires a two-mirror setup and a focusing aspheric lens. Furthermore, in order to position the focused laser beam directly onto the cavity of interest, one must be able to see where the laser spot is with respect to the sample; this requires an imaging mode in addition to the spectroscopy mode. Improvements were made in the spectroscopy mode, by means of increasing the power to the sample and subsequently to the spectrometer. Improvements were also made to the imaging mode by designing and implementing a Köhler illumination method to collimate the infrared light used to illuminate the sample. This increased both the brightness and contrast of the image in addition to improving the overall efficiency by making the setup one cohesive unit.

II. Spectroscopy Mode

As discussed previously, spectroscopy measurements conducted in this experiment involve exciting the quantum dots embedded in the photonic crystal with a laser. This causes the quantum dots to emit photons, which are then confined in the cavity and eventually released. These photons are then sent to a spectrometer, which sends the data to a computer for analysis. Figure 1 displays a schematic of the setup which was used to take spectroscopy measurements.
As mentioned previously, a two-mirror setup along with a focusing aspheric lens was required to couple the 780 nm laser beam onto the single mode fiber. This portion of the process was by far the most difficult and time consuming, because one must focus the laser directly on the three µm single mode fiber in order to get any significant power out the other end. Figure 2 displays the setup used to couple the laser to the single mode fiber.
The 780 nm laser was set at a constant power of 136 mW and 141.2 mA. After adjusting both the angle of the beam going into the fiber and the distance of the fiber from the lens, a maximum power output of 40 mW was attained out of the single mode fiber. The 40 mW power output corresponded to a 30 percent transmission efficiency. This was nearly double the previous maximum power output of 21 mW. Once the fiber was coupled to the laser the other end of the fiber was connected to the spectroscopy mode setup, pictured in figure 1. It was necessary to use a single mode fiber because the small fiber diameter kept the spot size of the laser beam going to the sample as small as possible. Figures 3 and 4 are pictures of the spectroscopy setup from an overhead and a perspective angle respectively.
A maximum power value of 2.5 mW to the sample out of the objective lens was achieved. This was more than three times the previous maximum of 800 µW. Finally, the
outgoing light was coupled to a multimode fiber whose other end was then sent to a spectrometer. A multimode fiber was used instead of a single mode fiber because its diameter is larger than that of a single mode, and therefore the maximum possible light could be collected and sent to the spectrometer. After coupling the outgoing beam to the multimode fiber a maximum power of 30 µW was sent to the spectrometer. This was around 15 times greater than the previous maximum of 2.1 µW.

Overall, by optimizing the spectroscopy mode of the photoluminescence setup three times more power was sent to the sample and 15 times more power was sent to the spectrometer. The increase in power was largely a result of minimizing the losses associated with coupling the laser to the optical fiber. This allowed for much more conclusive data from samples, due to an increased signal to noise ratio, as well as the ability to collect photoluminescence data from samples which require a large amount of power to photoluminesce.

III. Imaging Mode

In order to obtain consistent results of photonic crystal cavities by means of micro-photoluminescence measurements, one must implement an imaging mode in the setup. This is due to the fact that the photonic crystal cavities are so small, on the order of one micron, that one must be confident that the information being collected is from the correct cavity. Furthermore, imaging the sample allows for the exact placement of the laser on the cavity. This means more power can be delivered to the sample and subsequently more light emitted by the quantum dots and contained in the cavity. An infrared light emitting diode (LED) was used to illuminate the sample; whose image was
sent to a microscope and displayed on a television. Figure 5 displays a schematic of the photoluminescence setup in imaging mode.

An infrared LED was chosen to illuminate the sample because it offered the best image contrast. One problem however, was in order for the infrared light to illuminate the sample and send the information to a microscope for imaging, a total path length of approximately 70 cm was required. This meant that the LED light had to be collimated in order to assure the image quality was not significantly degraded due to diverging light rays. The task of collimating light from an LED is quite arduous due to the fact that the LED is not a point source, rather light is emitted from a semiconductor chip which is of finite size. Finite sized light sources such as LED's when placed in the focal plane of a lens produce a collection or bundle of collimated beams. The bundle of collimated beams will actually create an image of the LED semiconductor chip focused to infinity.
However, for the purpose of our setup this posed a problem, because imaging the LED surface to infinity is the same as imaging the LED onto the sample. Furthermore, because the sample is flat and mirror-like one will ultimately receive a mirror image of the surface of the LED, which is inhomogeneous, superimposed on the sample's surface. In addition to this unwanted effect, the high numerical aperture of the microscope objective lens caused the infrared light used to image the sample to have a high angular spread. This in turn meant that the illumination light rays would be diverging upon leaving the microscope objective lens from the sample; and thus the contrast of the final image would be degraded. Luckily this problem has been encountered before and has a solution in the form of the Köhler illumination method, which involves collimating the light after the microscope objective as opposed to before.

The Köhler illumination method resolves the problems discussed above of imaging a sample with a finite sized light source by "collimating" light after it passes through the microscope objective. While there is a vast amount of material on this method with instructive tutorials available on the internet, the basic idea is as follows. Instead of focusing the illumination light to infinity and thus onto the sample's surface, one images the light from the LED plane onto the backside focal plane of the microscope objective. When the light rays are focused by the objective lens they provide a uniform illumination of the sample because each individual light ray originated from a different point on the light source. Furthermore by imaging the LED plane on the back focal plane of the objective lens, one reduces the angular spread and thus increases the contrast of the final image sent to the microscope [6]. Figure 6 displays a schematic of the Köhler method.
One additional benefit of the Köhler illumination for μ-PL is that by using a condenser lens with a short focal length one could place the infrared LED very close to the setup. This allowed for LED to be physically attached to the setup by a simple base plate; which was very beneficial because when the setup moved on the translation stages to focus on a different region of the sample, the LED would move along with it and thus provide a consistent source of lumination over the entire sample. Figure 7 is a picture of the pl setup in imaging mode, the red line indicates the path of the infrared light going to the sample and the blue line indicates the path of the light reflected from the sample. A camera was attached the microscope eyepiece so the final image could be easily viewed on a television screen.
Figure 7: a picture of the pl setup in imaging mode, the red line indicates the path of infrared light from the LED going to the sample; and the blue line indicates the path of the reflected light from the sample.

Figure 8 is a close up picture of the LED, diaphragm, and condenser lens used to image the LED surface to the back focal plane of the microscope objective. All the components are held in place by screws which connect to the base plate. The beam path of the light from the LED is denoted by the red line and the reflected light from the sample is denoted by the blue line.
Figure 8: A close up picture of the LED, diaphragm, and collimating lens. Beam path to and from the sample are denoted by the red line and blue lines respectively.

Figure 9 shows a picture of a photonic crystal displayed on the television screen. Note that the contrast is not perfect; however the image quality is more than adequate for the purposes of this experiment.

Overall, the Köhler illumination method allowed for a clear and consistent setup for imaging photonic crystals. This was a vast improvement over the previous method.
which didn’t produce images with high enough contrast and needed to be readjusted every time a different area of the sample was viewed. I would like to acknowledge Martin Winger at ETH Zürich for explaining the flaws in our previous imaging mode setup as well as suggesting the Köhler method.

**Finite Difference Time Domain (FDTD) Simulations**

**I. Theory and Advantages**

Finite Difference Time Domain (FDTD) modeling is an extremely useful tool used to model the behavior of light in a photonic crystal. As discussed in the introduction, the solutions to the electric and magnetic fields inside dielectrics can be obtained directly from the master equation

\[ \nabla \times \left( \frac{1}{\varepsilon(r)} \nabla \times \mathbf{H}(r) \right) = \left( \frac{\omega}{c} \right)^2 \mathbf{H}(r), \]

where \( \omega \) is the frequency, \( c \) is the speed of light, and \( \varepsilon(r) \) is the dielectric constant as a function of position. However, in practice solving for the electric and magnetic fields by hand inside a photonic crystal cavity is a daunting task, due to the high complexity of the structure. Furthermore, attempting to solve Maxwell’s equations over a finite time period is especially cumbersome because the electric and magnetic fields are time dependent. One additional benefit of having simulation software is that it allows one to model the behavior of a cavity before it is built; this means that structures can be fine-tuned to meet specific needs so they function properly when fabricated, saving both time and money.

FDTD works by separating the photonic crystal structure into many finite sized grids. The software then discretizes the time dependent Maxwell equations using central difference approximations and then solves the equations using a time stepping algorithm. The algorithm involves solving for the electric field components in a specific element of
grid at an instant in time and then solving for the magnetic field components in the same
element of the grid at a later time; this is repeated for all the elements of the grid for as
long of a time as desired [7].

While FDTD is a useful software for nanophotonics, as with all simulation
software it does have its disadvantages. One shortcoming of the software is that one must
decrease the grid size to get more accurate results; which increases the simulation time.
Another limitation is that in order to model a photonic crystal cavity one must know the
exact parameters of their device, and there is a degree of fabrication error in photonic
crystals. This does have an upside however because one can match the experimental and
simulated results in order to infer what the true parameters of the photonic crystal must
be. This method was implemented in this experiment to explain certain differences
between experimental data and theoretical predictions.

II. Implementation

For the purpose of this experiment FDTD software was used in order to predict
the wavelengths and quality factors of the confined modes of light in the photonic crystal
cavities. FDTD Solutions, provided by Lumerical Solutions was the specific software
package used for this experiment. The software was also used to simulate the band
structure of the photonic crystals. Movies were also created, which provided for an
intuitive feel of how the light was behaving in the cavity. Figure 10 is a screen shot of
coupled photonic crystal cavities modeled in the FDTD software, and figure 11 is the
simulated electric field in those cavities.
Overall the software proved especially beneficial for the digital etching technique because the structure of the cavity changed in discrete steps and therefore the shifting of the modes was relatively straightforward to model.
Digital Etching of Photonic Crystal Cavities

I. Introduction to Digital Etching

As a result of the optical characteristics of photonic crystals being very structurally dependent, one can attempt to manipulate such properties in a predictable manner by altering the geometry of the photonic crystal. One especially interesting optical property to manipulate is the wavelength of the confined mode in the photonic crystal cavity. As discussed in the introduction, many applications of photonic crystal cavities incorporating quantum dots such as low threshold lasers, optical switches, and the investigation of cavity quantum electrodynamics rely heavily on the wavelength of the confined mode being in resonance with the quantum dot emission spectrum. Therefore the ability to control the wavelength of the confined mode can allow one to tune the mode into resonance with the quantum dot. This is especially useful because small errors in the fabrication of a photonic crystal can cause it to have a mode that is not in resonance with the photons radiated from quantum dots. Therefore having a post fabrication method for fine tuning devices is necessary to increase the light-matter interaction.

Digital etching incorporates the natural growth of oxide layers on Gallium Arsenide (GaAs) in order to alter the geometry of the photonic crystal and therefore tune the wavelength of the confined mode. GaAs when exposed to air will naturally grow an oxide layer; the thickness of the layer follows a logarithmic time dependence 
\[ d(Å) = 6 + 6 \times \log_{10}[t(\text{min})] \] [8]. For the time scales of this experiment the oxide layer was assumed to be on the order of two or three nanometers, because the time between etches was between one and two days. The oxide layer could be removed by placing the
photonic crystal in acid; citric acid ($C_6H_8O_7$) was used for this experiment, leaving the unoxidized GaAs material unaffected. The removal of the oxide layer thus offered a controllable manner for altering the geometry of the photonic crystal. Previous experiments conducted on single cavity photonic crystals found that the removal of the oxide layer blue shifted the wavelength of the modes two to three nanometers per etch. This discrete shifting of the modes suggests the name digital etching, because the wavelengths of the modes are shifted in a discrete manner of two to three nanometers at a time as opposed to continuously across all wavelengths. Before we discuss digital etching however, it is first beneficial to discuss the effects of coupling between cavities on their confined modes. This will allow us to determine which effects are due to the inherent coupling between cavities and which are do to the digital etching process.

II. Effects of Coupling between Cavities on Their Confined Modes

Coupled Photonic crystal cavities are quite analogous to quantum mechanical coupled systems. This relation is actually not surprising if one remembers the similarities between the respective eigenvalue equations and hermitian operators of electrodynamics and quantum mechanics discussed in the introduction. Therefore, to get a qualitative feel of how the spacing between cavities should affect the coupling of their confined modes, one just needs to remember the form of the energy splitting for all two state systems in quantum mechanics. From quantum mechanics we know that the wave function of any two state system will split into symmetric and antisymmetric modes, with the energy of the antisymmetric mode being higher then the symmetric mode. Furthermore, the splitting between the symmetric and antisymmetric energy levels is a function of how
strongly the two individual wave functions interact. Therefore, one can predict the energy splitting between the symmetric and antisymmetric modes to be larger as the coupling between the particles increases. Using this relation, one could expect that the energy splitting of the coupled photonic crystal cavities should behave in an analogous fashion, with the splitting between the energies increasing as the distance between the cavities decreases. The splitting of the bound energies of the confined modes as a function of the distance between the two cavities was observed in the coupled cavities studied in this experiment. Figures 17, 18 and 19 show the photoluminescence spectrum of 'dy'=3, 5, and 7 respectively. Note the splitting of the confined modes decreases as the distance between the cavities increases. The sample ‘dy’=1 is not shown because the energy splitting was presumed to be so large that the modes were shifted entirely outside of the photonic band gap; and the photoluminescence measurements were quite different from the ones shown below. A further discussion of the effects of modes shifted outside of the photonic band gap will be saved for later in the paper, see *Effects of Shifting Modes Out of the Photonic Band Gap*.

Figure 17: a photoluminescence spectrum of the confined modes in the coupled cavities of the sample 'dy'=3. The spacing between the modes is 5nm.
As a result of the coupling between cavities splitting the energies of the confined modes one cannot directly compare the photoluminescence data between different samples. This is because the effects of coupling cause each sample to have a different mode separation. Instead, each sample was examined separately in order to determine
how much both modes were shifted after each etch cycle. Then the change in the wavelengths of the modes per etch cycle was calculated and compared between all four samples; in order to determine any effects of coupling between cavities on the digital etching process.

### III. Digital Etching of Coupled Cavities

Due to the fact that the blue shifting of confined modes as a result digital etching has been investigated and reliably reproduced in single cavity photonic crystals, the natural progression is to examine how etching coupled cavities affects their confined modes [9]. For the purposes of this experiment, five cavities of varying geometry were implemented in order to examine how the coupling between cavities affected the shifting of their confined modes. One sample which contained just a single cavity was incorporated as control, and four other cavities all were virtually identical except for the distance between two cavities, defined by ‘dy’ for the purposes of this experiment. Figures 12, 13,14,15,16 are scanning electron microscope (SEM) images of the five photonic crystal samples used in this experiment.

![SEM image](image)

Figure 12: single photonic crystal cavity, (used as control)
Figure 13: coupled cavities with 1 row in between, sample referred to as 'dy'=1

Figure 14: coupled cavities with 3 rows in between, sample referred to as 'dy'=3

Figure 15: coupled cavities with 5 rows in between, sample referred to as 'dy'=5
From figures 13 through 16 one can easily see that four of the samples are virtually identical except for the vertical distance between the two cavities. This allowed for the investigation of whether the etch rate on coupled modes is a function of the spacing between the cavities. The four cavities in figures 13 through 16 will be referred to by the number of rows separating the cavities; they are 'dy'=one, three, five and seven respectively.

IV. Data Collection and Analysis

All samples underwent 13 digital etch cycles in 1M citric acid, with a timescale of approximately one to two days between each cycle. In single cavities the digital etching process has been shown to have an etch rate of two to three nanometers per etch cycle [10]. Therefore a photoluminescence measurement was conducted after every two etch cycles in order to more clearly observe the shifting of the modes; except for the sixth measurement in which three digital etch cycles were preformed. In total seven photoluminescence measurements were recorded, the control sample was observed to have an absolute blue shifting of 21 nm after 13 etches, with an average blue shift of 1.62
nanometers per etch. The samples 'dy'=3, 5 and 7 were observed to have a total blue shifting of 23.84, 24.76 and 35.93 nm respectively after 13 etches; with an average blue shift of 1.83, 1.90, and 2.76 nm respectively per etch cycle. Figure 20 displays a plot of the wavelength of the confined mode versus the simulated radius of the air holes for the single cavity control sample.

![Wavelength vs. Radius for control sample](image)

Figure 20: a plot of the wavelength of the confined mode versus the simulated radius of the air holes for the single cavity sample. Note the blue shift in the data as a result of digital etching

The simulated radius of the data points were obtained taking SEM images of the photonic crystal cavity and then modeling the exact dimensions of the cavity in the FDTD simulation software. Then the slab thickness was decreased and the radius of the holes was increased in order to simulate the removal of material via the digital etch process. The simulated removal of the oxide layer was then incremented until the wavelength of the confined mode matched with the experimental data point. An average increase of the radius of the holes of one and one half nanometers and decrease of the slab thickness of one half nanometers was necessary in order to obtain similar
wavelengths between etch cycles. The average blue shifting of the mode of 1.62 nm per etch was close to the two to three nanometers observed in previous experiments, and the simulated digital etch process in the FDTD software reinforced the hypothesis that the removal of material results in a blue shift of the confined mode [11]. Furthermore, the amount in which the simulated radius of the air holes was increased per etch cycle, one and one half nm, agreed with theory because the time scale between etch cycles allowed for an oxide growth of one to three nm. One interesting result of implementing the FDTD software in order to match the experimental data was that the dimensions of the slab thickness in the simulation software did not agree with the presumed thickness of the sample. The presumed thickness of the sample was approximately 126 nm; however when these dimensions were modeled in the FDTD software, the wavelength of the confined mode differed from experimental data by approximately 40 nm. By increasing the slab thickness to 135 nm the predicted wavelengths agreed to within one or two nanometers. This discrepancy in slab thickness of nine nm was within the fabrication error of the devices and could be a useful technique for inferring the true dimensions of photonic crystal cavities.

Figure 21 shows a plot of the wavelength of confined modes versus etch cycle for the control sample and 'dy'=1, 3 and 5. For the coupled cavities, the two confined modes are plotted separately, with different colors indicating different samples. The samples 'dy'=1,3, and 5 are blue, red, and brown respectively, with the control sample indicated in black.
Wavelength vs. Etch cycle

Figure 21: plot of wavelength versus etch cycle for the observed modes. The samples 'dy'=1,3,and 5 are the blue, red, and brown lines respectively. Note the blue shifting of the modes after every etch cycle.

From figure 21 one can see that the confined modes in each sample experienced a blue shift as a result of digital etching. As previously noted, the mode separation between each sample is different due to the coupling between cavities. Furthermore, the shift rates of the coupled modes was nearly identical for each sample, however the discrepancy in slopes between samples suggests that the coupling between modes may have had an effect on their etch rate. While there is a difference in the average wavelength shift per etch cycle between samples, the data is not strong enough to draw conclusive results. This is because each sample was not totally identical except for the spacing between cavities, due to fabrication errors. The SEM images of the cavities suggest a range in the radius of the holes and lattice constant of three and ten nanometers respectively. Therefore it is hard to determine if the discrepancy in etch rates between samples was solely due to the coupling between cavities or other factors such as the difference in the
geometry each device. To investigate this relationship further one would have to have samples which were virtually identical structurally and obtain more data points by performing more etch cycles. However, after 15 digital etch cycles, photoluminescence data collected from 'dy'=7 appeared similar to 'dy'=1, in the sense that the spectrum was incoherent, meaning that it was impossible determine which peaks were confined modes.

Figure 22 displays photoluminescence data from 'dy'=7 at etch 0 and etch 15. One can see that a clear spectrum in which one can conclusive identify the mode because seemingly incoherent.

![Figure 22: A side by side plot of the photoluminescence spectrum of 'dy'=7 before and after 15 etch cycles.](image)

As a result, additional digital etching was postponed and lasing data was collected instead, in order to investigate the cause of the peculiar photoluminescence spectrum. The cause of the different photoluminescence data was eventually determined to be a consequence of the absence of modes within the photonic band gap, and the numerous
peaks in 'dy'=1 and 7 were attributed to quantum dot emissions. A further discussion of
the investigation of this phenomenon is explained in the next section.

**Effects of Shifting Modes Out of the Photonic Band Gap**

As previously mentioned, photoluminescence data collected from the sample
'dy'=7 after 15 etches appeared drastically different from data collected before the digital
etch process, see figure 22. The most striking aspect of the seemingly incoherent
photoluminescence data collected from sample 'dy'=7 is that it closely resembled all
photoluminescence data collected from 'dy'=1. Figure 23 is plot of photoluminescence
data collected from 'dy'=1; one can see a resemblance to the data collected from 'dy'=7
after 15 etch cycles in figure 22.

![Figure 23: a plot of the photoluminescence spectrum for 'dy'=1 before digital etching.](image)

It is therefore reasonable to assume that both peculiar spectrums, noted
specifically by the absence of a dominant mode, had similar causes. One hypothesis is
that the reason photoluminescence data did not exhibit dominant modes is because the modes were no longer in the photonic band gap. As discussed in the introduction, modes are confined in the photonic crystal cavity due to their presence in the photonic band gap; which forbids them from propagating in outside of the cavity. In the previous section we discovered that digital etching blue shifts the confined mode; therefore one must consider the possibility that repeated digital etch cycles shifted the modes confined in 'dy' = 7 outside of the photonic band gap. Furthermore, in the section titled "Effects of coupling between cavities on their confined modes" we also concluded that the mode separation in coupled cavities is dependent on the distance between the two cavities; with the separation being larger when the cavities are closer together. Therefore it is also possible that the spacing between the modes in 'dy' = 1 is so large that they were no longer in the photonic band gap. In this case the observed peaks would be the emission spectrum from the quantum dots, which are usually overshadowed by the mode resonance. The hypothesis that the observed peaks are actually quantum dot emissions is also reasonable because quantum dots with different physical dimensions emit light at different wavelengths. Thus the wide range of the observed peaks may be due to the high number of quantum dots in the sample, 10^{10} dots per cm, whose emission covers the a broad spectrum of wavelengths inside the photonic band gap.

Another possible explanation for the incoherent photoluminescence data is that an equipment malfunction either in the micro photoluminescence setup or the spectrometer produced incoherent data. This explanation seems unlikely however because data collected from the control sample and 'dy' = 3 and 5 showed clear evidence of dominant modes; and one would expect an equipment failure to affect all collected
data. An alternative hypothesis is that the "peaks" observed in 'dy'=1 are lower order modes coupled to quantum dots in the sample. One problem with this postulate is that the photoluminescence spectrum varied significantly by adjusting the position and focus of the laser on the cavity. Due to the inherent nature of the confined modes in the cavity, it seems unlikely that one would get different resonance peaks by slightly adjusting the position and focus of the laser. This effect could be explained however if the peaks were quantum dot emissions, because adjusting the focus of the laser on the sample would change the spot size and therefore the number of excited quantum dots. Figure 24 shows two different spectrums for 'dy'=1 taken in the same data set; one sees a different profile by slightly adjusting the focus of the laser on the sample.

![Figure 24: two pl setup of 'dy'=1 with the focus of the laser adjusted slightly between measurements. One sees what appears to be an apparent mode in spectrum # 1 becomes one of many peaks in spectrum # 2.](image)

The vast difference between the photoluminescence measurements could be due to the fact that in spectrum one the laser was focused primarily on one quantum dot, around 970 nm, causing it to have a significantly higher intensity then the other quantum
dots. While in spectrum two the spot size was larger and therefore more quantum dots were excited with the intensity of each emission being similar.

While preliminary evidence does suggest that the observed peaks are quantum dot emissions, in order to investigate the possibility of the presence of multiple modes, each of the peaks observed in 'dy'=1 was categorized in terms of its wavelength and quality factor. One would expect modes coupled to quantum dots to have high quality factors and be inside the photonic band gap [11]. Figure 25 is graphical representation of the wavelengths of the 38 observed "peaks" for 'dy'=1 over 7 pl measurements; with each red line corresponding to an observed mode.

![Figure 25](image)

Figure 25: a graph of the wavelength of the 38 observed peaks in 'dy'=1; the wavelengths range from 885 to 972 nm

From figure 25 one can see a uniform distribution of peaks ranging from 885 to 972 nm. In order to determine if the identified peaks were in the photonic band gap FDTD simulations were run to identify the band gap for 'dy'=1. One important fact to note is that the photonic band gap of triangular lattice photonic crystals depends on the
dimensionless quantity \( r/a \), where \( r \) is the radius of the air holes and \( a \) is the lattice constant [13]. Therefore, because digital etching increases the radius of the air holes the photonic band gap will also vary. In this experiment the quantity \( r/a \) ranged from .264 to .28. Figure 26 displays the simulated band gap for \( \text{‘dy’}=1 \) at \( r/a = .264 \) and .28 respectively.

![Bandstructure and Bandgap](image)

Figure 26: A simulation of the photonic band gap for \( \text{‘dy’}=1 \). The right plot is the band gap before digital etching and the left plot is the band gap after 15 etch cycles.

From figure 26 one can see the band gap range from 898 to 1105 nm for \( r/a = .264 \) and 779 to 1020 nm for \( r/a = .28 \). The results of the band gap simulations suggests that all of the measured peaks were in the photonic band gap; which provides further evidence that the observed peaks were from the sample and not a result of an equipment failure.

Furthermore, the quality factor was calculated for each of the 38 observed peaks, in order to determine if any of the peaks were modes. High quality factors are characteristic of confined modes, therefore if peaks of slightly different wavelengths were observed to have similar quality factors it could be evidence separate peaks were in fact
different manifestations the same mode. Figure 27 displays a graph of quality factor versus wavelength, with each data point representing an observed peak.

Figure 27: a plot of quality factor versus wavelength for 'dy'=1, each of the data points corresponds to an observed peak.

Figure 27 shows a wide range of quality factors across all wavelengths, with no clear correlation between the quality factor of peaks with similar wavelengths. This suggests that the peaks were not different manifestations of the same mode but rather quantum dot emissions.

Lasing measurements were also conducted in order to determine if the observed peaks were modes. High quality factor modes have been shown to undergo lasing, which is characterized by a distinct increase in slope of the intensity versus power curve at the lasing threshold. Another characteristic of lasing is a decrease in the line width of the mode; known as the Schawlow-Townes law for standard lasers. This reduction of the linewidth above the lasing threshold is due to the fact that the mode will exhibit spectral
coherence only when the stimulated emission becomes predominant. Therefore the linewidth of the laser will decrease in inverse ratio to the number of photons in the cavity above threshold [14]. However, the absence of lasing does not necessarily mean that the peaks are not modes; because the power of the laser and quality factor of the mode needs to be sufficient for them to undergo spontaneous emission. Figures 28 and 29 are plots of the peak width versus power for the control sample and 'dy'= 7 devices respectively.

**Figure 28:** A plot of width versus power for the confined mode in the control sample
Figure 29: A plot of width versus power for the peak with the highest quality factor in 'dy'=7

Comparing figures 28 and 29, one can see that the width of the mode does decrease in the control sample while it remains fairly constant in the highest quality factor peak observed in 'dy'=7. This suggests that the control sample has a lasing threshold of around 40 microwatts and the sample 'dy'=7 is not experiencing lasing. While the absence of lasing in 'dy'=7 could be the result of the "mode" not having a high enough quality factor, it certainly does not provide evidence that the peaks are modes. Lasing data collected from the sample 'dy'=1 was similar to that from 'dy'=7 in that it also did not exhibit a decrease in the line width as the power was increased.

The results of the lasing data, quality factor analysis, band gap simulations, and the dependence of the peaks on the position and focus of the laser suggest that the observed peaks in samples 'dy'=1 and 7 were quantum dot emissions. However, if the peaks are in fact quantum dot emissions one obvious question is, Why do we only see these emissions in the photonic crystal and not over the entire GaAs sample where the are
obviously no confined modes? The answer may have to do with the interaction of quantum dots with etched holes reducing optical efficiency. Specifically, the location of the quantum dot in the cavity influences whether or not it will be in resonance with the confined mode. This because quantum dots located in regions of high electric field intensity inside the cavity are most strongly coupled with the mode. Figure 30 displays the optimal placement of the quantum dot with respect to the mode profile, noted by the green circle. Quantum dots in the regions of low electric field intensity will experience less coupling to the mode.

Figure 30: A quantum dot in a photonic crystal cavity would have an optimal placement, noted by the green dot, in the regions of the highest electric field intensity of the confined mode.

One possible experiment to explore and utilize this fact would be to etch the mode across the quantum dot spectrum, noting the intensity and quality factor of the peaks that increase dramatically. Then for the peaks that have high intensities and quality factors one could pump the sample at progressively higher powers in order to induce lasing. The lasing measurements as well as the information concerning the quality factor and intensity of the dominant peaks could provide information as to the number of quantum dots in the photonic crystal cavity as well as their position inside the cavity.
Conclusion

As the field of nanophotonic continues to flourish, entering the realm of commercially manufactured products, understanding the behavior of light inside photonic crystal cavities will be essential in the design and implementation of these devices. Digital etching offers a predictable and controllable post fabrication technique for tuning the mode of the photonic crystal into resonance with the quantum dot emissions. Furthermore, the ability to predictably tune modes in coupled cavities will provide a useful tool for more complex devices which rely on the integration of multiple photonic crystal cavities. Finally, the investigation of quantum dot emissions not necessarily in resonance with confined modes may provide additional information as to where the quantum dots are optimally located in the cavity, thereby offering a method for optimizing the light-matter interaction of photonic crystal cavity devices.
References


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