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A general strategy to fabricate photonic crystal heterostructure with Programmed photonic stopband

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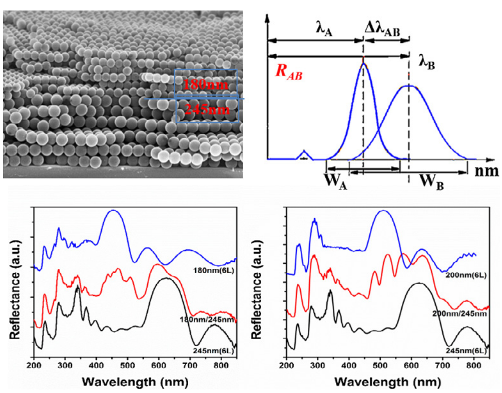
GRAPHICAL ABSTRACT



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ABSTRACT

In this paper, we present a general fabrication strategy to achieve the structure control and the flexible photonic stop band regulation of (2 + 1) D photonic crystal heterostructures (PCHs) by layer-by-layer depositing the annealed colloidal crystal monolayers of different sphere size. The optical properties of the resulting (2 + 1) D PCHs with different lattice constants were systematically studied and a universal photonic stopband variation rule was proposed, which makes it possible to program any kind of stopband structure as required, such as dual- or multi-stopbands PCH and ultra-wide stopband PCH. Furthermore, PCH with dual-stopbands overlapping the excitation wavelength (E) and emission wavelength(F) of Ru complex was fabricated by finely manipulating the spheres' diameter of colloidal monolayers. And an additional 2-fold fluorescence enhancement in comparison to that on the single stopband sample was achieved. This strategy affords new opportunities for delicate engineering the photonic behaviour of PCH, and also is of great significance for the practical application based on their bandgap property.

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1. Introduction

Photonic crystals (PCs) are a kind of dielectric materials with artificial periodic structure [1,2], which display many properties analogous to semiconductors, including the appearance of photonic bandgaps (PBGs). The existence of PBGs enables PCs to manipulate, confine, and control light, and have been proposed

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for applications such as optical filters, switches, waveguides for optoelectronics, self-cleaning properties for optical devices, chemical and biological sensors and environmental monitoring [3–9]. In recent years, photonic crystal heterostructures (PCHs) composed of two homogeneous PCs with different lattice constants have received extensive attention for their charming and plentiful photonic stopband features [10–12], which opens up the possibility of many novel applications, such as manufacturing integrated photonic crystal chips, multi-frequency optical Bragg filters, dual-stopband fluorescence enhancement and broadband reflective mirror [13–16]. What's more, a significant amount of application are taking advantage of the stopband matching of PCHs. Therefore, it is very important and necessary to get a general method and rule of bandgap regulation. Considerable efforts have been made to the fabrication and photonic stopband modulation of PCHs. Wang et al. [17] illustrated a room temperature floating self-assembled 3D colloidal crystal heterostructure with two apparently isolated stopbands, and showed that the two separate stopbands gradually got closer as the size difference of two homo crystals decreasing. Jiang et al. [18] adopted the multiple vertical deposition techniques to fabricate opaline colloidal crystals multilayer with approximately additive photonic bandgap properties, which can be tailored by manipulating secondary diffraction, film composition, and sphere size. Yan et al. [19] fabricated opaline hetero photonic crystals by sequentially layer transfer of the floating opal films, and found that when the sphere size difference of the compositional colloidal crystal is large, the opaline heterostructure exhibits two apparent isolated stopbands, and when the sphere size difference is small, a wide stopband appears. Although the self-assembled 3D PCHs have presented some special bandgap structure, it is still challenging for delicate bandgap engineering due to the poor control in film thickness and single narrow-sharp bandgap structure. Compared with 3D PCs, (2 + 1) D PCs possess unique advantages in both structural tunability (control in single layer level) and optical property (PBG broadening and deepening, Fabry-Pérot oscillations) [20–22]. Binary Langmuir-Blodgett composite (2 + 1) D PCHs have also been studied by Reculusa, Masse and Ravaine et al. [23,24], which illustrated more complex bandgap information induced by the artificially defects. However, the structural imperfection greatly limits the systematic study on the photonic stopband regulation. To achieve fine regulation of the stopband position and structure is still a big challenge.

In this paper, we presented the controllable fabrication of (2 + 1) D PCHs by layer-by-layer transfer technique, as schematically illustrated in Fig. 1. The PS colloidal monolayers with high mechanical strength were created by a combination of the air/water interface self-assembly and the solvent vapour annealing treatment, which affords the PCH with enhanced crystalline integrity. Monolayers of different colours represent polystyrene colloids of different sizes. This layer-by-layer technique gives us opportunity to accurate control and design the structure and photonic stopband of the (2 + 1) D PCHs in single layer level. Then, we systematically studied the optical properties of the resulting (2 + 1) D PCHs with different lattice constants and summarised the stopbands variation rule in detail. Under the guidance of this rule, some PCHs with special bandgap structures were constructed as will, such as multi-bandgap and ultra-wide bandgap. In addition, we demonstrated the effect of the stacking order of different colloidal monolayers on the optical properties of heterostructures.

2. Materials and methods

2.1. Reagents and materials

All chemicals, including styrene (St, ≥99.0%), potassium persulfate (KPS, ≥99.5%), ethanol (≥99.7%), sulfuric acid (95–98%), hydrogen peroxide (≥30%), and sodium dodecyl sulfate (SDS, 98%), methylbenzene ($C_7H_8 \geq 99.5\%$) and other chemicals were used as received without further purification from Sinopharm Chemical Reagent Co., Ltd. Deionized (DI) water (resistivity up to 18.2 MΩ·cm, Ultra Pure UV, China) was used in all experiments. The p-type 4-inch (1 0 0) silicon wafer with a resistivity of 1–10 Ω·cm was purchased from KYKY Technology Co., Ltd. The silicon wafer was single-side polished and cut into small pieces (1 cm × 1 cm) before use.

2.2. Synthesis of PS spheres and preparation of PS colloidal monolayers with high mechanical strength

Monodisperse PS colloidal spheres with diameters ranging from 100 to 600 nm were synthesized using the emulsifier-free emulsion polymerization method [25]. The as-synthesized PS spheres were purified and redispersed in DI water by at least four centrifugation/redispersion cycles before use. The large-area PS colloidal monolayers were fabricated by the air/water interface self-assembly method described in our previous paper [26]. In short, the PS emulsion mixed with equal volume ethanol of about 200 μL was added drop wise on the surface of a glass slide, which was pre-placed in the center of a glass Petri dish, just flush with the air/water interface. The glass slide and Petri dish were pretreated by soaking in piranha solution (H_2SO_4 and H_2O_2 in a 3:1 vol ratio) at room temperature for 2 h. Once the emulsion contacted the surrounding water at the edge of the glass slide, PS spheres spread rapidly onto the water surface and assembled into monolayer colloidal arrays in several seconds. A drop of 1 wt% SDS solution was added to consolidate the colloidal arrays into a large-area monolayer. The as prepared floating PS colloidal monolayers were transferred to a sealed glass vessel (20.0 cm × 13.0 cm × 7.0 cm) filled with saturated toluene vapour for annealing treatment. The mechanical strength could be easily tuned by controlling the annealing time [26,27]. In this way, the colloidal monolayers with high mechanical strength were fabricated.

2.3. Fabrication of (2 + 1) D colloidal PCHs with PS colloidal monolayers

The colloidal photonic crystal heterostructures were fabricated by a simple layer-by-layer transfer technique, as described in our

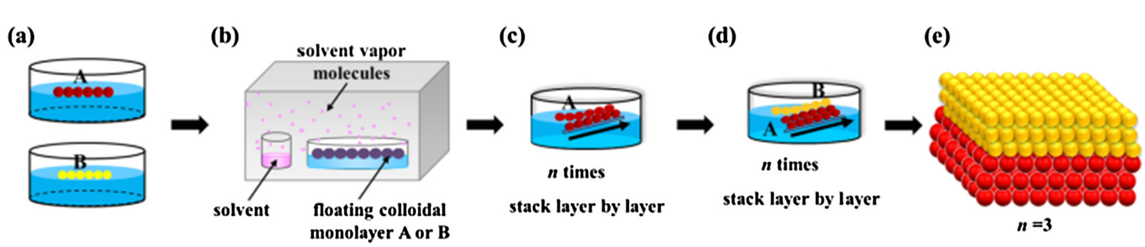

Fig. 1. Schematic illustration of the fabrication process for a colloidal photonic crystal heterostructure A_3/B_3. The different colors stand for PS spheres with different sphere sizes.

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