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Applied electric field to fabricate colloidal crystals with the photonic band-gap in communication waveband*

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The macropore silica colloidal crystal templates were assembled orderly in a capillary glass tube by an applied electric field method to control silica deposition. In order to achieve the photonic band gap (PBG) of colloidal crystal in optical communication waveband, the diameter of silica microspheres is selected by Bragg diffraction formula. An experiment was designed to test the bandgap of the silica crystal templates. This paper discusses the formation process and the close-packed fashion of the silica colloidal crystal templates was discussed. The surface morphology of the templates was also analyzed. The results showed that the close-packed fashion of silica array templates was face-centered cubic (FCC) structure. The agreement is very good between the experimental data and the theoretical calculation.

Keywords: colloidal crystal, photonic bandgap materials, optical communications, fiber
PACC: 4270Q, 8270D, 4200

1. Introduction

Colloid photonic crystals with pseudo band gap can not only be used for the production of filter, optical switches and biological sensors, but also provide an ideal template for the fabrication full band gap order structure. A number of methods have been developed for producing these materials, including selective etching,[1,2] self-assembly of block co-polymers,[3] and close-packed colloid crystal array templates.[4−7] The key of these methods, based on the close-packed array templates, is to assemble high-quality array templates. In recent years, some methods have been developed for the assembly of colloidal crystal templates,[8−14] for example, the vertical deposition method[15] and the gravity sedimentation method.

In this paper, we report an applied electric field to control the silica deposition method to fabricate the macropore silica colloidal crystal templates in a capillary glass tube. Since the photonic band gap (PBG) of colloidal crystal is in an optical communication waveband, 715 nm silica microspheres had been selected by the Bragg diffraction formula, and a single mode silica fiber system was utilized to measure the bandgap of colloidal crystals. We utilized a capillary glass tube as a coating substrate of colloidal microspheres and produced a cylindrical shell of colloidal crystals by an electric field method. The formation process and the close-packed fashion of the silica colloidal crystal templates were discussed. Simultaneously, the surface morphology of the templates was also analyzed. The results showed that the close-packed fashion of silica array templates was face-centered cubic structure. The measurement results show that the bandgap of silica colloidal crystals is at 1562 nm.

2. Experiment

2.1. Silica spheres selected

The position of stop bands (band gaps) in FCC photonic crystals can be estimated by using a modified form of Bragg's law which takes into account the refraction of light in the composite structure and the incident angle of the incoming light,

$$\lambda_{\max} = 1.633D\sqrt{n_{\text{avg}}^2 - \sin^2\theta}, \qquad (1)$$

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where λ_{max} is the wavelength of the reflectance peak maximum (i.e. the position of the PBG), n_{avg} is the average refractive index of the photonic structure and θ is the angle between the incident light and the surface normal of the sample.

For silica colloidal crystals in air at 25 °C, $n_{avg} = n_{silica}f_{silica} + n_{air}f_{air}$, where $n_{silica} = 1.460$, $n_{air} = 1.000$, and f_{silica} and f_{air} are the volume fractions occupied by silica spheres and air in the structure (generally taken as 74% and 26%, respectively, for an FCC lattice). In the case of first order Bragg diffraction from FCC [111] planes, $\theta = 0°$. For FCC arrays of spheres, D would generally be taken as $2r$, where r is the radius of the silica sphere. Because we want the PBG in the communications waveband, $\lambda_{max} = 1550$ nm is substituted into equation (1), we can get the approximate value of $D = 708$ nm. Based on this calculated result and our experimental condition, we selected the 715 nm diameter silica spheres.

2.2. Experimental procedure

The silica spheres with a relative standard deviation of about 2%, a solution containing 5% dispersion of colloidal silica microspheres in a water/ethanol (1:4 volume ratio) mixture. The solution in a vial is vibrated by ultrasonic for about 1 hour, and a milky white colloidal suspension is formed. The length, external diameter and internal diameter of a capillary glass tube are 50 mm, 5.5 m and 3.3 mm, respectively. It was cleaned ultrasonically in acetone, 0.1 mol/l HCl solution, ethanol and deionized water, respectively.

2.3. Assembly of the silica colloidal crystal templates

The setup of assembly of the silica colloidal crystal templates is shown in figure 1. The capillary glass tube is immersed in silica colloidal suspensions through a rubber stopper. This device was placed into a drying cabinet with an air pump at the temperature 50 °C to evaporate water and create colloidal crystals. At the same time, an electric field applied to this device and the strength of applied electric field is 100 V/m. Colloidal crystals grew on the internal-external wall of capillary glass tube under this condition; the water/ethanol mixture was dried over after 10 h at 50 °C. The silica templates appeared opalescent, as expected, prismatic colors like a rainbow, depending on the angle of observation, and clearly visible when the samples were illuminated from above with white light.

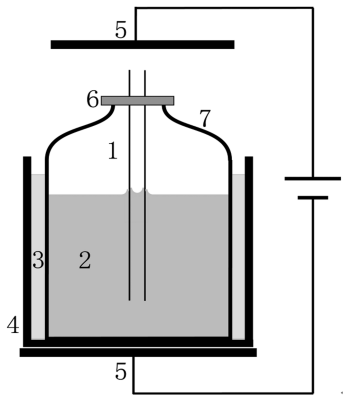


Fig.1. Schematic diagram of experimental setup. 1. Capillary glass tube. 2. Silica suspension. 3. Water. 4. Thermostat water bath. 5. Electrode. 6. Rubber stopper. 7. Vial.

2.4. Instrument and characterization

Electron morphology of the silica colloidal crystals was observed with a JSM-5610LV field emission scanning electron microscope (SEM). A thin layer of gold was coated on the samples before observation in order to prevent sample charging under the electron beam. The SEM was also used to examine the order degree of the array of these silica micro spheres. The transmission spectra of the silica templates were measured by using a sensing analyzer (MIO-720).

3. Results and discussion

3.1. Mechanism of template assembly

Figure 2 shows the schematic diagram of the applied electric field method, which is used to assemble silica colloidal crystal templates. There are four forces in the crystal growth: gravity force; electric force; flowing shear force and gathering force. The gathering force is van der Waals force. The basic idea of the crystal growth is that a clean glass tube is settled vertically into the emulsion of silica for several minutes, a meniscus region can be formed on the substrate due to the wetting from the solution, which leads to the flux and accumulation of silica caused by the lateral capillary forces. The template assembly process consists of silica accumulation at the intersectant place of air, silica emulsion and the wall of the tube, transport of silica microspheres in the emulsion, and successive crystallization, as depicted in figure 3. But,

the diameter of silica spheres is 715 nm, the gravity force becomes large and the deposition rate will be fast when the solution evaporated. It leads to the shortening of self-assembly time, and then the fracture will be formed in the colloidal crystals. In order to maximally decrease silica colloidal crystal template defects, an applied electric field is used. The electric force is an effective balance of gravity and flowing shear force at the meniscus, the deposition rate becomes slow and the self-assembly time is extended. Finally, the rate of nucleus formation, PS particles transport, and crystallization should keep a balance in the process.

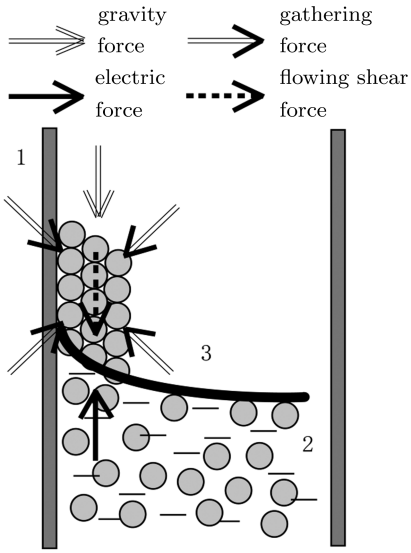


Fig.2. Schematic diagrams of the force equilibrium during the formation of a colloidal crystal. 1. Wall of capillary glass tube. 2. Silica suspension. 3. Meniscus.

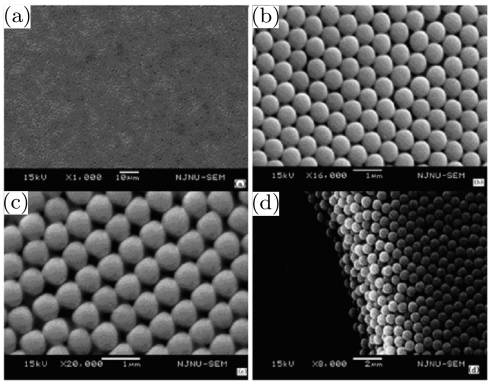


Fig.3. The SEM images [(a)–(d)] of the silica colloidal crystals.

3.2. The morphologies of templates

Figure 3(a) shows a scanning electron micrograph of the close-packed structure. The self-assembly of colloidal particles results in three-dimensional colloidal crystal, as observed by SEM. Some vacancies and dislocations are found in the ordered array. Figure 3(b) with a high magnification shows that the particles of the silica microspheres exhibit a hexagonal close-packed arrangement on the plane [111]. Figure 3(c) shows the tetragonal close-packed arrangement in some part. The argument that the face-centered cubic (FCC) structure is favored over the hexagonal close-packed (HCP) structure deduced from theoretical calculations which is also demonstrated in the present study, and the thermodynamically stable crystal phase of the array formed appears to be the FCC phase. Figure 3(d) shows the side-view of the SEM image of the colloidal crystal, it can be seen that the silica template consists of seven layers and has a better close-packed fashion. In general, the FCC colloidal crystal in three dimensions is clearly observed. The images confirm the growth of high quality colloidal crystals that conforms to the wall of the capillary glass tube, demonstrating that the method of capillary force with electric fields is feasible.

3.3. Optical characterizations

In order to measure the optical characterization for the silica templates inside the capillary glass tube, an experiment was designed. As shown in figure 4, the two single mode fibers were symmetrically placed into the glass tube and touched the external wall of the glass tube, the two optical fibers were connected to the sensing analyzer. The end face of one fiber is parallel to the plane [111], and the transmission spectrum is recorded through another fiber, as shown in figure 4, the incident light spectrum and the transmission spectrum were shown in figures 5 and 6.

The incident light spectrum is a flat spectrum line, the optical intensity is –10 dB. The transmission spectrum is investigated. Because the insertion loss and the reflection of optical fiber end face, the

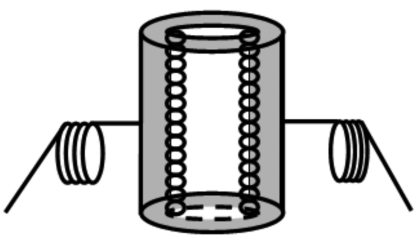


Fig.4. Schematic diagram of the characterization of the measured silica colloidal crystal.

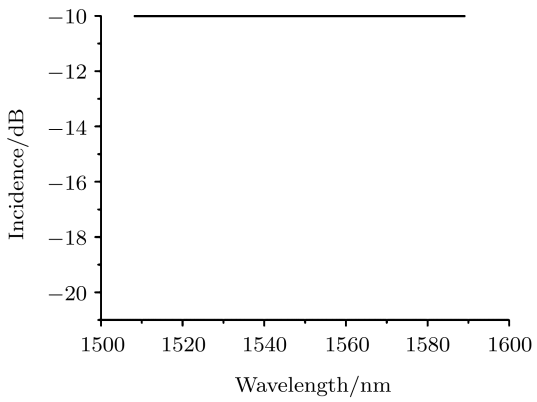


Fig.5. Incident light spectrum.

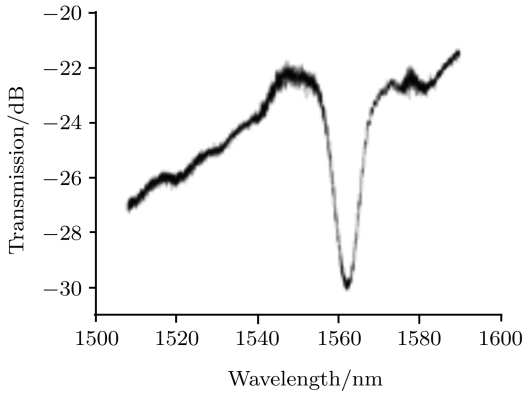


Fig.6. Transmission spectrum.

intensity of transmission spectrum is down to –22 dB. A moderately strong transmission dip of ∼30 dB at ∼1562 nm wavelength coincides with the PBG expected for the 715 nm silica microspheres. The quantity value $D = 715$ nm is substituted into equation (1), we can get the value of $\lambda_{\max} = 1565$ nm. It shows that the bandgap will appear at the wavelength of 1565 nm. We compared the experimental results with the theoretical results, the error is less than 3 nm, the experimental results are in very good agreement with the theoretical calculation.

From this transmission spectrum, we can get that the spectrum is parabola-shaped in 1554–1570 nm, so the cylinder-type colloidal crystals can be used as the central wavelength of 1562 nm optical filters.

4. Conclusions

The silica colloidal crystal templates with PBG in the communications waveband assembled orderly in a capillary glass tube using an applied electric field method to control silica deposition was demonstrated. The method of capillary force with electric fields is developed in this study. The electric force is used to balance gravity force, time of deposition and self-assembly was extended, which can fabricate a better macropore colloidal crystal on the wall of the capillary glass tube. Moreover, a fiber setup was designed to measure the bandgap of colloidal crystals, and it was preliminary research for the colloidal crystals combined with the fiber. The results show that the agreement is very good between the experimental data and the theoretic calculation, which also indicates that the measurement system can be used to measure the bandgap of colloidal crystals.

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