Experimental Study of Liquid Refractive Index Sensing Based on Colloidal Photonic Crystal Photonic Band-Gap

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***Abstract*- We use the changes of colloidal photonic crystals photonic band-gap center wavelength to study the refractive index sensing by experiment. The changes in the center wavelength of the colloidal crystals photonic band-gap are analyzed in theory, the mould is designed to obtain a controllable self-assembly method, colloidal crystals are observed by scan microscope and the band-gap is measured by infrared spectrometer. The results show that the measured results are well agree with the theoretical analysis. The experimental device is designed to test liquid refractive index. The couple of the fibers are used to measure the band-gap of colloidal crystals and the results are also analyzed in theory. The results show that the band-gap of colloidal crystals can be used to measure the liquid refractive index. The new sensing mechanism is formed and it provides a new application of colloidal crystals in the sensing.**

Keywords- Colloidal Photonics Crystals; Refractive Index; Sensing; Photonic Band-Gap

I. INTRODUCTION

Since Eli Yablonovitch [1] and Sajeev John [2] had presented the concept of photonic crystal, it has been a very active area of research. Photonic crystals are artificial periodic dielectric structure with characteristics of photonic band-gap (PBG) [3-5]. Colloidal photonic crystals are the sub-micron monodisperse colloidal microspheres spontaneously under suitable conditions to form a three-dimensional ordered periodic structure. Colloidal photonic crystals are material periodic dielectric distribution as the photonic crystal, and it also has a photonic band-gap. It costs little and is easy to operate, and can change the transmission of light through the modulation of its refractive index. So the colloidal photonic crystals can be used as a polarizing film, optical switches, and other special optical devices [6-9]. Self-assembled colloidal crystal is the most effective and promising preparation method in a near-infrared, optical three-dimensional photonic crystal. And colloidal photonic crystals can provide an ideal template for other nanomaterials [10-12]. Refractive index is the basic parameters for the optical material. So the measurement methods of refractive index have been researched hotspot in optics, such as: geometrical optics measurement, measurement of the interference stripes, and biochemical surface plasmon sensor measurement in recent years [13-14]. In those measurement methods of refractive index, research based on the band-gap of three-dimensional colloidal photonic crystal has not been reported.

In this paper, we fabricate a three-dimensional colloidal photonic crystal with 635 nm SiO_2 colloidal microspheres and present a method to measure liquid refractive index by the photonic band-gap. The mold is designed to fabricate colloidal photonic crystal, and two single-model optical fibers are embedded in the mold. The fibers are used to measure the photonic bang-dap of the colloidal photonic crystal. The measurement results show that the center wavelength of 1445.5 nm SiO_2 colloidal crystal photonic band-gap. Based on the colloidal crystals, the refractive index of the liquid sensing experiment is measured.

II. THEORETICAL ANALYSIS

Colloidal crystal has a periodic structure as the photonic crystals, the distribution of the dielectric constant for the colloidal crystal is periodic, it can be expressed:

$$\varepsilon(r) = \varepsilon(r + R) \tag{1}$$

Where $R = ma_1 + na_2 + la_3$, and a_1, a_2, a_3 are the base vectors of the photonic crystal, and m, n, l is an arbitrary integer. The reciprocal of the dielectric constant is periodic, and it can be represented as the superposition of a series of plane waves. We use the plane wave expansion method [15-16] to analyse the band gap of colloidal photonic crystal.

A magnetic field at any point in the three-dimensional colloidal crystals can be expressed as:

$$H(r) = \sum_G H_G e^{i(k+G)r} \tag{2}$$

In order to facilitate the calculation, the magnetic field can be expressed as the superposition of two polarization directions, we can get:

$$H_G = H_G^1 \hat{e}_G^1 + H_G^2 \hat{e}_G^2 \tag{3}$$

In the Eq. (3), $\hat{e}_G^1$ and $\hat{e}_G^2$ mean that the two independent polarization directions, they are two mutually perpendicular unit vectors. According to Maxwell's equations, $\nabla \bullet H = 0$. It requires each plane wave of the above formulas to meet the (k+G) $\bullet$ H_G=0, and the $\{\hat{e}_G^1, \hat{e}_G^2, k+G\}$ constitutes a mutually orthogonal coordinate system. Substituted Eq. (3) into Eq. (2) and simplified, we can obtain the three-dimensional photonic crystal plane wave intrinsic equation:

$$\sum_{G'} |k+G||k+G'| \eta_{G-G'} \begin{pmatrix} \hat{e}_G^2 \hat{e}_{G'}^2 & -\hat{e}_G^2 \hat{e}_G^1 \\ -\hat{e}_G^1 \hat{e}_{G'}^1 & \hat{e}_G^1 \hat{e}_{G'}^1 \end{pmatrix} \begin{pmatrix} H_G^1 \\ H_G^2 \end{pmatrix} = \frac{\omega^2}{c^2} \begin{pmatrix} H_G^1 \\ H_G^2 \end{pmatrix} \tag{4}$$

We simulation calculated this equation with Rsoft, Figure 1 is Energy band diagram of the FCC structure colloidal crystal fabricated by SiO_2 microspheres. It can be seen from Fig. 1, the reduced frequency at 0.60~0.66 is a photonic band-gap, it means that the electromagnetic wave propagation along the [111] direction in the colloidal crystal is prohibited at the reduced frequency. The center of the band-gap of reduced frequency a/λ = 0.62, where a is periodic constant of colloidal photonic crystal. For the FCC structure, the relationship of a and microsphere diameter D is a = 1.414D. Accordingly, the band-gap wavelength of the colloidal crystal formed by 635 nm SiO_2 microspheres with FCC structure can be calculated at 1448.2 nm.

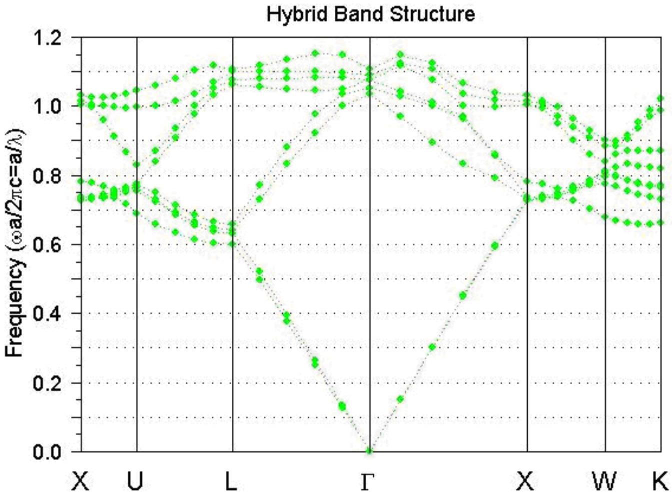

Fig. 1 Energy band diagram of the FCC structure colloidal crystal fabricated by SiO_2 microspheres

In order to further confirm the relationship between the band-gap center wavelength and refractive index of the material, the correction Bragg formula to estimate the colloidal crystal photonic band-gap [17]:

$$\lambda_{\max} = \frac{2d_{hkl}}{m} \sqrt{n_{avg}^2 - \sin^2 \theta} \tag{5}$$

where λ_{max} is the weakest wavelength light transmittance (i.e., the position of the center wavelength of the band-gap), d_{hkl} is a the [*hkl*] crystal plane space, m is the Bragg diffraction fringes level, and n_{avg} is the effective refractive index of the colloidal crystal. $n_{avg} = n_{SiO2} f_{SiO2} + n_t f_t$, where f_{SiO2} and f_t *are* occupancy ratio of SiO_2 and filler material, respectively. θ is the angle between the incident light and the normal to the surface of the crystal.

If the light vertically incident, the θ can be taken 0^o. For the FCC structure f_{SiO2} = 0.74, f_t = 0.26, d_{hkl} = 0.8165D, when m = 1, the Eq. (5) can be changed:

$$\lambda_{\max} = 269.6\, n_t + 1187.1 \tag{6}$$

The relationship between the refractive index n_t of filler material and corresponding center wavelength of band-gap is obtained. So we can use the Eq. (6) to establish filler material refractive index sensing.

III. PAGE STYLE COLLOIDAL CRYSTALS FABRICATION AND MEASURED

A. Colloidal Crystals Fabricated

Water / ethanol (1:4 volume ratio) with a single dispersion containing 15% 635 nm SiO_2 colloidal spheres is produced, the diameter of the relative standard deviation of less than 2%. Two glass substrates are repeated cleaned with ultrasonic waves and deionized water, and some single-mode fibers are stripped coating and repeated cleaned too. We product a mould to fabricate colloidal crystals, the mould diagram is as shown Fig. 2. One side of a glass substrate is coated with a layer of paraffin by means of whirl glue method; thickness of paraffin layer is about 10 μm. Then, two optical fibers sandwich between the two glass substrate at the edge, and the end face of two fibers is cut by fiber cleaver and the fibers are insert the mould between the glass substrates. And the two optical fibers are tested through light and optical power meter to confirm the transmission of light. Two glass substrates are clamped by fixture, and the opening at the bottom is closed and remains a small hole with silicone. Then the mould is formed.

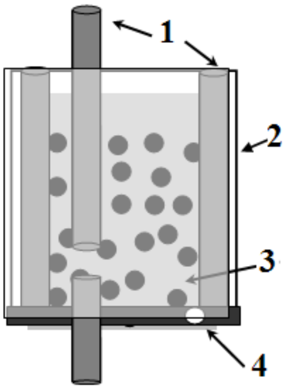

Fig. 2 Diagram of the device to fabricate colloidal crystals
(1. fiber, 2. glass substrate, 3. colloidal solution, 4. silicone with a hole)

The prepared colloidal solution is infused into the upper opening for the cavity, and the colloidal solution is suction into the cavity with capillary attraction. The air in the cavity is discharged along the bottom hole. When the colloidal solution was filled with the cavity, the hole is closed by silicone. And then, this apparatus is taken in a vacuum oven at 50^{o}C, the colloidal solution is evaporated over after 20 minutes; the colloidal crystals are grown in the cavity. The glass substrate with paraffin is separated, and the colloidal crystals are on the glass substrate without paraffin. Then the colloidal crystal glass substrate is taken in a muffle furnace at 200^{o}C and sintered cured for 5 minutes.

B. The Characterization and Measurement of Colloidal Crystals

The field emission scanning electron microscope (SEM) is used to observe the structure of colloidal crystal. Fig. 3 is scanning electron micrographs. Fig. 3A is micrograph of colloidal crystals at the edge positions, the colloidal crystals only have a small number of defects and cracks. Fig. 3B is a scanning electron micrograph under higher magnification, the colloidal crystals have the orderly arrangement with the face-centered cubic (FCC) structure. The results show that the mould can control the crystalline layers, it overcomes the drawback of quickly deposition of large diameter colloidal microspheres to fabricate high quality colloidal crystals.

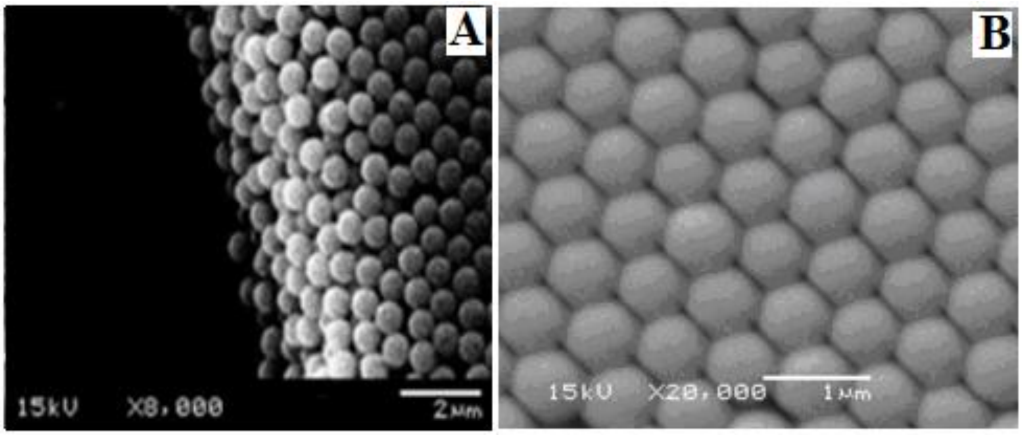

Fig. 3 The SEM images
(a).The SEM image of the edge position of colloidal crystals. (b).The SEM image of the array in order

Optical properties of the colloidal crystals are measured by using the Buker infrared scanning spectrometer, its transmission spectrum of the colloidal crystals is shown in Fig. 4, a weak valley value at the wavelength 1445.5 nm. It indicates the position of a center wavelength of the photonic band-gap at 1445.5 nm, and we calculate the theoretical result is 1448.2 nm, the error is 2.7 nm. Measurement results are well in agreement with theoretical results. We analyze the cause of the error still exists in a small number of defects, and the structure is not only FCC structure.

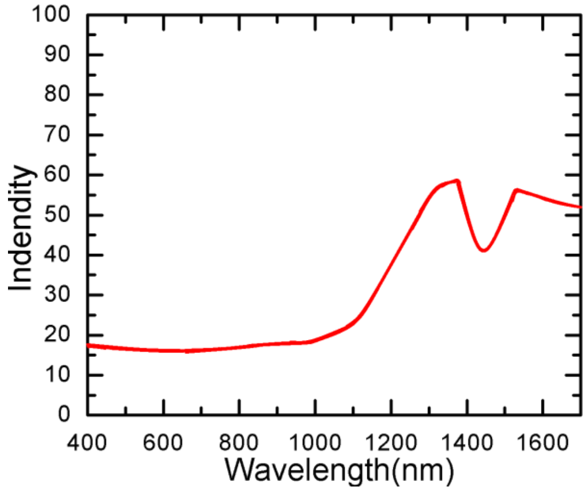

Fig. 4 Transmission spectra of colloidal crystal

Two optical fibers inserted into the cavity are connected to an Ando AQ6317B optical spectrum analyzer (OSA) and a Sctg AS3700 broadband light source, respectively. The refractive index sensing properties of colloidal crystals are measured.

The measured liquids are pure water and acetone, Fig. 5 is the transmittance spectrum of the colloidal crystals are immersed different liquid materials. Curves 1, 2, 3, 4 are obtained in pure water, pure water with acetone (1:1), pure water and acetone (1:2), acetone, respectively. The weaks are 1545.2 nm, 1549.5 nm, 1551.7 nm, and 1554.2 nm, respectively. Substituted the results into Eq. (6), the refractive indexes of the different liquid are as follows: 1.329, 1.344, 1.352, and 1.361. Referenced international engineering tool [18], the refractive index of pure water and acetone are 1.33 and 1.36. It shows the refractive index can be used to measure in this method. Defining the sensor sensitivity S = $\Delta(\lambda_{R1}-\lambda_{R2})/\Delta n_{sen}$, and the sensing sensitivity is about 270 nm/RIU.

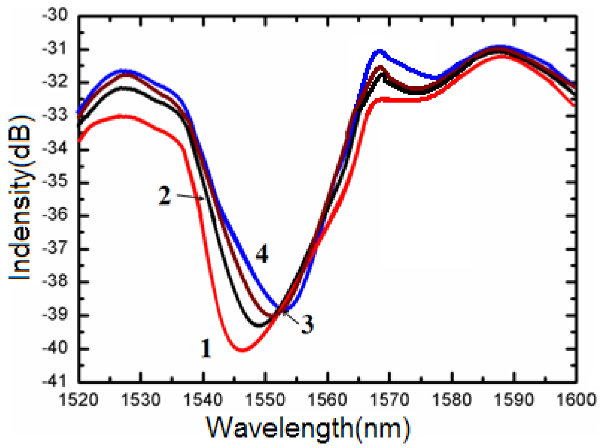

Fig. 5 the transmittance spectra of colloidal crystals immersed in the different liquid materials
(1. pure water, 2. pure water with the acetone(1:1), 3. 2. acetone with the pure water (1:2), 4. acetone)

IV. CONCLUSIONS

In this paper, the liquid refractive index experimental measurement is investigated by using colloidal crystals photonic band-gap. We product a mould to fabricate high quality colloidal crystals, it overcomes the drawback of quickly deposition of large diameter colloidal microspheres. The measuring fibers are pre-embedded in the mould to test the spectra of colloidal crystal, and the fibers and colloidal crystals are integration. This system is used to measure sensing of the liquid refractive index. The results are in well agreement with the theoretical analysis results. The photonic band-gap of colloidal crystals can be used as sensing system, and the sensing sensitivity is about 270 nm/RIU. This experiment reveals the application of colloidal crystals on the sensing.

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