Construction of Photonic Crystal Defects by Combined Self-Assembly and Nanorobotic Manipulation

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Abstract — This paper presents the construction of engineered photonic defects through a combined use of chemistry-based self-assembly and SEM-based nanorobotic pick-and-place of submicron spheres. A carbon nanotube forest is used as a substrate to decrease the particle-substrate adhesion and to facilitate sphere manipulation. Finite-difference time domain simulations of the resonant response of a defect placed in this manner predict localized defect states at frequencies associated with the complete photonic band gap of the bulk crystal. The approach of combined self-assembly and nanorobotic manipulation permits development of unique photonic devices.

The capability of manoeuvring nanometer-scaled objects into pre-defined positions is essential for nanodevice construction. Applications include the precise positioning of nanotubes and nanowires to construct nanoelectromechanical systems (NEMS), manipulation of quantum dots to build nano electronics, and characterization of electromechanical properties of nanomaterials. The application under our investigation is the construction of photonic crystals (PCs), a class of dielectric materials with a one-, two-, or three-dimensional periodic variation in refractive index [1]. Defects in photonic crystals can be engineered to guide the propagation of light, allowing the design of compact, low-loss photonic waveguides and integrated optical circuit elements (e.g., photonic switches).

Nanorobotic manipulation has been demonstrated for forming a three-dimensional PC by serially placing submicron particles into a regular lattice [2]. Instead, this paper presents a nanomanipulation strategy that combines SEM-based nanorobotic manipulation and chemistry-based self-assembly, which allows the photonic properties of self-assembled PC films to be precisely engineered by the inclusion of defects of various sizes and materials. Nanorobotic manipulation allows the incorporation of structural defects that go beyond the resolution limits of optical lithography techniques, and also permits the inclusion of impurity sites with properties that differ from that of the bulk crystal, such as luminescence or chemical functionality.

The manipulation of submicron particles requires some degree of control over surface and adhesion forces, particularly under irradiation of the SEM electron beam [3]. Multi-walled carbon nanotube forests (MWCNTFs) have been demonstrated as an effective substrate for reducing the particle static friction in the SEM environment [4]. In our study, polystyrene spheres dispersed on MWCNTF substrate served as a defect pool during nanomanipulation. The MWCNTF facilitated the operation of picking up individual spheres and transferring them one at a time onto the self-assembled PC substrate, both by reducing the particle stiction to ease the picking up of defect spheres, and by providing a mechanically flexible surface which prolonged the usable life of the probe tips.

Evaporation-induced self-assembly of spherical colloidal silica spheres of diameter 500nm was conducted to grow ordered planar films in a close-packed face-centered cubic lattice. Polystyrene spheres of 300nm dispersed in ethanol were deposited on a MWCNTF substrate (Fig. 1). The self-assembled colloidal crystal film and the MWCNTF substrate were placed together inside an SEM, where a piezoelectric nanomanipulator was used to pick up a single polymer particle, transfer it onto the [111] surface of the f.c.c. colloidal crystal film, and place the sphere at a desired location (Fig. 2). A second regrowth of colloidal silica particles was conducted to encapsulate the polymer defects inside the colloidal crystal lattice. A subsequent O₂ plasma etch removed the polystyrene sphere, leaving behind a vacancy in the three-dimensional photonic crystal.

A colloidal crystal film with engineered defects, such as the one shown in (Fig. 2(f)), can serve as a template for the fabrication of an inverted structure of air spheres in high-index material such as silicon [5]. Finite-difference time domain simulations of the resonant response of such a point defect in the inverse structure were performed (Fig. 3), which reveal that the structure features a complete photonic band gap between the eighth and ninth bands (Fig. 4). The results predict highly resonant behavior at frequencies associated with the complete photonic band gap of the inverse silicon structure, indicating highly-localized photonic states trapped at the defect site.

The pick-and-place process shown in Fig. 2 can be repeated to flexibly create various defect patterns with defects of different sizes and materials (Fig. 5). A chain of such resonators built up one at a time with our technique can act as an efficient coupled-cavity waveguide with a high single-mode bandwidth [6]. Furthermore, nonlinear substances (e.g., Kerr effect materials for electro-optic switching or luminescent particles for optical gain) can also be precisely placed into the crystal structure using this method. In this way, more complex structures can be built, opening the door to novel experimental studies and the development of new types of photonic crystal devices.

REFERENCES

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Fig. 1. SEM image of a MWCNT forest seeded with 330nm polystyrene spheres.

Fig. 2. Nanorobotic manipulation sequence. (a) probe approaching MWCNTF; (b) pickup of a 330nm polystyrene sphere; (c) defect sphere attached to probe; (d) approaching self-assembled colloidal crystal; (e) defect placement; (f) defect release.

Fig. 3. Simulated inverse opal cavity response (solid line) to a broadband near-infrared pulse (dashed line). Inset: exploded view of the simulation region, 3×3×3 f.c.c. unit cells of 500nm air spheres in a silicon background, with a central missing-sphere cavity defect.

Fig. 4. Calculated photonic band structure of a photonic crystal of 500nm air spheres in a silicon background.

Fig. 5. Various-sized defects formed by repeated nanorobotic pick-and-place on a self-assembled colloidal crystal film.