Extreme Light-Bending and Trapping with a Simple Cubic Optical Photonic Crystal

CNF Project Number: 2173-12

Principal Investigator: Shawn-Yu Lin

Users: Brian Frey, Alex Kaiser

Affiliation: Department of Physics, Rensselaer Polytechnic Institute, Troy, NY 12180

Primary Source of Research Funding: United States Department of Energy, Office of Science, Basic Energy Sciences

Contact: sylin@rpi.edu, freyb3@rpi.edu, kaisea2@rpi.edu

Primary CNF Tools Used: PVD75 sputter deposition, AJA sputter deposition, ASML deep-ultraviolet stepper, Oxford reactive-ion-etcher, Trion inductively-coupled plasma etcher, GSI PECVD tool, Orbis chemical-mechanical polisher, Zeiss scanning electron microscope, Veeco atomic force microscope, CVC electron-beam evaporator

Abstract:

A sub-micron TiO_2 simple cubic photonic crystal with lattice constant 450 nm was fabricated and used to characterize a newly-discovered light-bending mechanism wherein the Poynting vector lies nearly parallel to the photonic crystal interface. Absorption enhancement approaching 100 times was observed compared to a reference TiO_2 film. Several enhancement peaks in the region from 600-950 nm wavelength far exceed both the ergodic and square surface-grating light-trapping limits. These results can be applied to any future light trapping applications such as phosphor-converted white light generation, water-splitting, or thin-film solar cells, where increased response in areas of weak absorption is desired.

Summary of Research:

In several areas of opto-electronics, the efficient conversion of light into useful energy is paramount. Typically, performance is limited by different factors, such as weak near-infrared absorption (crystalline silicon [1]), or charge diffusion length (amorphous silicon [2]). To circumvent these limitations while addressing cost [3], and efficiency concerns [4], it is beneficial to engineer structures that can alter the optical-path-length through these devices without using more material. This is referred to as "light trapping" [5].

In this research, we identify a precise light-trapping mechanism, which is due to photonic crystal (PC) refraction. This effect, called parallel-to-interface refraction (PIR), extends the path-length by orders of magnitude by coupling light into modes for which the Poynting vector lies nearly parallel to the PC interface [5,6]. Accordingly, we have constructed a simple cubic PC from weakly-absorbing TiO_2 to demonstrate orders-of-magnitude enhancement over a reference TiO_2 film. The conclusions that follow are general and not restricted to any material.

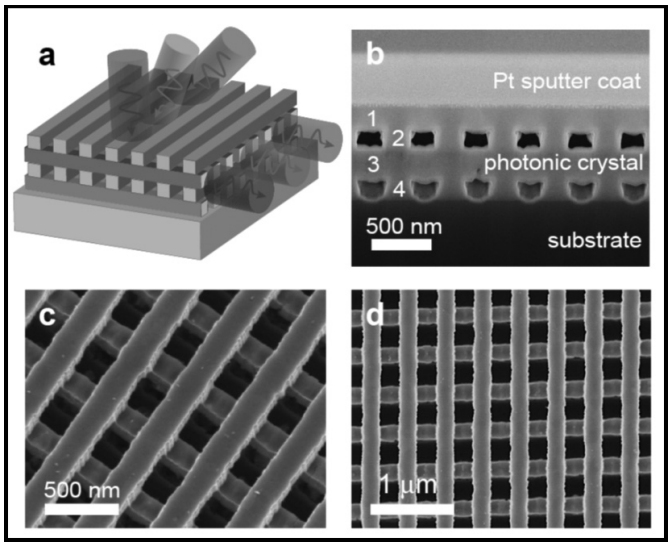

Figure 1: Schematic of a TiO_2 simple cubic photonic crystal. (a) Schematic of TiO_2 PC depicting parallel-to-interface refraction. (b) Cross-section side view, (c) perspective view, and (d) top-view pictures of fabricated TiO_2 PC.

The structure used for this study, depicted in Figure 1.a, is a stacked, 4-layer TiO_2 simple cubic PC [7]. It was fabricated with photolithography and etch steps in a layer-by-layer process using the ASML deep-ultraviolet stepper and Oxford reactive ion etcher. A complete description of the fabrication process is described elsewhere [8], but the results are summarized in Figure 1.

To investigate PIR, we measured the absorption of our PC, which is plotted in Figure 2. The absorption of a

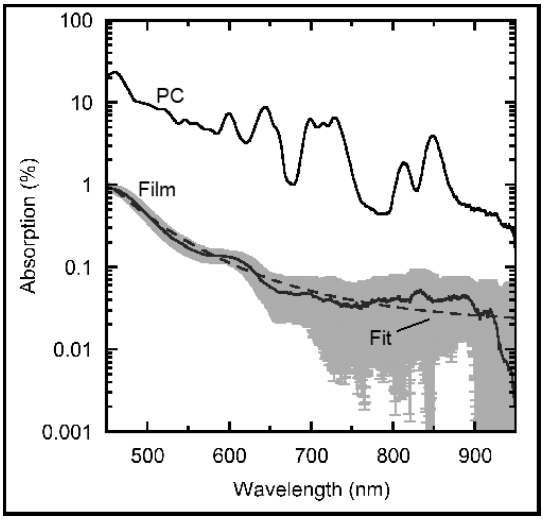

Figure 2: Absorption spectra for PC and reference film.

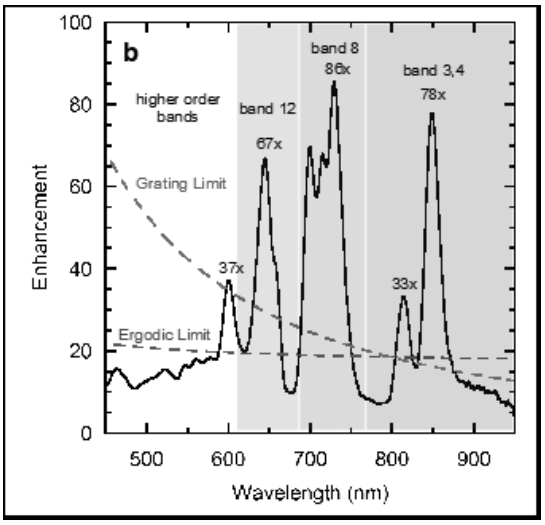

Figure 3: Absorption enhancement for PC. Also shown are the lines for the ergodic limit and 2D grating limit.

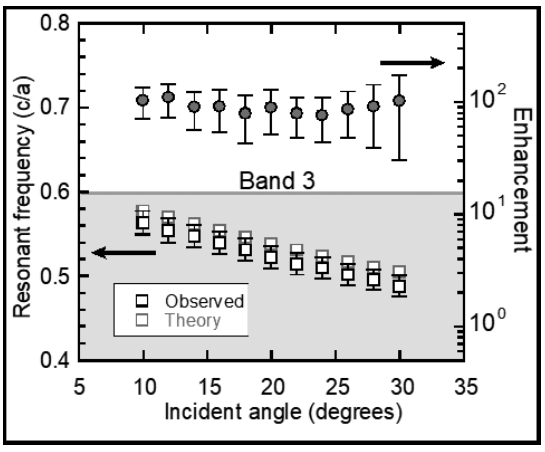

Figure 4: Absorption peak frequency and peak enhancement vs. incident angle for band 3. Filled circles are measured enhancement at the peak frequency. The bounded box shows the frequency range for band 3.

reference TiO_2 planar film of comparable thickness is also shown for comparison. Figure 2 shows that the film absorption below the bandgap is less than 1% and decays exponentially. Notably, in the range from 600-800 nm, the PC shows a series of absorption peaks that approach 10%, while the film absorption is < 0.1%. Also, a pair of peaks observed for the PC between 800-900 nm with max values of ~ 2-4%; here the film shows ~ 0.03% absorption.

In Figure 3, the enhancement factor η, defined as the ratio of the PC and film absorption values, is plotted as a function of wavelength. Here, the doublet of peaks observed at longer wavelengths corresponds to η ~ 30 and 80 times, respectively. The maximum enhancement for peaks in the mid-wavelength region is close to 100 times. These peaks also surpass, by multiple times, two theoretical limits also shown for comparison: one is the ergodic limit of $4n^2$ [9], and the other is based on a square surface-grating architecture [10]. To show that this is attributable to PIR, the angular dependence of the resonant frequencies for the band 3 absorption peaks is shown in Figure 4. The data not only agree well with the predicted PIR frequencies from theory, but there is a one-to-one correspondence between theory and observation and the scaling of the resonant frequency with θ_0 is virtually identical. Furthermore, the peak enhancement is approximately angle-independent at η ~ 100 times. The data experimentally validate PIR and provide direct proof of its contribution to absorption enhancement in a simple cubic PC.

PIR provides an opportunity to use simple cubic PCs as an ordered, three-dimensional network that refracts light according to the dispersion relation. This approach to absorption enhancement is amenable to infiltration by various agents, such as dyes, polymers, and nanophosphors, and is also suitable for investigating PC-induced light emission enhancement. We anticipate that the scope of these results will extend beyond thin-film solar cells to other applications, like phosphor conversion in light-emitting diodes, and water-splitting.

References:

[1] Redfield, D. Multiple-pass thin-film silicon solar cell. Appl. Phys. Lett. 25, 647-648 (1974).

[2] Carlson, D. E., and Wronski, C. R. Amorphous silicon solar cell. Appl. Phys. Lett. 28, 671-673 (1976).

[3] Shah, A., Torres, P., Tscharner, R., Wyrsch, N., and Keppner, H. Photovoltaic technology: the case for thin-film solar cells. Science 285, 692-698 (1999).

[4] Vetterl, O., et al. Thickness dependence of microcrystalline silicon solar cell properties. Sol. Energ. Mat. Sol. 66, 345-351 (2001).

[5] Chutinan, A., and John, S. Light trapping and absorption optimization in certain thin-film photonic crystal architectures. Phys. Rev. A 78, 023825 (2008).

[6] Kuang, P., Deinega, A., Hsieh, M. L., John, S., and Lin, S. Y. Light trapping and near unity solar absorption in a three-dimensional photonic-crystal. Opt. Lett. 38, 4200-4203 (2013).

[7] Frey, B. J., et al. Effectively infinite optical pathlength created using a simple cubic photonic crystal for extreme light trapping. Sci. Rep. 7, 4171 (2017).

[8] Frey, B. J., Kuang, P., Lin, S. Y., Jiang, J. H., and John, S. Large area fabrication of a simple cubic metal-oxide photonic crystal for light trapping applications. J. Vac. Sci. Technol. B 33, 021804 (2015).

[9] Yablonovitch, E. Statistical ray optics. J. Opt. Soc. Am. 72, 899-907 (1982).

[10] Yu, Z., Raman, A., and Fan, S. Fundamental limit of light trapping in grating structures. Opt. Express 18, A366-A380 (2010).