Fabrication of Nanoparticles Deposited Photonic Crystals

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The negative refraction in a photonic crystals (PC) [1] is due to the band folding effect of a strongly modulated PC, which leads to a negatively sloped dispersion curve, e.g. negative group velocity with $k \cdot \partial\omega/\partial k < 0$ for a range of frequencies. However, a negative index PC cannot fulfill light confinement alone because light diverges after self-focusing. Super lattice Bragg media of both negative and positive refraction index can confine light in collimation [2] or resonance [3] in the near infrared (NIR) spectral region. Visualizing such confinement at technologically relevant wavelengths, however, is difficult due to the precise setup with NIR camera. Here, we present the use of upconversion nanoparticles ($NaYF_4$:Yb^{3+}, Er^{3+}), to enable the visualization of NIR light propagation in PC waveguide with conventional optical microscopy.

We report two metamaterial structures composed of positive and negative index media. One is "zebra" structure with periodic arrangement of negative index PC and positive index air in alternation; another one is triangle resonator with equal-lateral triangles composed of negative index PC and positive index air. The negative index (n=-1) 2D silicon-based PC is comprised of air holes arranged in a hexagonal lattice when the ratio of hole radius *r* (180nm) and lattice parameter *a* (470 nm) is 0.38 at the normalized 1.55 µm wavelength. The simulations of light propagation in 1.55µm wavelength confined in the structure are shown in Fig. 1(a, b). The sample was fabricated on silicon-on-insulator (SOI) wafer with a 1.5 µm silicon layer on top of 1 µm oxide providing vertical light confinement. The fabrication diagrams, as shown in Fig. 2, include e-beam lithography, inductively coupled plasma (ICP) etching, and nanoparticle deposition. The process flow is as follows: (1) The SOI wafers were coated by e-beam resist Zep 520A, and patterned by Vistec VB300 e-beam lithography; (2) Oxford PlasmaPro System100 was used to etch Si on SOI in low temperature with mixed gas SF_6 and O_2 and a high aspect etching ratio 15:1 is achieved, as shown in Fig. 3 (a, b, c); (3) Upconversion nanoparticles ($NaYF_4$: 20% Yb^{3+}, 2% Er^{3+})[4] were

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[1] M. Notomi, Phys. Rev. B, **62**, 10696 (2000)
[2] V. Mocella, S. Cabrini, *et al.* Phys. Rev. Lett., **102**, 133902 (2009)
[3] S. A. Ramakrisha, *et al*., Phys. Rev. A, **75**, 063830 (2007)
[4] J. C. Boyer, F. Vetrone, L. A. Cuccia, and J. A. Capobianco, J. AM. CHEM. SOC., **128**, 7444-7445 (2006)

deposited in the voids of the PC samples. These particles upconvert 1.55 µm radiation to 800 nm and 480 nm due to two-photon absorption and four-photon absorption respectively, thus enabling the visualization also in the visible range of the propagation of NIR radiation when deposited in the PC structures (Fig. 3 d, e, f).

In conclusion, we report the fabrication and optical characterization of high aspect ratio photonic crystals embedded with upconverting nanoparticles.

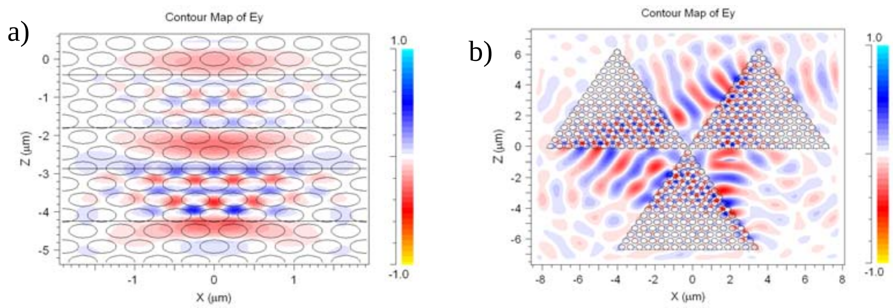

Figure 1: Devices Simulation: (a) Light collimation in zebra structure and (b) light resonance in triangle resonator in 1.55 µm wavelength.

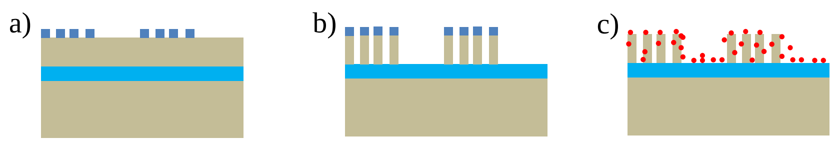

Figure 2: Fabrication Diagram: (a) E-beam lithography, (b) cryo Si etching, and (c) nanoparticles deposition.

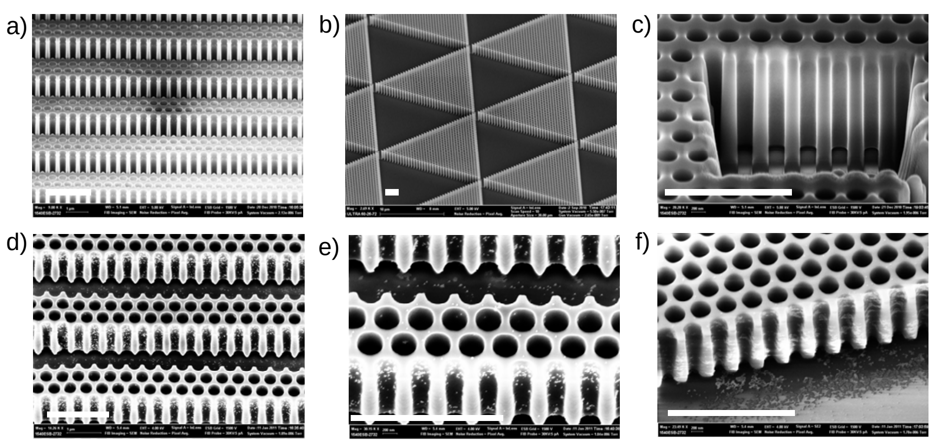

Figure 3: Fabrication Process: SEM pictures of (a) 30° view of cryo Si etching zebra structure, (b) 30° view of cryo Si etching triangle resonator, (c) 54° view of high aspect ratio Si etching PC on SOI wafer by FIB milling, nanoparticles $NaYF_4$ (20%Yb^{3+}, 2%Er^{3+}) deposition on (d) zebra structure and (e) large magnification of zebra structure, and (f) large magnification nanoparticles in triangle resonator. The scale bar is 2 µm.