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A New Cavity Defect for Terahertz Photonic Crystal Slabs

Prepared for
Dr. Mark Sherwin
University of California Santa Barbara

By

Stephen Parham
College of Creative Studies
University of California Santa Barbara

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Abstract

This paper presents a new type of photonic crystal cavity which is implemented as terahertz frequencies. The photonic crystal is a 380 μm thick silicon slab with a triangular lattice of air holes that has a pitch of 140 μm and hole diameters of 130 μm. The cavity consists of two holes filled with silicon, surrounded by the crystal. The frequency and Q of the cavity were measured using direct coupling from a waveguide to the cavity. The experimental data is in good agreement with finite difference time domain simulations.

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Introduction

Photonic crystal research involves manipulating and confining light with the use of photonic crystals. A photonic crystal (PC) acts as a perfect mirror for certain frequencies of light. The crystal is comprised of two different dielectric materials arranged periodically in one, two or three directions. Examples include a silicon slab with a triangular array of air holes or silicon rods arranged in a square lattice [3]. When the periodicity of the structure is broken, by removing a rod for example, a defect is formed and that part of the crystal will not reflect the light as well. These defects can be shaped into waveguides or cavities, which allow light to be molded and confined.

Photonic crystals designed for visible light have already been researched [1]. However, my research involves crystals that work at terahertz (THz) frequencies, which are between infrared and microwaves. THz radiation has applications in security systems, earth based telescopes, and other areas [6]. Emerging THz technologies require the ability to manipulate THz radiation and photonic crystals provide a promising solution.

A Photonic Crystal Slab (PCS) is a three-dimensional structure that consists of a two-dimensional photonic crystal in which the third dimension is typically of the order of half to a couple times the lattice constant of the photonic crystal. PCS relies on the two dimensional photonic crystal for confinement in the plane of the slab and total internal reflection for confinement in the perpendicular direction of the slab. They do not have a real gap in the sense of a three dimensional photonic crystal. However it has several advantages over a three dimensional PC; they are easy to fabricate and if designed carefully the losses due to the total internal reflection can be minimized.

PCS's can come in two forms, single-mode and multi-mode. A single-mode slab has a thickness less than the wavelength of light in silicon, while a multi-mode slab has the thickness between one to several wavelengths. Thus, a single-mode slab can only support a half wavelength in the z-direction whereas the multi-mode can support higher harmonics. The situation is analogous to a particle in a box, which has modes of integer numbers of half-wavelengths. This means that a multi-mode PCS will have a much higher density of allowed states and thus more modes to deal with as compared to single-mode slabs. The PCS's in our research are multi-mode and therefore the cavity defect may have more than one resonance frequency.

When studying cavity defects it is important to quantify how well the cavity confines light. Cavities have an intrinsic quality factor (Q) which is approximately how many times the light bounces in the cavity before escaping [2]. Light can be polarized with its electric field either in the crystal plane or perpendicular to the crystal plane. These two polarizations are called transverse electric (TE) and transverse magnetic (TM) respectively. In general, a certain PC will only have a gap for one of the two polarizations.

TE photonic crystals have been studied much more extensively than TM PC's. This is due to TE having a larger and deeper gap in general, as compared to TM [1]. This allows for higher Q resonators, which is why the majority of research is focused on TE. However, TM has some advantages that make it worth investigating. Due to the boundary conditions for metals, TM modes are not affected by the metal slit that holds the sample in the laser beam (discussed in methods section). This allows electrical contacts or other metallic structures to be adjacent to the cavity without changing the mode itself. Our research focuses on high-Q, TM.

The purpose of this paper is to present a new type of photonic crystal cavity. The cavity is comprised of two adjacent air holes filled with silicon and is called an L2 defect. It is a TM cavity with a Q ~ 400. The paper presents the lens mechanism that amplifies the power in the cavity and the fabrication process. Finite difference time domain (FDTD) simulations are compared to experimental data to determine if the cavity behaves as expected. The losses due to the waveguide will not be discussed.

The paper presents the fabrication process first, followed by the experimental setup. The data is shown and compared with theory calculations. Next we give our interpretation of the data. Finally, recommendations for further research are given.

Fabrication Process to Produce Photonic Crystals

Before any experiments are done, the crystal must be designed and fabricated. Using FDTD simulations (discussed in methods section), we determine the most promising crystal design for upcoming experiments. This design is transferred to a mask plate, which will be used to imprint the design on the raw material. Once the mask is complete we can begin to fabricate sample PCS's.

Figure 1 shows a THz photonic crystal with a 380 μm thickness and a 140 μm hole diameter. Fabrication of these crystals occurs at the UCSB Nanofabrication Facility using the Silicon Reactive Ion Etching (SiRIE) Based Fluorine Etcher (see Figure 2). Fabrication has four main stages: preparation, lithography, etching, and recovery.

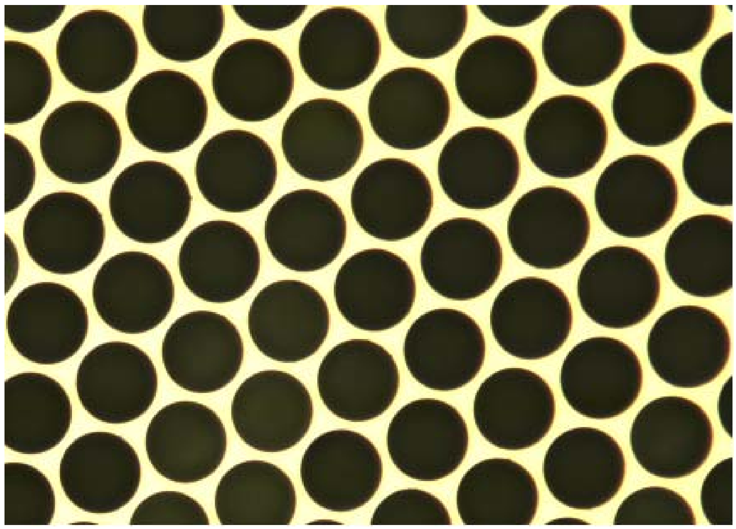

Figure 1: A completed photonic crystal slab viewed with an optical microscope. The structure is top illuminated so the silicon is reflecting the light and the air holes appear black. The yellow tinge is due to the filter used on the camera.

Figure 2: The Silicon Reactive Ion Etching (SiRIE) system at UCSB's Nanofabrication Facility. [5]

Preparation Stage

The raw material is a high resistivity silicon ρ>20000 ohm-cm^{-1}, 380 μm thick silicon wafer. It must be glued to a base, a thicker 500 μm wafer, via a 2 μm coating of photo resist (PR). The base will provide stability during the etching stage. The exposed side of the 380 μm wafer is also coated with a 7 μm layer of PR. A pre-designed mask plate is placed on top of the exposed PR layer and the whole setup is moved to the lithography machine. The mask is a stencil that can be made into any pattern. One pattern is a triangular array of holes shown in Figure 1.

Lithography Stage

Exposing PR to ultra-violet (UV) radiation changes its chemical composition, which allows it to be selectively removed from the sample. During the lithography stage the sample is illuminated with UV radiation, but only the parts not protected by the mask are affected. Afterward, the mask is removed and the wafers are developed and the affected PR is removed with a solvent. Once complete, the wafers are placed in the SiRIE etcher.

Etching Stage

The etching stage is controlled by a computer that runs the SiRIE system. The system alternates between a polymer deposition cycle that uses C_4F_8 gas, and an etching cycle that uses a SF_6 / Ar mixture [5]. The deposition cycle alters the exposed layer of silicon so it can be etched away during etching cycle. The cyclic nature of the procedure is shown in Figure 3. The gases are accelerated toward the sample via a capacitor and they chemically etch away the pattern designated by the lithography. The nominal etch rate is 2 μm per minute which corresponds to a total etch time of 200 minutes. Back-cooling with a flow of liquid helium prevents damage from the very hot, accelerated gases.

When etching thicker samples, such as the 380 μm multimode slab, it is difficult to maintain the pattern for the entire depth. This is a limitation of the fabrication process and can result in what is called an over-etch. When an over-etch occurs, the radius of the holes becomes larger than nominally designed.

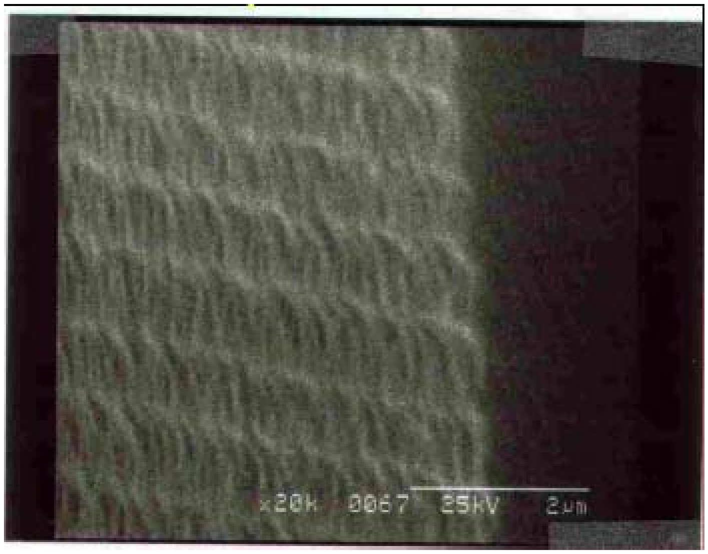

Figure 3: Sidewall view of the SiRIE etch. Shows how etch occurs in cycles. [4]

Recovery Stage

Once the sample is done etching it is removed from the SiRIE system and placed in an acetone solution. The acetone dissolves the PR on both sides of the silicon wafer. This stage can take up to 12 hours because the acetone cannot efficiently reach the PR between the slab and the base. After the PR is completely removed the sample is ready for use.

Fabrication Summary

Cristo Yee fabricated the samples and further details of the fabrication process can be found in his Ph.D. dissertation. First in the process, the raw material is prepared with the use of PR and a mask. Second, the mask's pattern is transferred via UV lithography. Third, the SiRIE system etches the pattern away from the silicon, producing a photonic crystal. Finally, the chemicals used in fabrication are removed with acetone and the crystal is complete.

Experimental Methods & Procedures

Figure 4 shows the setup for transmission experiments. The source produces a diverging beam of THz radiation. The beam is passed through a wire-grid polarizer to select the proper polarization for the experiment. Using two parabolic mirrors the beam is focused to a spot of 2 mm diameter and directed at the sample. The transmitted light is collected by two more parabolic mirrors and sent to the THz detector. The detector is wired to a computer to record the data.

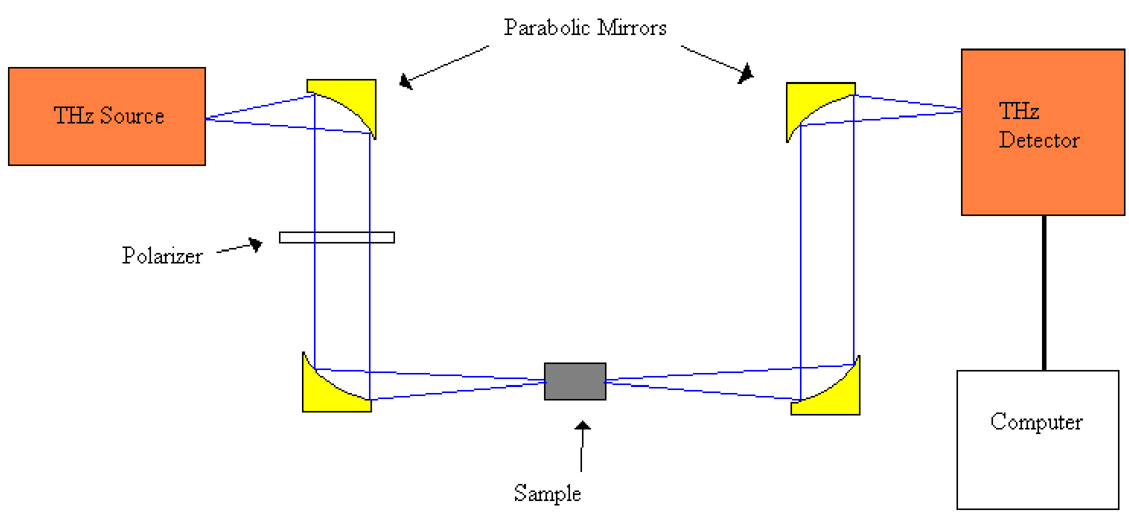

Figure 4: Transmission experiment setup.

To ensure a valid measurement we must block all the light that isn't coming through the crystal slab. The slab is held in a metal slit to prevent light from passing over or under the slab. In addition, we place the slab next to a 2 mm pinhole that is positioned at the focus of the beam. This ensures that no light goes around the crystal. These two techniques ensure that all the light getting to the detector is coming from the slab itself.

It was found that the metal pinhole was causing too many stray reflections. In order to avoid using the pinhole, we changed to the second experimental setup (see figure 5). This setup has the sample placed at the output of the source and uses two mirrors to collect the light from the sample and direct it to the detector. A polarizer is placed between the mirrors to allow only the TM light to reach the detector. A combination of foam and metal slit exposes only the crystal's output lens to the parabolic mirror. This ensures that any light reaching the detector traveled through the crystal and is not a product of stray reflections.

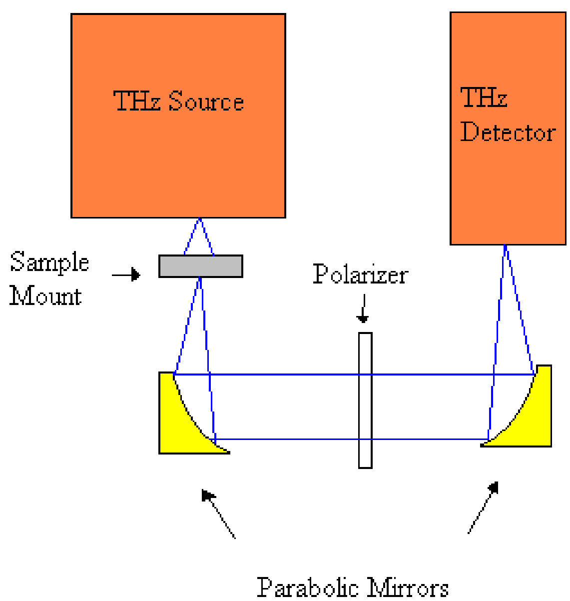

Figure 5: Second transmission setup. The sample is placed near the output of the source.

The source is a tunable VDI terahertz source. A microwave synthesizer produces radiation between 13.3 – 15 GHz, tunable in 1 kHz increments. This radiation passes through a series of three frequency doublers and two frequency triplers and comes out 72 times higher than it started. The result is a 957.6 – 1080 GHz range tunable in 72 kHz steps. The power of the source is frequency dependent, but is of the order of 4 μW. 90% of this power is polarized in the TM direction with the remaining 10% in the TE direction. This is the reason for using a polarizer in the experimental setup; we don't want the TE light to make it to the detector. In addition, the smallest spot to which the laser can be focused is 2 mm, appreciably larger than the ~150 μm waveguide opening of the sample.

We are experimenting with silicon semicircle lenses to increase the signal through the PCS. The lens, shown in figure 6, consists of a 3 mm semicircle of silicon attached to the opening of the waveguide. A semicircle lens focuses all incident light to a point in the center, which is positioned at the waveguide entry. Without the lens only the light incident on the 150 μm waveguide opening makes it into the waveguide. However, with the lens all light within 2 mm of the waveguide opening is focused into the waveguide. An output lens is used in a similar fashion; it collimates the exiting light and sends it to the parabolic mirrors. The lenses increase the power in the waveguide by over a factor of ten and substantially improve the signal through the crystal.

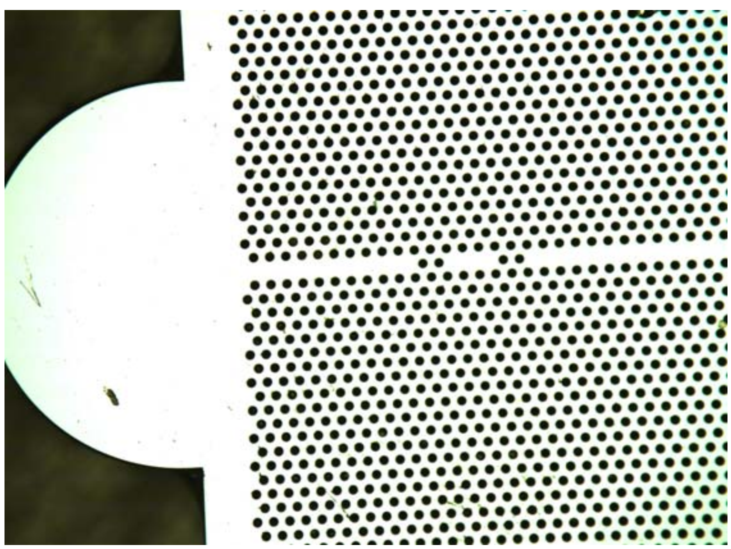

Figure 6: Semicircle Lens used to amplify light in the PC waveguide.

The use of a metal slit will alter TE modes traveling in the crystal. TE modes have their electric field polarized in the plane of the slab but the metal slit orientation requires the electric field be perpendicular to the slab plane. As a result, the metal slit reflects TE modes and is not effective for measuring TE polarization.

Two possible solutions are to use a non-metallic slit or to study TM polarization, which is not affected by the metal slit. However, a non-metallic slit, which absorbs light instead of reflecting it, lets enough light through that the signal from the crystal is buried. The other option, using TM polarization, allows us to take full advantage of the experimental setup without affecting the modes that we are trying to measure. That is partly why we are studying TM photonic crystals.

Figure 7 shows the metal slit used as both a sample mount and a light blocking agent. The sample is placed in a metal trough 10 mm wide by 400 μm deep. The top of the trough is covered by a metal plate that serves to hold the sample in the trough and block light not traveling through the sample. The sample mount has a 2” square backing with an 8 mm by 800 μm slot. This slot is designed to fully expose the output lens while not exposing the edges of the sample. This helps block any light that travels around the crystal, instead of through it.

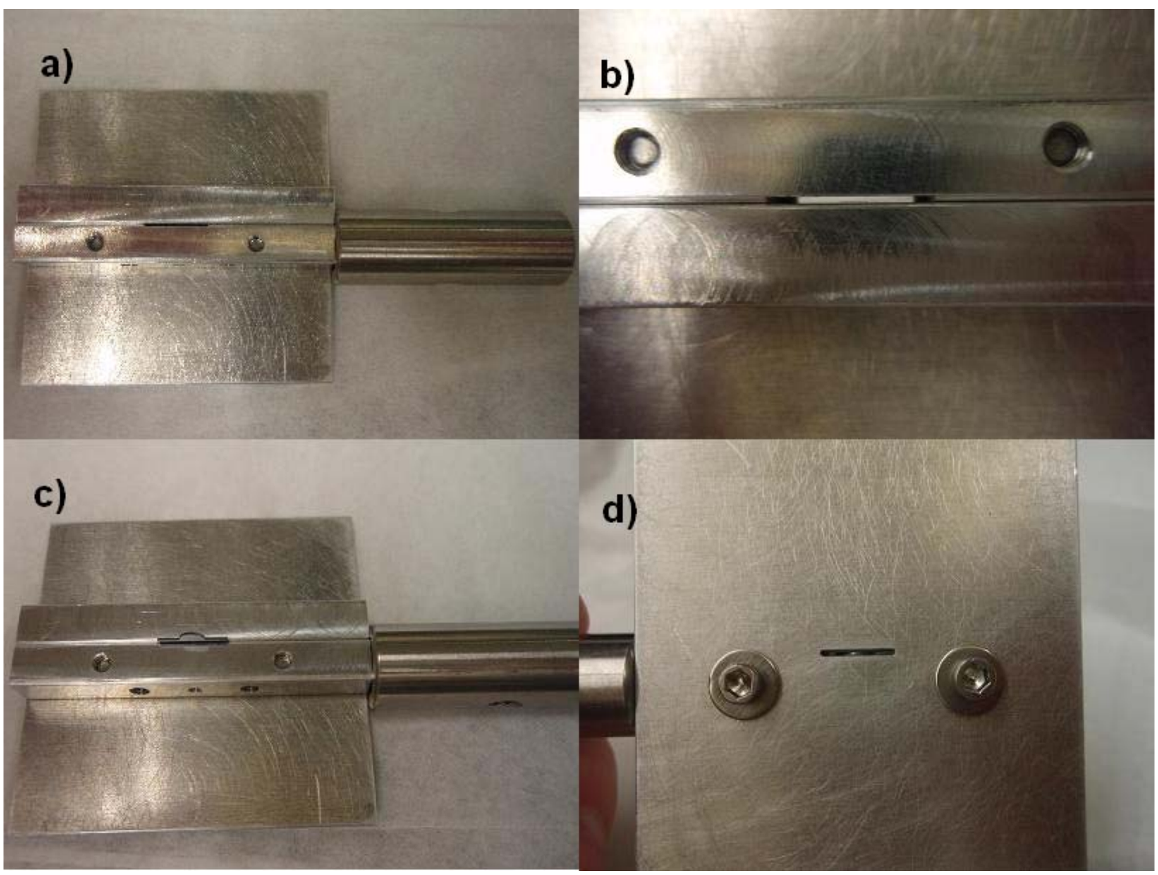

Figure 7: (a) This apparatus acts as both a sample mount and a light blocking agent. (b) The exposed slot without a sample in place. (c) Mount with sample in place. The exposed lens is placed near the source output. (d) With the sample mounted no stray light can pass around the sample.

The PC is designed in a direct coupling setup, which has the cavity placed in the waveguide with multiple holes isolating the cavity from the waveguide. Only light tuned to the frequency of the cavity will be able to tunnel into the cavity and out the other end of the waveguide. All other frequencies are reflected when they reach the holes isolating the cavity. Therefore, the transmission spectrum will have a peak at the resonant frequency of the cavity.

Simulations

The cavity properties were studied using finite difference time domain (FDTD) simulation program from MIT called Meep. The program uses a control file with information about the following: the geometry of the structure; which materials are present; the position and type of sources; the length of time to run the program; and whatever outputs are desired by the user. Outputs include pictures of electric and magnetic fields, computed flux through specified regions, and calculated frequencies of modes inside the cavity.

Systems which obey reflection symmetry along one or more axes are faster to simulate. The Meep program can use the symmetry of the structure to reduce the calculation time by half for each axis that is symmetric. For example, employing a z-axis symmetry implies that the structure's upper half space is a mirror of its lower half space and allows Meep to only calculate one of the half spaces. Symmetries in Meep include sources as well because the E&B fields must obey the same symmetries as the structure. Different cavity modes have distinct mode profiles that obey different symmetries. Only the modes that share the symmetries being used will be excited during the simulation.

Meep simulations play two roles in this research. First, the simulations are used to predict where peaks in the transmission will be in dimensionless frequency units. This allows us to design the crystal with the proper lattice constant in order for the peaks to be in the range of the source. Once the crystal is fabricated, the parameters are measured and simulated to confirm the modes seen in the experimental data.

We did simulations of the direct coupling setup and simulated both the cavity modes and the transmission of the structure. Figure 8 shows the structure used in the simulation. To simulate the cavity modes, two Gaussian pulses were turned on in the cavity. The reason for two sources is to obey the symmetry rules about the structure. The transmission simulation employed a line source at the waveguide's left entry to emulate the lens focusing onto the waveguide.

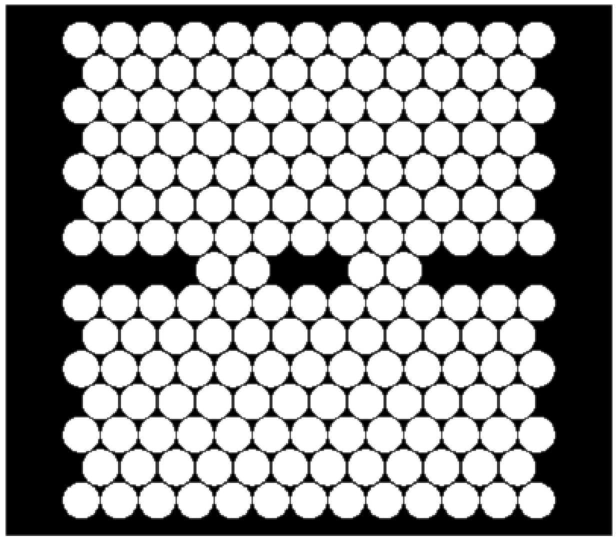

Figure 8: Structure used in simulations.

Experimental Data

The Meep simulation program calculates frequencies in dimensionless units (c/a) because the properties of the photonic crystal do not depend on the lattice constant, but on the ratio between the size of holes and the lattice constant. This allows PC's to be scaled to any frequency by changing the lattice constant. In order to prove that the cavity modes measured were coming from the cavity, and not some artifact of measurement, we built samples with four different lattice constants: a=150, 145, 140, and 135 um. The resonance signature of the cavity should shift depending on a, while any artifact of measurement will remain at the same frequency.

The data in figure 9 shows precisely this shift in the peaks for the 140 and 135 samples. And the shift matches the predictions for the given lattice constants. When both spectra are converted to dimensionless units (see fig. 10) the peaks overlap, showing that the same modes are present in both samples. As figure 10 shows, the 150 sample does not cover the range for the main peak but does mimic the structure of the 140 and 135 samples in the overlapping range. With large radii the PCS are mostly air and very fragile. The 145 sample was broken before being measured so we do not have the data for that sample. However, even without the 145 data it is clear that the spectra overlap very well.

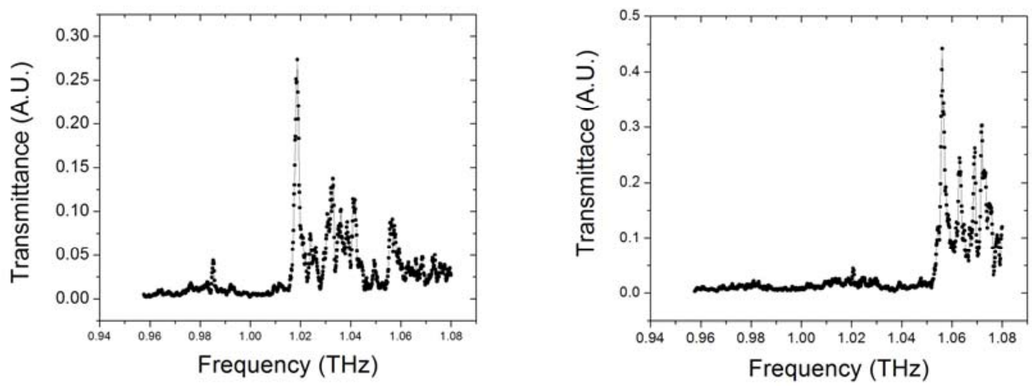

Figure 9: (a) Data for a=140 um sample. The main peak occurs at 1.02 THz and has a Q~400. (b) Data for a=135 um sample. The main peak occurs at 1.058 THz with a Q~ 400.

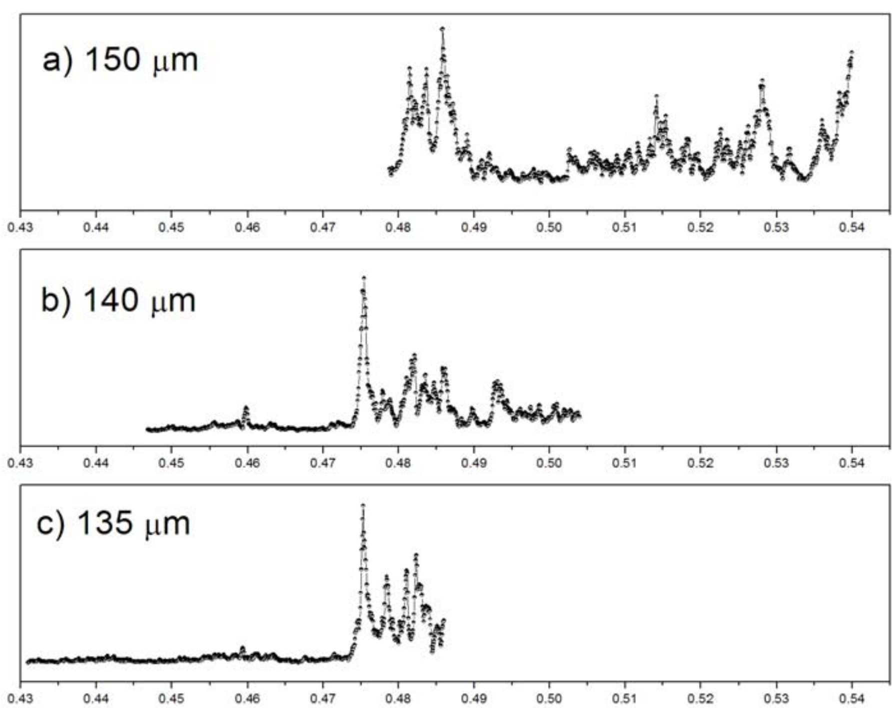

Figure 10: Data converted to dimensionless units. (a) 150 um spectrum. (b) 140 um spectrum. (c) 135 um spectrum. The x-axis is frequency in (c/a) units. The main peak appears at f= 0.475 c/a in both (b) and (c).

The structure was imaged with an optical microscope on high magnification. We printed the image and measured the radius by comparing the diameter of the holes to the hole spacing. The radius was found to be $r=0.47a \pm 0.01a$. The nominal radius was 0.45a, which indicates that an over-etch occurred during the fabrication process.

The thickness was measured using a dial indicator accurate to micron precision. The thickness has slight fluctuations over the length of the sample, but ranges between 380 um and 385 um for these samples. Since all the samples were made with the same wafer, they all have this thickness. However, the various samples will have different thickness in terms of multiples of the lattice constant. For example, the 150um sample has a thickness $t= 2.53a$ whereas the 135um sample has $t= 2.81a$. These changes in thickness were incorporated into the simulations but did not affect the resonance peaks much.

Discussion

Figure 11 shows the simulated transmission spectra for a complete PC and a PC containing a waveguide. The PC has a gap over the whole range, starting deep and getting weaker at 1.05 THz. The waveguide has a high transmission for a broad range of frequencies, indicating that it channels most of the light through the structure. When the cavity defect is placed in the waveguide and isolated with holes, the transmission looks completely different. Instead of broadband transmission like the waveguide alone, this spectrum shows several distinct peaks which correspond to particular modes of the cavity defect.

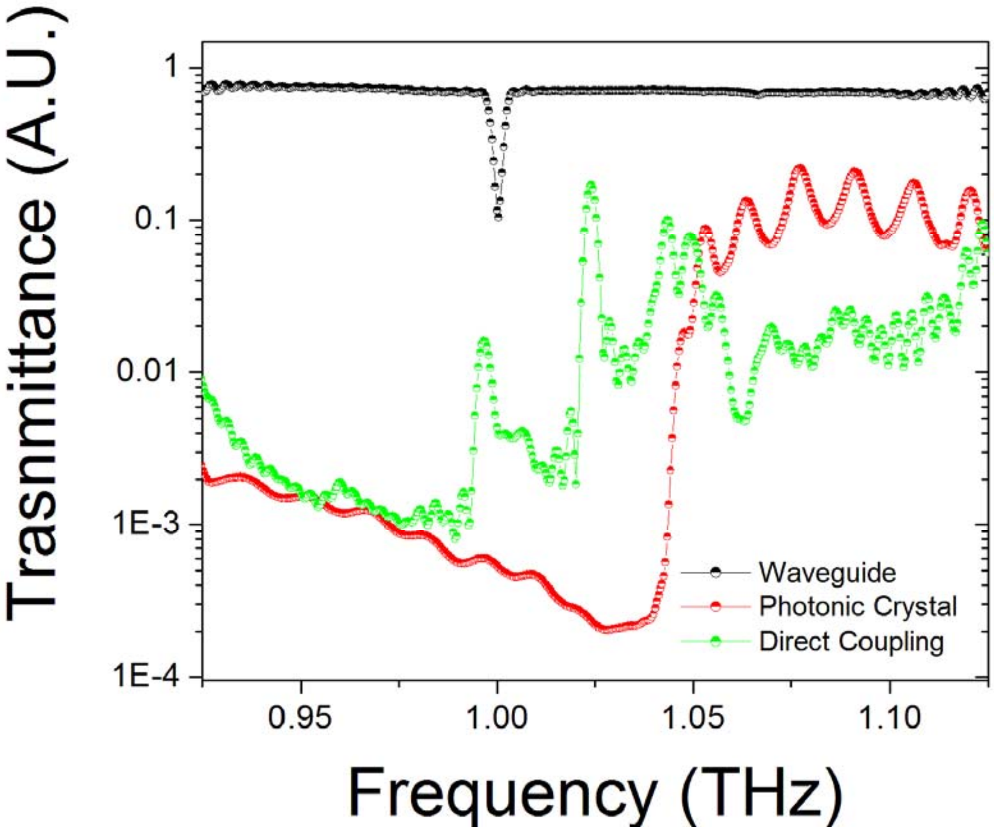

Figure 11: Simulations of a complete PC, PC with waveguide, and Direct Coupling Setup. Note that the PC has a gap that disappears when the waveguide is added. The Direct Coupling looks different than both, indicating that the cavity is interacting with the waveguide.

If a photon matching the frequency of a cavity mode tunnels into the L2 cavity, it will resonate and remain in the cavity for a time determined by the Q of the mode. A larger Q means the photons remain in the cavity longer before tunneling back into the waveguide. If, on the other hand, the photons are off resonance with the cavity then most will be reflected. That frequency cannot build enough power in the cavity to tunnel a measurable amount of light into the output waveguide. Thus, all frequencies that don’t correspond to a cavity mode will be blocked by the setup and the spectrum will show peaks at the frequencies of the cavity modes.

We ran simulations with the measured parameters of the structure and obtained a transmission with distinct peaks. The transmission of the structure is very sensitive to changes in the hole radius. Figure 12 shows how the spectrum shifts with radius change.

With a radius change from 0.455a to 0.465a, the main peak shifts by 0.01 c/a. This corresponds to a 20 GHz shift for the 140 um sample. The simulation for r=0.46a matches the data most closely, differing from experiment by only about 5 GHz. Figure 13 shows the experimental data overlapped with the simulation. The simulation is manually shifted so the main peaks coincide; the shift is -6.43 GHz for 140 um and -5.33 GHz for 135 um. Notice that these shifts are less than a 1% change (1% of 1 THz is 10 GHz) and are well explained by the uncertainty in the measured radius.

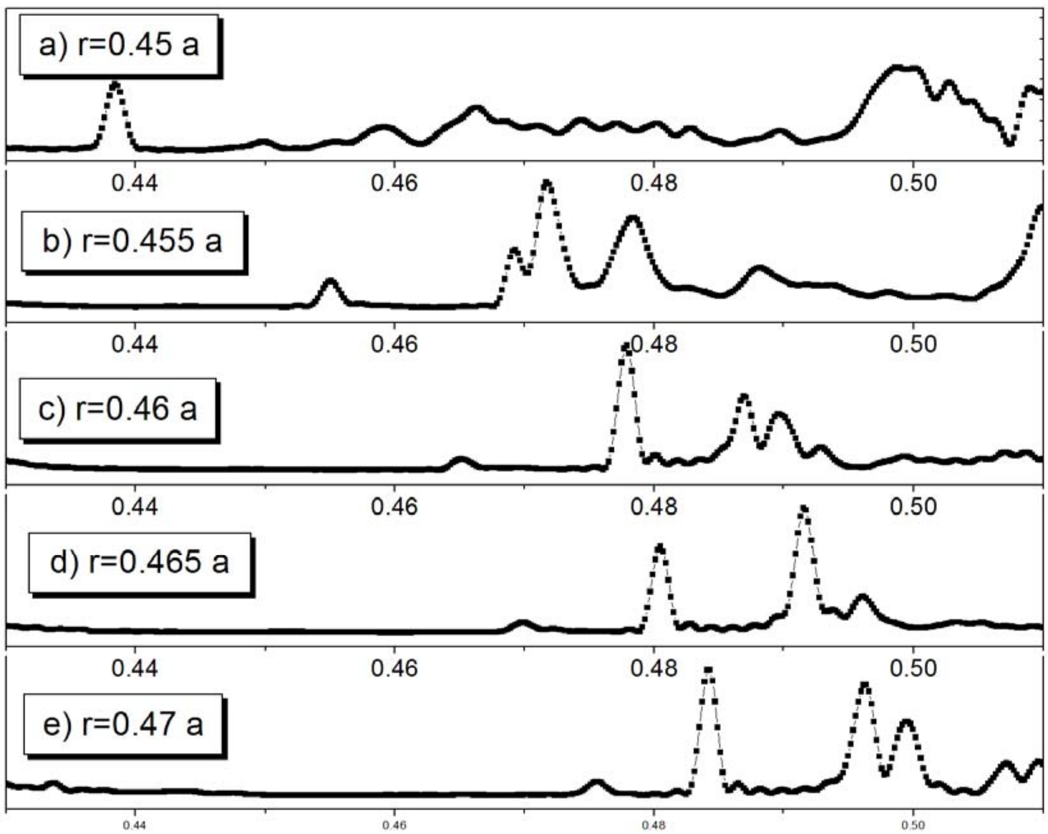

Figure 12: Transmission simulations for various radii. The x-axis is frequency (c/a) and the y-axis is removed because the interesting behavior is along the x-axis. It is clear that the transmission spectrum changes with radius and the peaks move to higher frequency with larger radius. The change is not one-to-one, so the peaks do not all move the same amount relative to each other, but the general trend is clear.

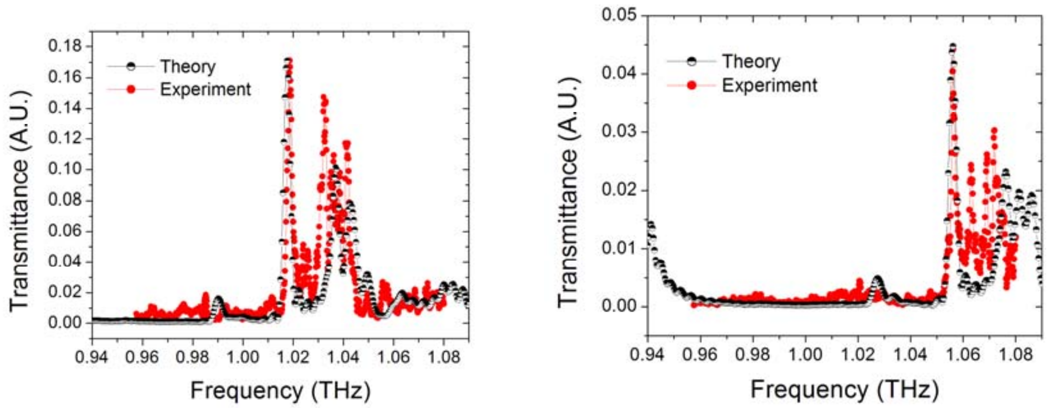

Figure 13: Data and simulations overlapped. The theory was manually shifted slightly to align the main peaks. (a) a=140 um with theory shifted -6.43 GHz. (b) a=135 um with theory shifted -5.33 GHz.

Also, we simulated the modes of the cavity by exciting with sources inside the cavity. The frequencies of the cavity modes match the frequencies of the transmission peaks. In addition, the Q calculated from the cavity mode simulations match with the peak widths in the transmission spectrum. This is strong evidence that the cavity modes are the peaks in the transmission spectrum. Figure 14 shows the mode profiles in the xy-plane and the yz-plane. The profiles obtained from the cavity mode simulations show that the mode is confined to the cavity and doesn't extend into the photonic crystal. This means the mode is truly a cavity mode.

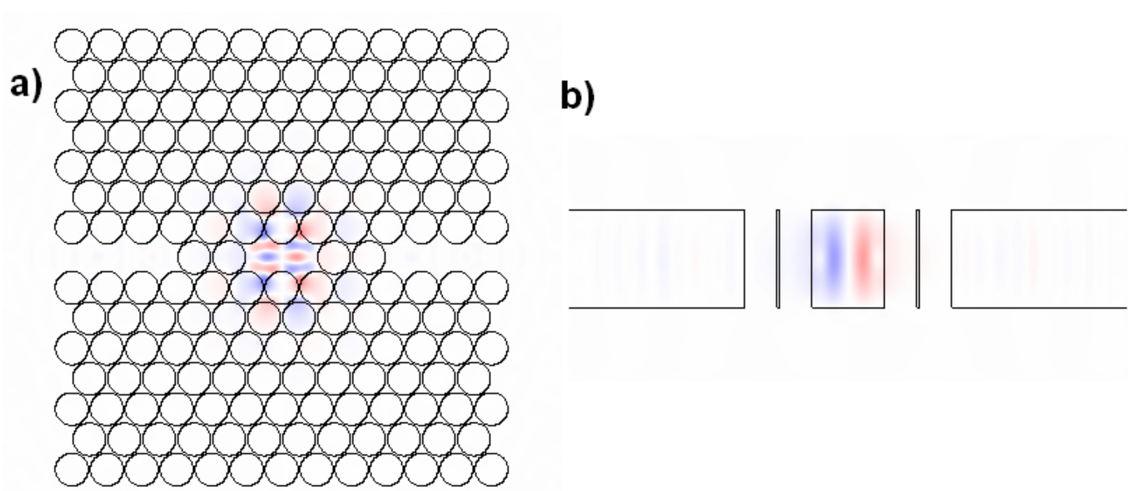

Figure 14: (a) xy-plane profile of cavity mode. (b) yz-plane profile of same mode.

Conclusions

We have shown that the L2 photonic crystal cavity can work at THz frequencies. The crystal is a silicon slab 380 um thick, and has a triangular lattice of holes with ~130 um diameters and a 140 um pitch. Using a direct coupling, transmission experiment we measured the frequency and Q of the L2 cavity defect to be 1.02 THz and 400 respectively. The data agrees with the simulations to within 6 GHz, which is a good indicator that the PC is behaving as expected. The simulations show a mode with similar Q at a frequency within 1% of that measured.

The direct coupling (DC) setup is very useful for interrogating cavity defects. It allows only the light resonant with the cavity to transmit and thus provides an easy way to measure resonant cavity modes. The integrated silicon lenses help boost the power in the waveguide and provide a measurable signal when using the 4 μW source. Using the DC setup, we have found high-Q modes of the TM L2 cavity. These modes are extremely sensitive to changes in radius.

The cavity spectrum does not exhibit the same behavior as the waveguide spectrum. This means the cavity must be interacting with the waveguide. We have shown that the transmission peaks correspond to modes of the L2 defect and have matched the measured frequencies to those of the Meep simulations.

Future research will involve optimizing the Q of the L2 defect by slightly modifying the holes surrounding the defect. These defects, called superdefects, can theoretically have much higher Q than the unmodified L2 defect [1]. Using FDTD simulations, we will determine a promising superdefect to fabricate. Once complete, we can measure the defect’s properties using the same experimental techniques discussed above.

Glossary of Terms

Photonic Crystal: A periodic arrangement of two dielectric materials with different dielectric constants.

Photonic Crystal Slab: A three-dimensional structure that consists of a two-dimensional photonic crystal in which the third dimension is typically of the order of half to a couple times the lattice constant of the photonic crystal.

Direct Coupling: A crystal design that has a cavity defect in the middle of a waveguide so that light must tunnel from the waveguide to the cavity in order to be transmitted.

TE: Stands for transverse electric. TE polarization has the electric field in the plane of the photonic crystal slab.

TM: Stands for transverse magnetic. TM polarization has the electric field perpendicular to the plane of the photonic crystal slab.

Q: Quality factor. A dimensionless number that represents how many times light will bounce in a cavity before escaping.

THz: Stands for terahertz. Terahertz radiation is part of the electromagnetic spectrum that lies between infrared and microwaves.

L2: Stands for linear, two-hole defect. This is the type of cavity studied in this paper.

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