DEVELOPMENT OF BROADBAND OPTICAL FILTER USING PHOTONIC CRYSTALS

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Introduction

Photonic crystal(PC) is a periodic structure, which is composed of two dielectric materials. The electromagnetic wave of a particular wave band could not transmit to this structure. The band is called photonic bandgap. The PCs are classified 1D, 2D, or 3D-PC according to periodic direction. Currently, applications of PCs include optical switch, negative reflection lens, emitter, sensor, and optical filter.

A 3D-PC only possess single-narrow bandgap, and it unable to form above the surface of a normal glass. In order to solve former two problems, this research predict photonic bandgap using high-accuracy 3D plane-wave expansion method. Then, our team find the two particle diameters of polystyrene (PS) spheres whose photonic bandgap are very close to each other. On the other hand, this research constructed an isothermal ultrasonic oscillation system for self-assembling PCs in order to fabricate 3D PCs quickly and stably. The two particle sizes of former are fabricated on the both surfaces of our special glass substrate. Finally, this research use transmittance spectrum to verify the sample whether successfully realize broadband optical filter.

Methodology

Isothermal ultrasonic oscillation system for self-assembling PCs

In this work, the ultrasonic oscillator was used to supply the driving force. The water in sink would absorb a part of oscillating energy so that the water temperature would increase with time. Fig. 1 shown the relation between oscillating time and water temperature.

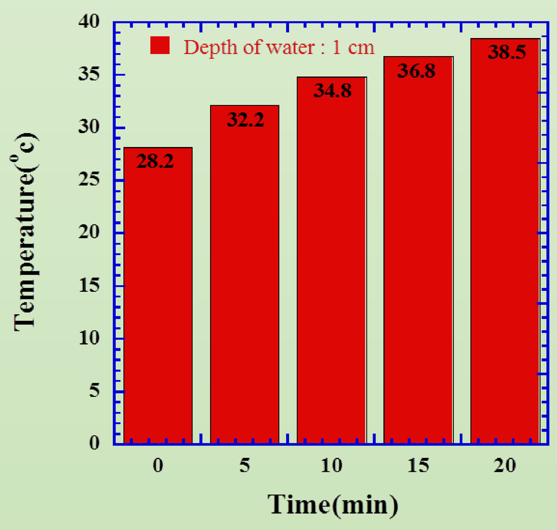

Fig. 1 The relationship between the oscillating time and the water temperature

In order to eliminate heat factor in fabrication process, our team constructed an isothermal ultrasonic oscillation system for self-assembly PCs. Fig 2(a) is a schematic diagram of our setup. In this system, thermostatic water bath stably supplied 55°C hot water. Then, the hot water was circulated in the system by two pumps. Therefore, the water temperature in sink could always be kept constant. Fig. 2(b) show that our system can maintain the water temperature of the oscillation sink at 54°C.

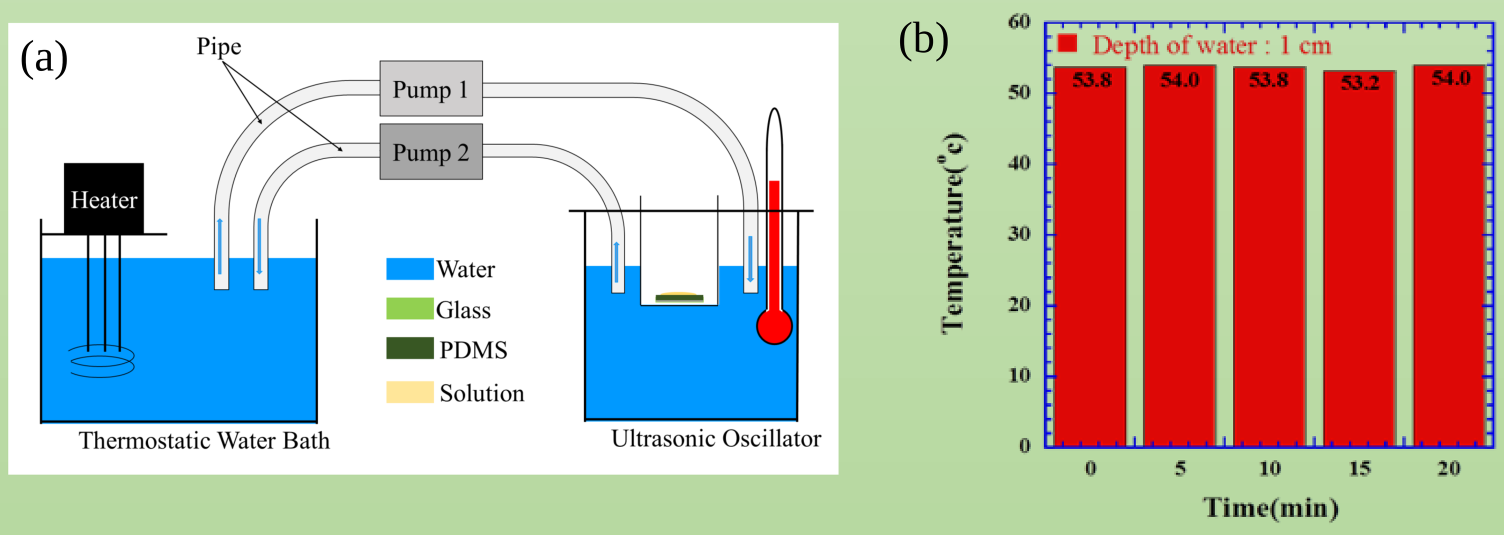

Fig. 2 Isothermal ultrasonic oscillation system for self-assembly: (a) schematic diagram; (b) thermostatic performance

Fig. 3 shown the SEM image for 3D-PC sample which was composed of particle diameter 203 nm, or 216 nm, respectively. Those sample were fabricated using our setup. From SEM images, our setup was confirmed that can fabricate high-uniformity 3D-PCs.

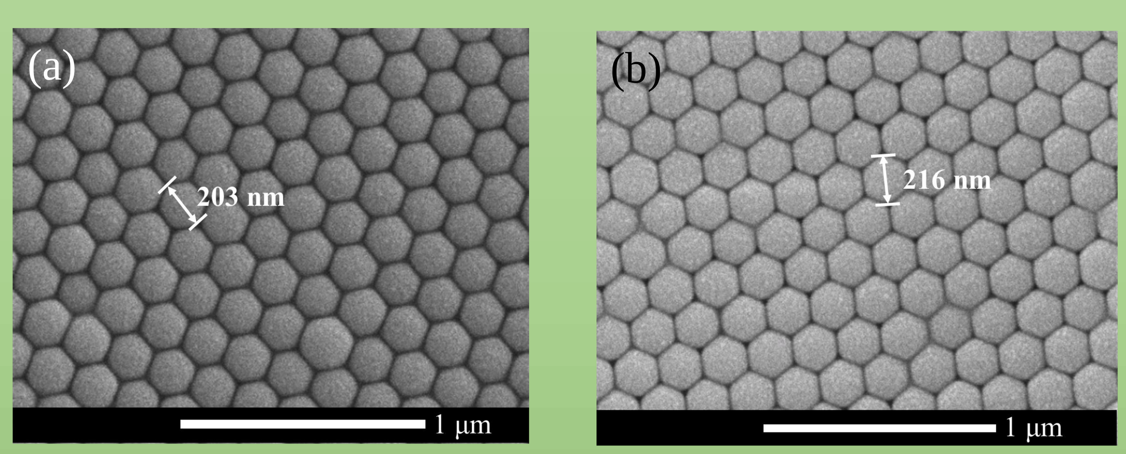

Fig. 3 The SEM images show two different components of 3D-PC.: (a) sphere diameter is 203 nm; (b) sphere diameter is 216 nm

Special glass substrate

The surface of a normal glass is hydrophilicity so that PC can't be fabricated on its surface. Therefore, our team made a special glass substrate which had hydrophobic surfaces. The special glass substrate was made by coating the hydrophobic material "PDMS" on the both surface of a normal glass.

Three-dimensional plane-wave expansion method

This method is deriving from Eq. (1) and Eq. (2), which are in Maxwell equations. Those two equations undergo a series of complex derivation, and then we could obtain Eq. (3). Eq. (3) is a standard eigenvalue problem. The theoretical value of photonic bandgap can be obtained by solving Eq. (3).

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \qquad (1a)$$

$$\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t} \qquad (1b)$$

$$\sum_{\mathbf{G}'}\sum_{n'=1}^{2} H^{n,n'}_{\mathbf{G},\mathbf{G}'} h^{n'}_{\mathbf{G}'} = \frac{\omega^2}{c^2} h^{n}_{\mathbf{G}} \qquad (3)$$

Results and Discussion

Photonic bandgap calculation

Three-dimensional plane-wave expansion method can be used to calculate a theoretical photonic bandgap. This research utilized existing MATLAB codes to solve the eigenvalue problem for our 3D PCs structure. The PCs are face-centered cubic structures that are composed of PS spheres (relative permittivity is 2.5) and air (relative permittivity is 1). Finally, our team used the computational results to plot the band diagram, as shown in Fig. 4.

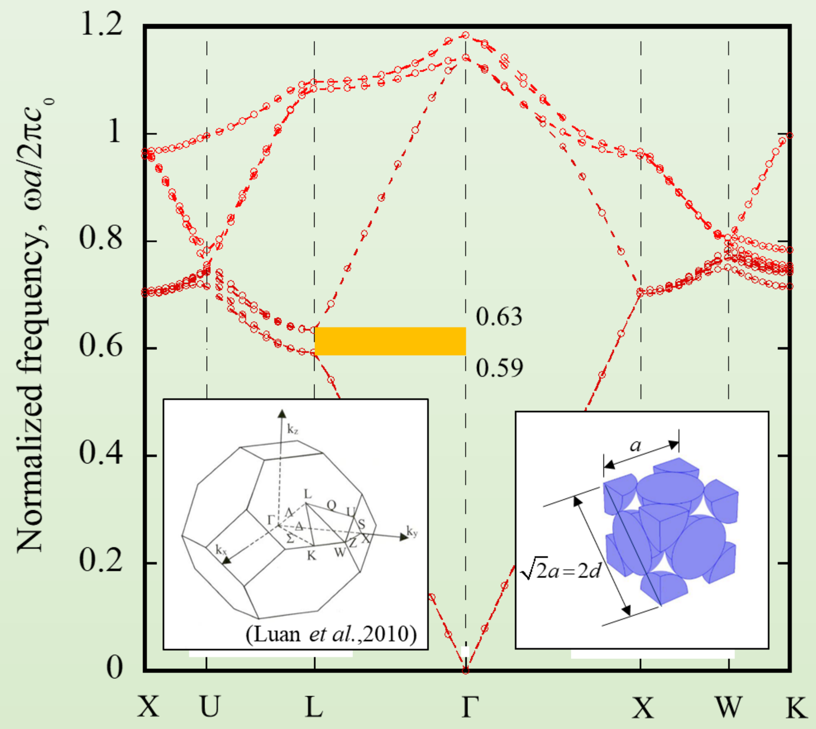

Fig. 4 Band diagram of the 3D PC composed of PS spheres and air

Fig. 4 is the band diagram of our 3D PC. From the diagram, a bandgap exists between 0.59-0.63 normalized frequency along the L-Γ direction (equal to normal direction). We also can know the relation between the particle diameter (d) and the unit lattice constant (a) from one inset. When we have the information of particle size, the theoretical photonic bandgap will be got. The corresponding bandgaps with particle diameter of 203 nm and 216 nm are aggregate to Table 1.

$$\frac{2d}{0.63\sqrt{2}} \le \lambda \le \frac{2d}{0.59\sqrt{2}} \qquad (4)$$

Table 1 The corresponding bandgap with particle diameter of 203 nm and 216 nm

Diameter, *d* (nm)	Bandgap (μm)
203	0.45 - 0.48
216	0.48 – 0.52

Broadband photonic bandgap

Our team used stacking method to fabricate two kinds of particle diameter on the both surfaces of our special glass substrate. Fig. 5 is the normalized transmittance spectrum of broadband sample at normal incidence. From the spectrum, we observed that the bandwidth of photonic bandgap was successfully expanded from 0.05 μm to 0.10 μm. The broadband optical filter of PCs was realized in this work.

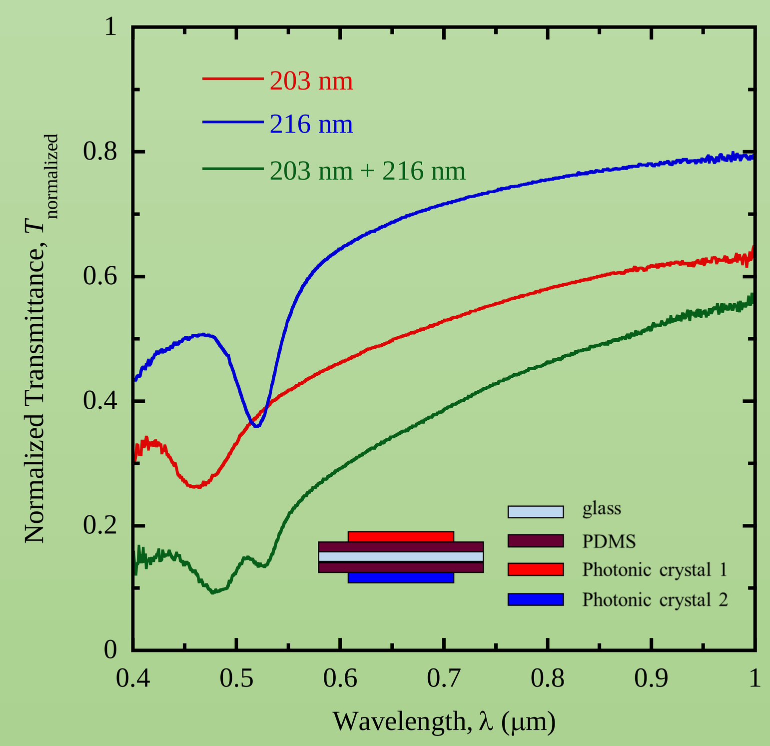

Fig. 5 The normalized transmittance through PCs consisted of one and both particles (diameter 203 nm or 216 nm) at normal incidence.

Conclusions

This research has utilized three-dimensional plane-wave expansion method to successfully predict the photonic bandgaps constructed by PS spheres of different diameters, and discovers two sizes of PS spheres (203nm and 216nm) corresponding to similar photonic gaps. On the other hand, this research has constructed a fabrication system which is low-cost, short process time, stable in process environment, and available in making highly-uniform PC samples. The system is called "isothermal ultrasonic oscillation system for self-assembling PCs". In addition, stacking method is applied to construct 3D PC using PS spheres of two different diameters on both sides of the special glass substrate respectively. By observing the measured transmittance spectrum of sample, it is proved that the overall photonic gap expands to twice its original values. This research successfully realized "Broadband optical filter of PCs". Potential application areas of developed broadband optical filters include the botanical lamp shade and filtration membrane for blue light.

Acknowledgment

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