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Atomic layer deposition (ALD) has become a powerful tool for the fabrication of high quality 3-dimensional photonic crystals (PCs) from both inorganic (opal) and organic (holographically patterned polymer) templates [1,2]. With ALD, highly conformal films can be grown with a precision of 0.05 nm, which, when combined with the availability of a wide range of low temperature film growth protocols, enables a high degree of control over material and structural properties to precisely tune optical properties [3]. Two-dimensional photonic crystals have been developed extensively for applications in optical interconnects, beam steering, and sensor devices; and are predominantly fabricated by electron-beam lithography. The optical properties of 2D photonic crystal slab waveguides are determined by the precision of the lithography process, with limited post fabrication tunability.

Here we report the application of ALD to 2D photonic crystal silicon slab waveguides as a means to precisely tune the dispersion properties of the as-fabricated device. A triangular lattice of air holes in a 300 nm thick single crystal silicon slab, shown in Fig. 1 (lower section), was fabricated on a silicon-on-insulator substrate by e-beam lithography and inductively-coupled-plasma etching. The periodicity of the lattice was 360 nm with a hole radius of 123 nm. The optical properties of the as-fabricated device were characterized with a resonant-coupling reflectance technique [4] along the main PC lattice symmetry directions, Γ -M and Γ -K, over a wavelength range from 700-1700 nm. Amorphous TiO_2 (refractive index of 2.31 at 800 nm) layers were then conformally deposited by ALD at 100 °C in steps of 20 nm (392 cycles at 0.051 nm per cycle) using TiCl_4 and H_2O precursors. The upper section of Fig. 1 shows the same PC after coating with 40 nm of TiO_2 and confirms the conformality and precision of ALD in uniformly reducing the structure hole radii. The device was optically probed between each deposition to monitor the progressive shifts in band structure. 3D finite-difference

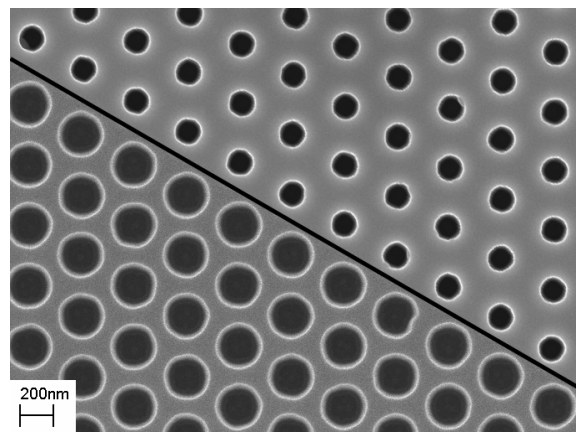


Figure 1. Scanning electron microscope images of a bare triangular lattice PC (lower section) and after being coated with 40 nm of TiO_2 (upper section).

time-domain calculations were performed to model the coated device using a conformally-defined dielectric function to accurately represent the TiO_2 coatings. Figure 2 shows both the experimental data and FDTD calculations along the Γ -K direction for the uncoated (left) and 40 nm TiO_2 coated (right) sample. The arrows in Fig. 2 illustrate the shifts in the measured and also calculated bands from the uncoated to coated sample. The FDTD data are observed to be in excellent agreement with the optical measurements for the lowest band and in very close agreement for all higher bands. As expected, the TiO_2 coating shifts the bands to lower frequency by increasing the average dielectric constant of the device. These results demonstrate a technique capable of simultaneously enabling very large static adjustments ($\sim 20\%$) in the photonic band structure with very high precision ($\sim 0.09\%$ per nm or $\sim 0.004\%$ per ALD cycle). It follows that this simple and unique process, which can be applied to any 2D structure, enables precise control over the optical properties of photonic crystal devices.

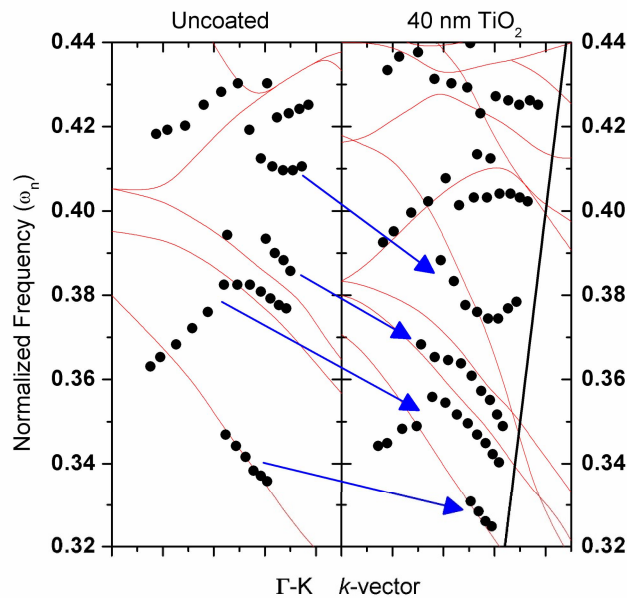


Figure 2. Measured (dots) and FDTD calculations (lines) of photonic band structure in the uncoated (left) and 40 nm TiO_2 coated (right) Si slab waveguide.

In summary, we have demonstrated a technique in which the photonic bands of two-dimensional triangular lattice photonic crystal slab waveguides can be statically tuned by nanoscale modifications, thereby enabling unprecedented adjustment to the dispersion properties of any 2D photonic crystal. Additionally, the technique facilitates the formation of layered and composite 2D PC waveguides thus opening new fabrication routes to control dispersion, propagation and dielectric contrast.

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