

# Optical Characterization of TiO<sub>2</sub>-Infiltrated Photonic Crystal Structures

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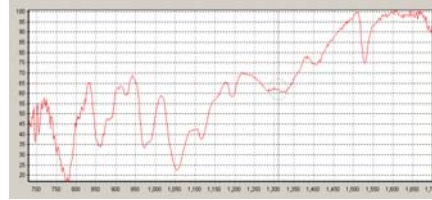
## Introduction

Photonic Crystals (PC's) are materials with a periodic dielectric constant ( $\epsilon$ ). Depending on the number of dimensions of dielectric periodicity, the lattice arrangement and the dielectric contrast between neighboring constituents, incident light of wavelength on the order of periodicity can be losslessly guided, slowed or stopped, confined, self-collimated and prohibited in specific frequency regimes. Band Structure Diagrams – plots of frequency vs. wavevector for the allowed light modes in the crystal (derived as discrete solutions to Maxwell's Equations) – reveal lattice directions along which particular frequencies are disallowed to propagate (called Photonic Band Gaps) and where the group velocity of modes tends to zero. Experimentally acquiring these plots and relating them to numerical simulation is necessary and complete for a full optical profile of a PC. The present work investigates experimental procedures towards attaining Band Structure Diagrams for two separate 2-D PC lattices of air holes etched in Silicon (Si) as they are conformally coated with TiO<sub>2</sub> in 10 nm steps. Observing the change in the mode profiles between TiO<sub>2</sub> coats allows for a discussion of the viability and usefulness for such a technique in static tuning of PC structures.

## Procedure

Two 2-D crystal lattice structures are examined in this work: a lattice of equal-sized air holes (diameter 270 nm) ion-etched into a Si substrate to form orthogonal rows and columns – called a *square* lattice – and a geometrically-equivalent lattice but of alternating large and small holes (dia = 144 nm; 282 nm), called a *square superlattice*. A homemade Atomic Layer Deposition (ALD) system is used to coat the samples with TiO<sub>2</sub>. For each coat, the samples experience timed pulses of TiCl<sub>4</sub> and H<sub>2</sub>O, separated by N<sub>2</sub> purges, to conformally grow monolayer TiO<sub>2</sub> films. Since the process is self-limiting, the growth is absolutely consistent and restricted to 0.5 Å steps. To acquire Band Structure Diagrams for each crystal lattice, a profile of incident light reflectivity vs. wavelength is first recorded. Samples are placed on a stage under focused white light that is directed through a frequency-controllable fan – called an optical chopper – set at ~155 Hz. The azimuthal angle of the stage with respect to the incident light (denoted  $\Phi$ ) is chosen so the incident wavevector points along one of the crystal's reciprocal lattice vectors, and the polar angle (denoted  $\theta$ ) of the incident light with respect to the stage is variably chosen to provide a host of data points between lattice directions in the Band Structure Diagram. The reflected light passes through a polarized filter and into a fiber-optic line, which is directed to a rotating diffraction grating to dynamically split the light into its constituent wavelengths and their respective intensities, as indicated by voltage pulses. The reflected light is sent to a lock-in analyzer referenced to the optical chopper to admit only voltage pulses at the chopper frequency, thereby filtering-out any noise from different frequency sources as in, say, the wall lights at 60 Hz. After A/D conversion the resulting signal is sent to a computer with a SpectraSense<sup>TM</sup> DAQ program capable of plotting the incoming voltage intensity corresponding to each wavelength. Since the PC's examined are to be used in the

visible – near IR wavelength regime, the program scans 700 nm – 1400 nm in 2nm steps, causing a total processing time for each run of approximately 6 min. The resulting curve differs from a typical interference pattern with the Si/SiO<sub>2</sub> substrate in the

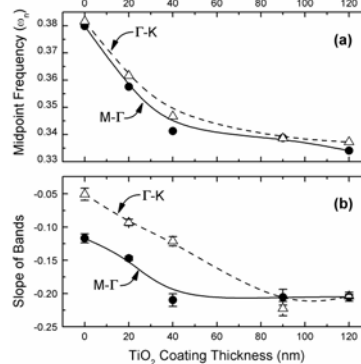


prevalence of sharp dips in reflectivity at particular wavelengths, indicating the coupling of a mode into the Photonic Crystal. Thus, each

sharp dip on these curves corresponds to a point on a crystal's Band Structure Diagram for the particular  $\theta$  and  $\Phi$  under examination, since it indicates a mode being allowed to propagate inside the crystal (i.e. less reflection). A complete collection of curves for all necessary  $\Phi$ , multiple  $\theta$  and both TE/TM polarizations is thus sufficient for a full optical profile of unguided modes in the PC.

## Results and Discussion

For the square lattice, the necessary reciprocal lattice vectors to examine are  $\Phi = 0^\circ, 45^\circ$  and for a large data set,  $12^\circ < \theta < 65^\circ$  in steps of  $5^\circ$  are taken. With both TE/TM modes to examine, this results in  $2(\Phi) \times 12(\theta) \times 2(\text{TE/TM}) = 48$  individual curves to acquire per 10 nm TiO<sub>2</sub> coating. For the supersquare lattice, the necessary reciprocal lattice vectors to examine are  $\Phi = 0^\circ, 26.6^\circ, 45^\circ$  and again,  $12^\circ < \theta < 65^\circ$  in steps of  $5^\circ$ , resulting in  $3(\Phi) \times 12(\theta) \times 2(\text{TE/TM}) = 72$  individual curves to acquire per 10 nm TiO<sub>2</sub> coating. Unfortunately, unforeseen leaking in the ALD system barred the possibility of layering TiO<sub>2</sub> coats on the Si substrate, exempting reflectance curves beyond the ground, uncoated state. Since the principle goal of the experiment is to study band shifts between different coats using ALD, no comparable results are yet available. However, in accordance with results obtained from an identical experiment involving a



triangular lattice of air holes etched in Silicon, band shifts toward lower frequencies and regions of zero group velocity are expected to arise. Using data collected upon revitalization of the ALD system, the exact shifting patterns of the bands for both the square and supersquare lattices will be obtained and utilized as guides

for static tuning of PC's tailored for individual needs.

## Conclusions

The static tuning of basic PC structures is easily within reach using current knowledge of ALD and methods for optical profiling. Collecting the experimental data necessary for the realization of optically tunable devices provides the next steps towards a faster and more efficient future of data transmission.