Optik 125 (2014) 1914–1917

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

Experimental research of liquid refractive index sensing by optical fiber and colloidal crystal's photonic band-gap

Haitao Yan[a,*], Zhi Zhang[a], Xiaoyan Zhao[a], Zhiqiang Zhen[a], Hui Hao[b], Ming Wang[b]

[a] College of Physics and Engineering, Henan University of Science & Technology, Key Laboratory of Photoelectric Functional Materials, Luoyang 471003, China

[b] Nanjing Normal University, Jiangsu Key Lab on Opto-Electronic Technology, Nanjing 210097, China

ARTICLE INFO

Article history:
Received 5 May 2013
Accepted 28 September 2013

Keywords:
Colloidal photonics crystals
Refractive index
Sensing

ABSTRACT

We use the changes of colloidal photonic crystal photonic band-gap center wavelength to research the refractive index sensing by experiment. The changes in the center wavelength of the colloidal crystals photonic band-gap are analyzed. A mold is designed to obtain a controllable self-assembly method, colloidal crystals are observed by scan electronic microscope (SEM) and the band-gap is measured by infrared spectrometer. The results are agreed well with the theoretical analysis. An 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 discussed 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.

1. Introduction

Since Yablonovitch [1] and John [2] had presented the concept of colloidal photonic crystal, it became a very active researched area. Photonic crystals are artificial periodic dielectric structure with characteristics of photonic band-gap (PBG) [3–5]. Colloidal photonic crystals are three-dimensional ordered periodic structure, which could be spontaneously formed from sub-micron monodisperse colloidal microspheres under suitable conditions. The colloidal photonic crystal is a sort of artificial photonic materials with periodic dielectric distribution as the photonic crystal, and it also has a photonic band-gap. It costs low and is easy to operate, and can change the transmission of light with the refractive index modulation. 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 crystal can provide an ideal template for other nano-material [10–12]. Refractive index is the basic parameters of optical material. The measurement methods of refractive index always are the investigative hotspot in optics, such as: geometrical optics measurement, interference stripes measurement, and biochemical surface plasmon sensor measurement in recent years [13,14]. In those measurement methods of refractive index, 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. A mold is designed to fabricate colloidal photonic crystal, and two single-mode optical fibers are embedded in the mold. The fibers are used to measure the photonic bang-dap of the colloidal photonic crystals. The results show that the center wavelength of SiO_2 colloidal crystal photonic band-gap is 1455.5 nm. And then, the refractive index of the liquid sensing experiment is measured by the colloidal crystals.

2. Theoretical analysis

Colloidal crystal has a periodic structure as the photonic crystals, the distribution of the dielectric constant for the colloidal crystal is periodic, and 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 analyze the band gap of colloidal photonic crystal.

* Corresponding author.
E-mail address: yanhaitaoyht@163.com (H. Yan).

0030-4026/$ – see front matter. Crown Copyright © 2013 Published by Elsevier GmbH. All rights reserved.
http://dx.doi.org/10.1016/j.ijleo.2013.09.083

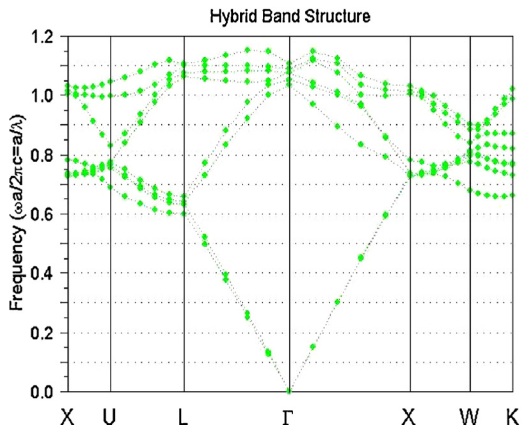

Fig. 1. Energy band diagram of the FCC structure colloidal crystal fabricated by SiO_2 microspheres.

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

$$H(r) = \sum_{G} H_G e^{i(k+G)r}, \quad (2)$$

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

$$H_G = H_G^1 \hat{e}_G^1 + H_G^2 \hat{e}_G^2, \quad (3)$$

In 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, $\nabla \cdot H = 0$. It requires each plane wave of the above formulas to meet $(k+G)\,H_G = 0$, and the $\{\hat{e}_G^1, \hat{e}_G^2, k+G\}$ combination 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:

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

This equation is simulated by Rsoft. Fig. 1 is energy band diagram of the face centered cubic (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 (1 1 1) direction in the colloidal crystal is prohibited at the reduced frequency. The center of the band-gap of reduced frequency $a/\lambda = 0.62$, a is periodic constant of colloidal photonic crystal. For the FCC structure crystal, the relationships between a and microsphere diameter D are $a = 1.414D$. Accordingly, the band-gap center wavelength of the colloidal crystal formed by 635 nm SiO_2 microspheres with FCC structure can be calculated at 1448.2 nm.

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]:

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

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.

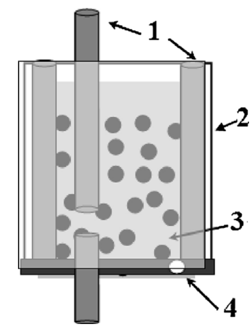

Fig. 2. Diagram of the device to fabricate colloidal crystals (1, fiber; 2, glass substrate; 3, colloidal solution; 4, silicone with a hole).

$n_{avg} = n_{SiO_2} f_{SiO_2} + n_f f_t$, where f_{SiO_2} 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°. For the FCC structure $f_{SiO_2} = 0.74$, $f_t = 0.26$, $d_{hkl} = 0.8165D$, when $m = 1$, Eq. (5) can be changed:

$$\lambda_{max} = 269.6 n_t + 1187.1, \quad (6)$$

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

3. Colloidal crystals fabricated and measured

3.1. 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 mold to fabricate colloidal crystals, and the mold diagram is shown as 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 mold between the glass substrates. And the two optical fibers are tested through light source 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 mold is formed.

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 °C, the colloidal solution is evaporated over after 20 min; 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 into a muffle furnace at 200 °C and sintered cured for 5 min.

3.2. 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