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Novel phenomena in macroscopic photonic crystals

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ABSTRACT

Photonic crystals provide superb opportunities for tailoring of the photonic density of states. This ability can in turn be explored to control radiation into far-field, enhance fluorescent light emission, as well as optimize laser emission. In order to make these phenomena useful for large macroscopic devices, large-area nano-fabrication techniques have to be successfully implemented. In this talk, I will present some of our recent theoretical and experimental progress in exploring these opportunities.

Keywords: Photonic Crystals, Fano states, Surface emitting lasers

1. INTRODUCTION

Photonic crystal (PhC) slabs have been widely used in the experimental study of light manipulation by sub-wavelength structures, largely due to their relative simple fabrication process and the ability to intimately integrate them with other on-chip devices. Defects were introduced to form resonances, demonstrating intriguing lasing behavior and cavity quantum electrodynamics phenomena, owing to the strong confinement of light in small volumes with high quality factors. Uniform PhC slabs have been monolithically integrated on top of light emitting devices to enhance the extraction of light while similar structures have been used to reshape the emission of thermal sources. These structures have recently been shown theoretically to allow for low threshold laser operation due to the high quality factor dark Fano resonances they support: here, we show experimental realizations of these promising phenomena.

2. OBSERVATION OF HIGH-Q FANO RESONANCES IN MACROSCOPIC PHOTONIC CRYSTAL SLABS

Although this has been shown to be theoretically possible, experimental observation of high-Q Fano resonances over macroscopically large areas has eluded researchers due to structural perturbation inherent to fabricated structures. The physical origin of Fano resonances in PhC slabs lies in the coupling between the guided modes supported by the slabs and external plane waves. This coupling is due to Bragg diffraction that occurs because of the periodic modulation of the dielectric constant. Remarkably, in the case of perfect infinite periodic PhC slab, due to symmetry considerations, some of the Fano resonances are completely decoupled from the external world. Therefore, in a perfect structure, the radiative quality factor (Q_{rad}) theoretically becomes infinite despite lying above the light line, and hence its radiation losses into the far-field vanish. In practical structures however, in addition to limits imposed by material absorption, fabrication imperfections partially break the symmetry which results in coupling of those Fano resonances to radiating modes, hence limiting their maximal attainable Q_{tot} . Moreover, while the existence of Fano resonances in a uniform PhC slab is due to the nano-structured periodic dielectric profile, the mode itself needs to extend over a macroscopic area in order to support ultra-high Q_{tot} , posing a significant fabrication challenge. Here, we experimentally demonstrate the existence of Fano resonances for visible wavelengths in a PhC slab (Figure 2), fabricated using interference lithography (Figure 1) over macroscopic area ($\sim \text{cm}^2$) and exhibiting Q_{tot} as high as 10^4 (Figure 3). We confirm numerically and via symmetry arguments that for modes with k vector normal to the PhC plane (Γ point) the radiative lifetimes of some modes of an ideal structure can be infinite. Through angle resolved spectral measurements, we display the behavior of these modes in k -space, close to the Γ point where large Q_{rad} occur. Using temporal coupled-mode theory (Figure 4) we study the measured Fano line shapes and discuss the effect of the change in the mode symmetries away from the Γ point on the lifetimes of these resonances.

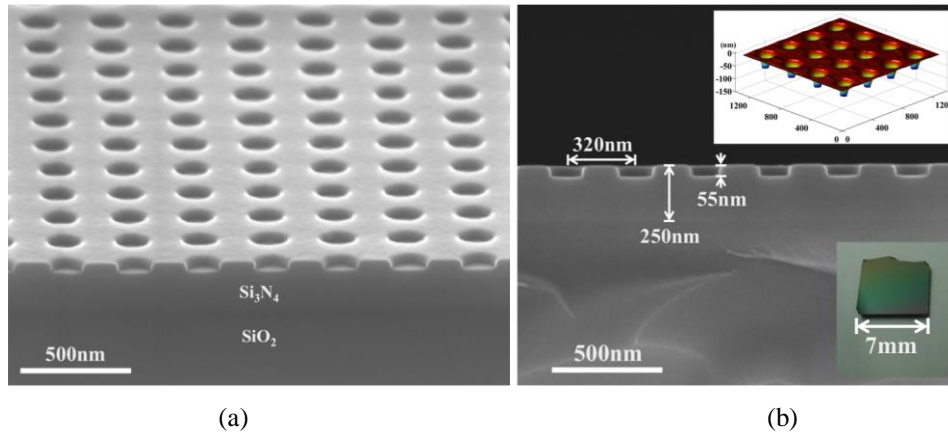


Figure 1. (a) Tilt-view SEM of the fabricated PhC. This uniform pattern was produced over the entire area of the sample. (b) Side-view SEM of the same PhC. The top layer is the 250 nm Si_3N_4 layer with periodic 55 nm deep cylindrical air holes, and the underlying layer is the 5 μm thick SiO_2 layer. RIE produced a vertical and clear sidewall profile. The average period of the pattern is 320 nm, the average hole diameter is 160 nm, and the average hole depth is 55 nm. Top inset: Image obtained from AFM analysis. Bottom inset: Image of the large sample.

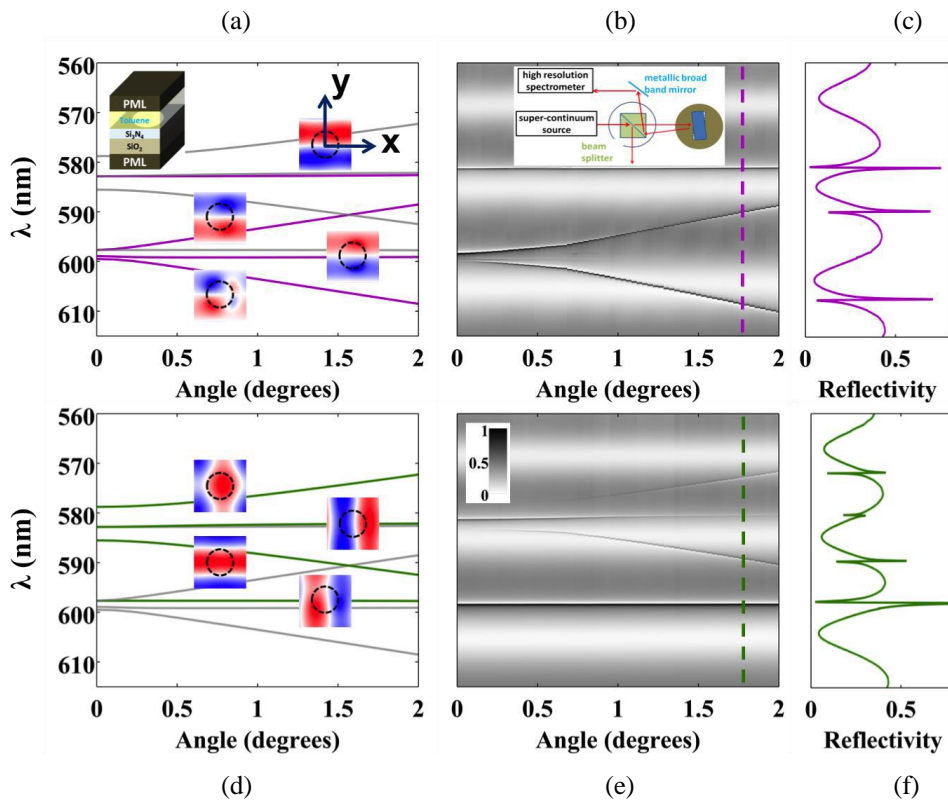


Figure 2. (a),(d) Band diagram of the eight lowest energy leaky modes (measured at the Γ point) of the PhC obtained from finite difference time domain (FDTD) simulation. Modes excited externally by odd (even) polarized source with respect to the x -axis are colored purple (green) and their E_z field profiles at the center of the Si_3N_4 layer at $k = (0.01, 0) \cdot (2\pi/a)$ are shown, other modes are colored gray. Contour of the hole is shown with black dashed circle. The inset depicts a schematic of the unit computational cell used in the simulation. (b),(e) Reflectivity measurements of the PhC with E_y (E_x) polarized beam. The Inset shows a schematic of the experimental setup. (c),(f) A slice of the reflectivity measurement results at 1.8° .

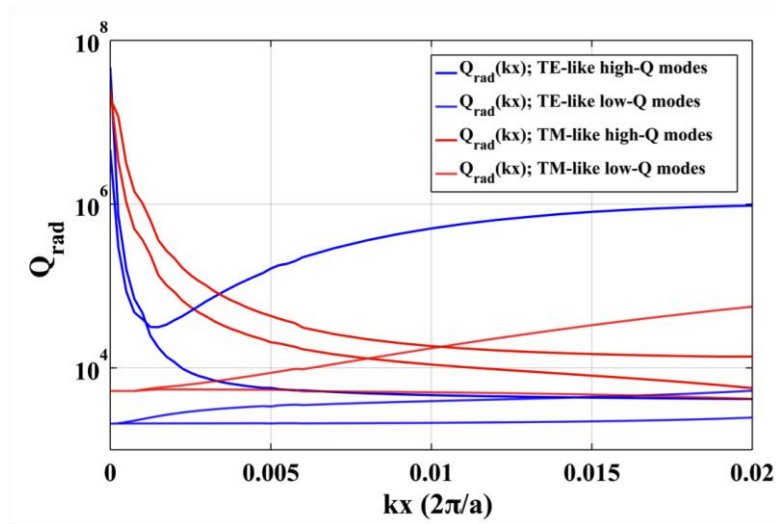


Figure 3. Simulation results for radiative quality factors of different modes are shown with respect to different k_x between 0 and $0.02 \cdot (2\pi/a)$. The two TE-like high-Q modes are plotted with blue solid lines, while the two TE-like low-Q modes, which are doubly degenerate modes at Γ point, are shown with blue dotted lines. The two TM-like high-Q modes are shown with red solid lines, while the two TM-like low-Q modes are shown with red dotted lines.

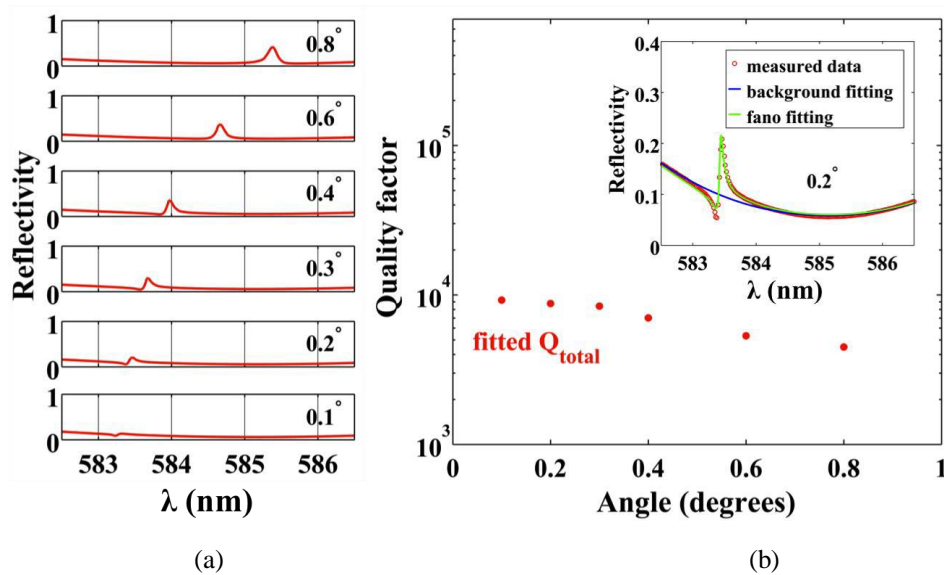


Figure 4: (a) The reflectivity spectra of the sample's lower frequency TM-like high Q_{rad} mode measured at a range of angles of 0.1° to 0.8° from the normal of the PhC slab. (b) Q_{tot} (red solid dots) retrieved by fitting to the measured data in (a). Inset shows an example of the curve fitting process applied on the data measured at 0.2° shown in (a). A good match between the fitted lineshape (green line) and measured data (red dots) is attained.

3. ENABLING ENHANCED EMISSION AND LOW THRESHOLD LASING OF ORGANIC MOLECULES USING SPECIAL FANO RESONANCES OF MACROSCOPIC PHOTONIC CRYSTALS

The nature of light interaction with matter can be dramatically altered in optical cavities, often inducing non-classical behavior. In solid state systems, excitons need to be spatially incorporated within nanostructured cavities to achieve such behavior. While fascinating phenomena have been observed with inorganic nanostructures, the incorporation of organic molecules into the typically inorganic cavity is more challenging. Here we present a novel optofluidic platform comprising organic molecules in solution suspended on a photonic crystal surface (Figure 5), which supports macroscopic Fano resonances and allows strong and tunable interactions with the molecules anywhere along the surface. We develop a theoretical framework of this system and present a rigorous comparison with experimental measurements showing dramatic spectral and angular enhancement of emission (Figure 6&7). We then demonstrate that these enhancement mechanisms enable lasing of only 100nm thin layer of diluted organic molecules solution with substantially reduced threshold intensity (Figure 8), which has important implications to organic light emitting devices and molecular sensing.

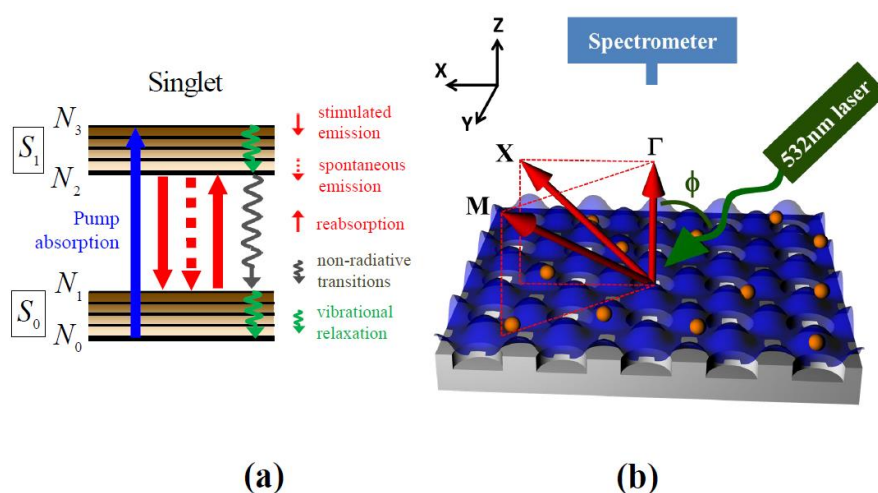


Figure 5: Optofluidic platform of organic molecules coupled to Fano resonances of the macroscopic photonic crystal. (a) Schematic drawing of the two lowest singlet energy levels of a dye molecule and transitions it undergoes during fluorescence emission. (b) Schematic drawing of the experimental setup of the angle-resolved fluorescence measurements of Rhodamine 6G (R6G) dissolved in methanol at 1 mM concentration placed on top of the PhC. The grey substrate is the macroscopic PhC slab. The orange spheres are schematic drawings of the R6G molecules in solution. The blue surface represents the equal energy density surface of the Fano resonance. Fluorescence spectra of the organic solution for both cases were recorded using a high-resolution spectrometer placed close to the normal of the PhC. By tuning the position of the spectrometer, fluorescence spectra of the molecules along Γ to X and Γ to M were measured.

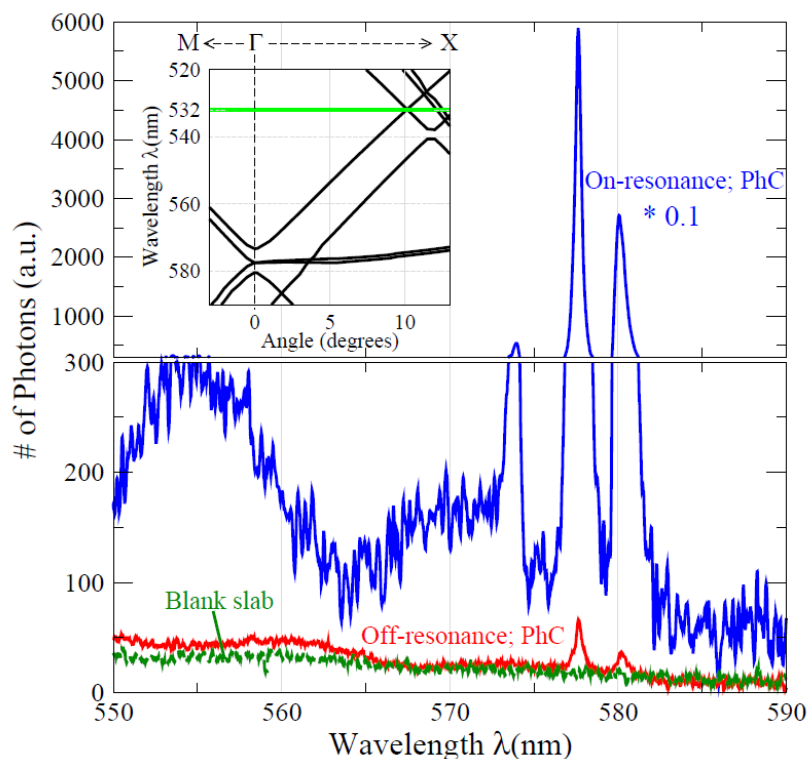


Figure 6: Significantly enhanced fluorescence emission from R6G molecules. Comparison of fluorescence spectra of R6G molecules measured in the normal direction, along on the PhC (solid lines) both pumped on-resonance (blue) and off-resonance (red) as well as on a uniform unpatterned slab (dashed green line). By comparing the spectra, we obtain the excitation, extraction, and total enhancement factors, which are compared with the theoretical predictions. The inset of the figure shows FDTD calculation results of the band structure from which the incident angle for on-resonance coupling is determined ($\phi_{\text{the}}=10.0^\circ$), showing a good agreement with the experiment ($\phi_{\text{exp}}=10.02^\circ$).

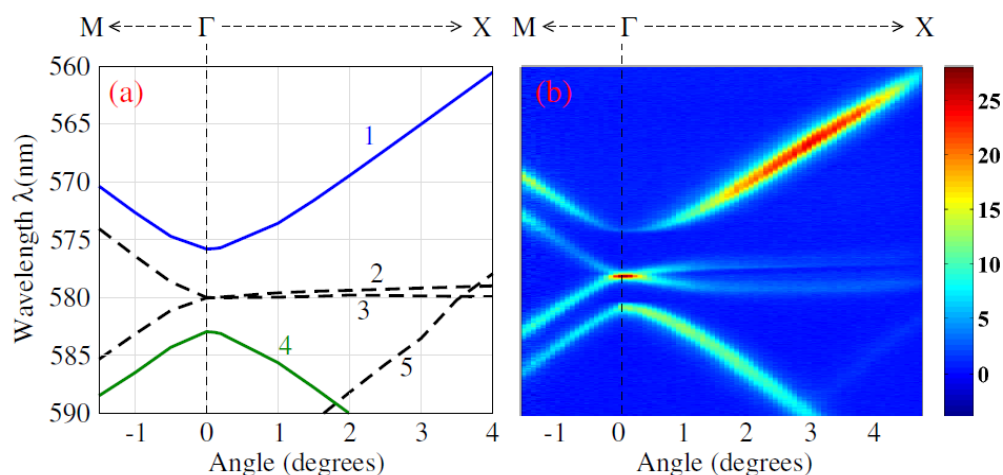


Figure 7: Comparison between theoretical model and experimental results of the enhancement mechanisms. (a) The band structure of the PhC along Γ to M and Γ to X directions. (b) Angle-resolved fluorescence measurements of R6G solution suspended on top of the PhC. The correspondence between the color and number of photons (arbitrary units) is given in the color bar on the side.

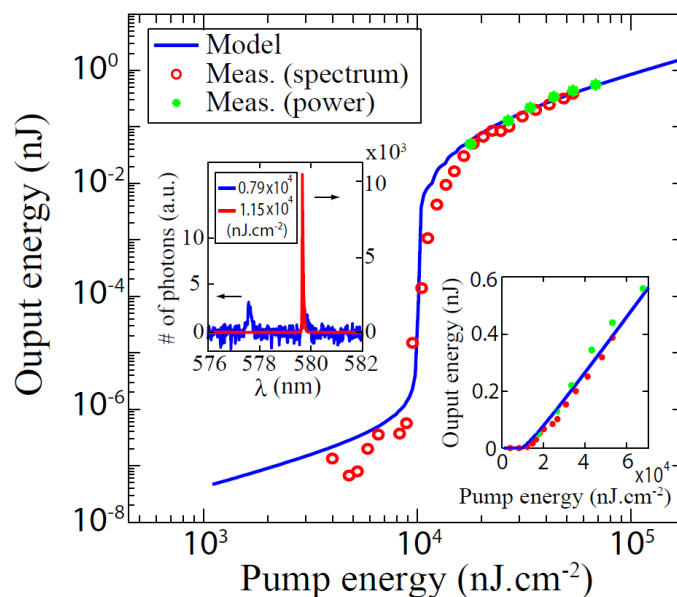


Figure 8: Low threshold lasing of 100 nm thin layer of R6G molecules in solution. Input-output energy characteristics of lasing through mode 4 in Figure 7a (580 nm) under pulsed excitation. The solid lines are analytic predictions from our lasing model while red circles are energies measured using the spectrometer. Green circles are data measured with a power meter. The jump in output power clearly indicates the onset of lasing. The lower inset shows the same results in linear scale, where the output grows linearly with the pump energy beyond threshold. Top inset is the measured power spectrum of emission from the PhC slab at normal incidence below (blue) and above (red) the lasing threshold. Single-mode lasing is attained at approximately $9 \mu\text{J}/\text{cm}^2$ (corresponding to the intensity of $1.8 \text{ kW}/\text{cm}^2$).

REFERENCES

- [1] Jeongwon Lee, Bo Zhen, Song-Liang Chua, Wenjun Qiu, John D. Joannopoulos, Marin Soljacic, and Ofer Shapira. *Phys. Rev. Lett.* **109**, 067401, (2012).
- [2] “Enabling Enhanced Emission and Low Threshold Lasing of Organic Molecules Using Special Fano Resonances of Macroscopic Photonic Crystals” Bo Zhen, Song-Liang Chua, Jeongwon Lee, Alejandro W. Rodriguez, Xiangdong Liang, Steven G. Johnson, John D. Joannopoulos, Marin Soljacic, and Ofer Shapira. *PNAS*, in press.