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Effects of influential factors on sedimentation self-assembly processing of photonic band gap crystals by relative humidity-controlled environments

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Abstract

The quality of the produced photonic band gap (PBG) films from colloidal silica in different sedimentation conditions was investigated according to the stop band intensity of the films. The PBG films were fabricated using the solution of monodispersed silica colloids with different alcohol-content solvents for a sedimentation self-assembly process under a relative humidity (RH)-controlled environment. The produced PBG films were analyzed by SEM images for the morphology of the crystal structures and by spectrometer measurements for their stop band intensities. Results show that the quality of the produced films was significantly influenced by the solvent evaporation rates in different sedimentation environments. Higher quality of the PBG films was produced at low evaporation rates by adopting a high RH-controlled conditions or a low alcohol-content solvent.

Keywords: Silica particle; Photonic band gap; Sedimentation; Relative humidity; Self-assembly

1. Introduction

Photonic band gap (PBG) crystals utilize dielectric materials with periodic array structures to manipulate and control pathways of certain light waves. The unique phenomenon is attributed to the light inside the array interacting with the crystal structures. The applications of the PBG technology have been rapidly developed especially in opto-electronic systems to take advantages of the particular property, such as waveguides for optical fibers. The recent development and applications of the studies was discussed in Yablonovitch [1].

Several approaches were proposed to fabricate PBG crystals, such as lithography processing [2], and particle sedimentation self-assembly methods [3]. In recent years, the sedimentation self-assembly methods have been taken as a low-cost and simple way to fabricate three-dimensional PBG crystals in a large area. In general, the fabricating procedure of this method starts with the synthesis of monodispersed colloidal particle, followed by particle suspension, self-assembling by sedimentation, and then thermal treatment at the end [3]. The preparation of the monodispersed silica particles was received considerable attention by many researchers to enhance the quality and performance for practical applications [4–6]. Moreover, each of these fabrication steps can greatly affect the PBG characteristics and quality, such as stop band intensity due to the defects of the crystal structure formation. The typical crystal defects, i.e. vacancies, dislocations, and grain boundaries can be formed during the growth of the crystals. Besides, the sedimentation approach usually needs a long period of time to produce high quality of 3D PBG crystals.

Silica particles are one of the typical sources of materials to fabricate PBG crystals [7,8] and the fabricating process was reviewed by Xia et al. [4]. The behaviors of the colloidal silica particles in a solution were reviewed and discussed by Lewis [9]. The interparticle forces mainly include Van der Waals attractive interactions between particles, and repulsive electrostatic force based on the PH value in the solution between the charged particle surfaces. During the precipitation of each individual particle, the physical system can be basically explained by fluid mechanics, involving the balance of gravitational, buoyancy, and drag forces in the fluid solution. Besides, the motion of the small col-

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loidal particles is random and can be described by the Brownian motion phenomenon in the liquid solution. When the colloidal particles precipitate and adhere on the substrate surface, there exist force interactions among the substrate, the solvent and the particles, mainly the capillary forces [10]. In addition, it is reported that the final step of solvent drying was the essential role for the crystal growth [11]. The self-assembling mechanism of the PBG films on horizontal substrates was proposed by Yan et al. [12].

During the process of colloidal sedimentation self-assembly, the influential factors of the PBG crystal growth proposed in the literature are evaporation rate which is affected by the system temperature and relative humidity [13–15], particle size [16], concentration of the suspension particle [13,14,17], solvent [17–19] and surface characteristic of substrates, i.e. surface tension [12,17,20]. However, the detailed mechanisms and effect of each influential factor mentioned above on the PBG formation still cannot be clearly understood [11]. It was also pointed out that the solvent flow by the external forces was one of the major effects on the crystal growth system [11]. Therefore, it is of interest to study the solvent effect on the crystal formation to improve the quality of the produced PBG films.

In this work, the effects of the influential factors on the growth of PBG films, fabricated by the method of sedimentation self-assembly, were investigated under the RH-controlled environments. The monodispersed silica particles were synthesized by sol–gel methods. After the fabrication of the PBG films in different operating conditions, the quality of the produced films was evaluated using the stop band intensity of the sample films. The effect of the influential factors on the PBG growth can be revealed according to the experimental results.

2. Experimental method

The experimental procedure of the PBG film production includes colloidal particle synthesis, powder suspension, deposition, self-assembling by sedimentation, and then thermal treatments. The detailed description of the procedure is described in the following.

2.1. Silica particle synthesis

The sol–gel process was utilized to synthesize the desired colloidal silica particles in a sub-micron range, which is used for the fabrication of photonic crystals. In the experiment, TEOS, purchased from ACROS Corp., was dissolved in ethanol and stirred for 5 min followed by the dropwise addition of ammonia (30 wt%) dissolved in ethanol. The solution mixture was stirred at room temperature for 2.5 h to synthesize SiO_2 particles. This sol–gel reaction was terminated by adding a large amount of deionized (DI) water. The particle size and its distribution were measured and characterized using a Dynamics Light Scattering (DLS) instrument (Beckman N4 plus). In addition, the silica particle size and its morphology were also analyzed using SEM (HITACHI S-3000H).

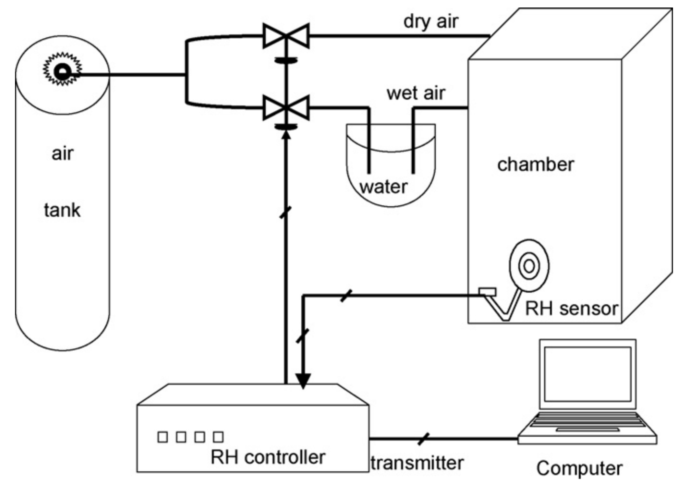

Fig. 1. Schematic plot of the RH-controlled system.

2.2. Silica powder suspension

The SiO_2 powder was obtained by centrifuging the colloidal particle solution at 6000 rpm for 10 min. The prepared powder was washed three times with DI water using ultrasonic cleaner (ULTRAsonik model 104 H) about 20 min. After the sample was dried at 40 °C for an hour, the powder was then sintered for 2 h at 250 °C. The prepared powder was dispersed in DI water by ultrasonic cleaner for 1 h as 100 ml water per gram of the powder.

2.3. Growth of photonic crystal films

The evaporation rate of the solvent was estimated using a precision balance measurement. The weight change of the liquid sample associated with time was automatically recorded under a RH-controlled environment. The slope of the plot of the weight change with time indicates the evaporation rate of the sample.

The prepared liquid sample consisting of silica particles and solvent was drop onto glass substrates, washed with DI water by ultrasonic cleaner. The photonic crystals were fabricated under RH control in a chamber. The schematic plot of the experimental system is shown in Fig. 1. After being kept in the controllable environment of relative humidity for a period of time at room temperature, the PBG films were formed on glass substrates which were placed horizontally after dried. The prepared films were heated for 24 h at 105 °C. The prepared PBG sample properties were analyzed using several instruments. The stop bands of the PBG samples were measured using a UV–vis spectrometer (Perkin Elmer Lambda 900). In addition, the morphology of the PBG samples was analyzed by a HITACHI S-3000H SEM.

3. Results and discussion

This study was focused on the effects of different influential factors on the growth of the PBG films under RH-controlled environments. Monodispersed silica particles have to be first prepared for the further fabrication of the PBG films. Next, the effects of different influential factors on the PBG crystal growth