Tunable ferroelectric photonic crystals using epitaxial barium titanate thin films as the nonlinear medium

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Proposal Title: CNM-292 Fabrication of nano electro-optic devices on epitaxial Barium Titanate thin films

Research Achievement: The optical properties of two dimensional photonic crystal (PhC) were investigated using ferroelectric barium titanate (BTO) thin films. BTO is a promising non-linear electro-optic (E-O) material with a high E-O coefficient and fast response time. Beyond its application in the optical communication, BTO has the potential to replace current semiconductor processors, which are limited by their speed and high energy consumption. To utilize BTO as a micron scale device for their enhancement of E-O coefficient is required. This can be achieved by using "slow light" effects observed in PhC structures. In this project the PhC structure was fabricated by ion milling using a dual beam focused ion beam (FIB). Because BTO is a chemically inert and mechanically hard material, conventional wet etching is not practicable for its nano patterning.

Highly uniformed PhC structures were fabricated and imaged by scanning electron microscopy (SEM). Fig. 1 (a) shows the top surface of a PhC consisting of a square array of air holes. The lattice constant is 450 nm. The black circles are the milled air holes and the gray area is the BTO dielectric stack. From the cross sectional view in Fig. 1 (b), the hole depth from is 450 nm where the hole diameter at the opening is 250 nm and 220 nm at the bottom. Hence an aspect ratio greater than two is achieved. The hole is slightly wider at the opening due to the ion beam having a Gaussian beam profile. Nevertheless there is minimal stigmatism in the focused ion beam optics since there is no distortion of the circular air hole. The photonic band structure of fabricated PhC shown in Fig. 1 (c) is calculated by 2-D finite difference time domain (FDTD) method. The vertical green lines indicate the photonic band gaps at X and M points. The calculation is along the Γ-X and M- Γ which are <1 0> and <1 1> directions in k space, respectively. From Fig. 1 (c) the gap is wider at the X point than the M point. The broad band gaps tell the BTO PhC has a broad bandwidth which is attributed to the high refractive index contrast between BTO and air.

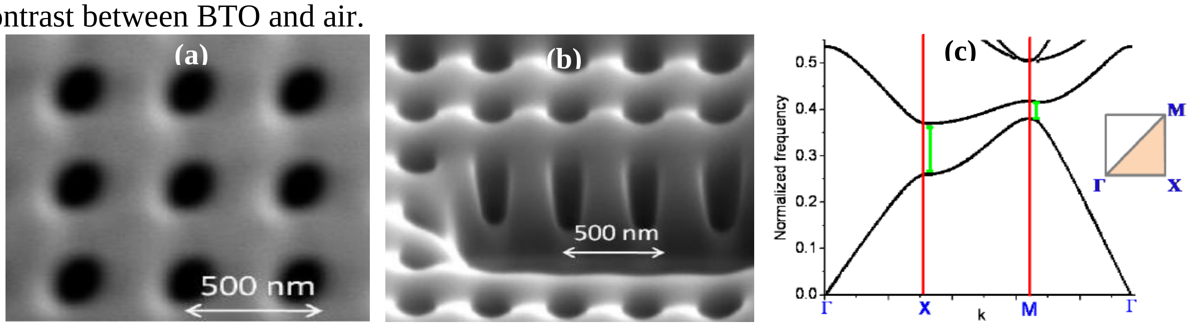

Figure 1

Optical diffraction patterns were analyzed to determine the symmetry of the PhC structure. A 3 dB modulation of light intensity is demonstrated from its thermo-optical response. Fig. 2 (a) shows the transmission diffraction pattern using a multiple wavelengths argon ion laser. The spots in Fig. 2 (a) represent 1st order diffraction. The pattern has diffraction along the [1 0] and [1 1] symmetry directions as would be expected for a PhC with square lattice symmetry. The bright diffraction spots result from a very small patterned area. That indicates the PhC has a very high spatial uniformity. The thermo-optical response of the BTO PhC is shown in Fig. 2 (b). The normalized 1st order diffraction efficiency η decreases from 2.1 to 1 when temperature increases from 30°C to 150°C. No variation of the diffraction angle θ is found during the heating or cooling process. This indicates the thermal response is solely attributed to the temperature dependence of n_{BTO}; no thermal expansion of PhC lattice parameter is involved. The observed thermo-optical effect can be applied in the tuning of the photonic band gap. The PhC spectrum shifts if there is a change of n_{BTO}. From the FDTD calculation heating to 120°C leads to a 57 nm red shift of the band structure. Strong light scattering from the BTO PhC is also observed as shown in fig. 2 (c). The light is coupled to the PhC cavity through the waveguide edge. The bright rectangle at the right of the image is the scattering light from PhC and it indicates the light is highly localized within the PhC cavity. The scattering light intensity is proportional to the degree of light localization. The strong light confinement can significantly enhance the optical nonlinearity of the BTO thin films, potentially leading to ultra compact photonic devices.

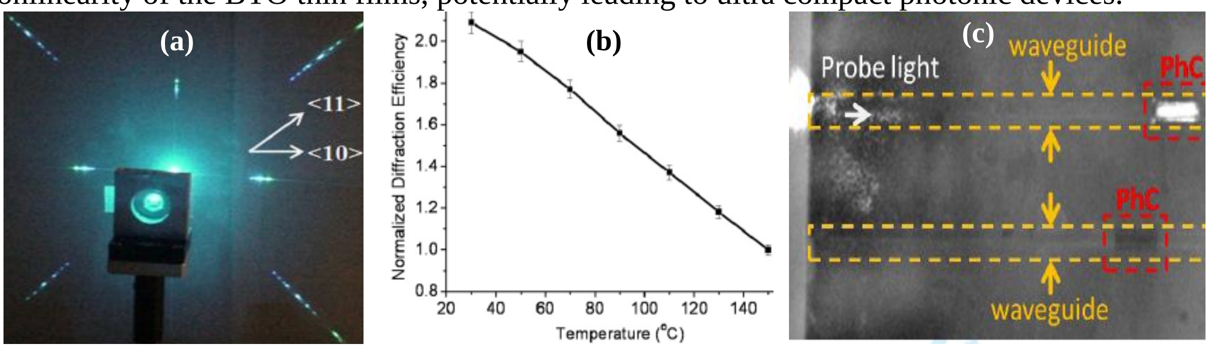

Figure 2

Future Work: CNM-827 Fabrication of integrated nano-photonic circuits on epitaxial barium titanate thin films

Further work is directed toward tunable 2-D photonic circuits. E-O devices having fabricated PhCs can be potentially used in a low V-pi waveguide modulator, slow light buffer, tunable filters, and high Q resonators. We are interested in photonic circuit fabrication using non-linear optical materials such as BTO thin films. BTO has low absorption constant in both IR and visible range. Furthermore BTO has a large E-O coefficient and exhibits broad band second harmonic generation.

The proposed nonlinear optic circuits are composed of micro-rings and photonic crystals which have a sharp transmission line and a well defined photonic band structure. The optic circuits can be generated by high resolution FIB and laser writing techniques. The device tunability is characterized by measuring the shifting of the resonant frequency with bias. The device performance is evaluated by comparing the experiments with the FDTD simulation. Successful completion of the project would lead to new generation of integrated and tunable non-linear photonic devices and circuits.

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Publications: **1.** "Two dimensional ferroelectric photonic crystal waveguides: simulation, fabrication, and optical characterization," *J. Lightwave Tech.* (2009) **2.** "Thin film ferroelectric photonic crystals and their application to thermo-optic switches," Opt. Commun. (2009) **3.** "Ferroelectric thin film photonic crystal waveguide and its electro-optic properties," *J. Opt. A: Pure Appl. Opt.* (2009) **4.** "Cascaded Bragg Reflectors for Barium titanate Thin Film Electro-optic Modulator," *J. Opt. A: Pure Appl. Opt.* 10 015302 (2008) **5.** "Non-linear Photonic Crystal Waveguide Structures Based on Barium Titanate Thin Films and their Optical Properties," *Appl. Phys. Lett.* 90, 201104 (2007)