Optics & Laser Technology 64 (2014) 278–287

Contents lists available at ScienceDirect

Optics & Laser Technology

journal homepage: www.elsevier.com/locate/optlastec

Latest research progress on methods and technologies for tunable photonic crystals

Yong Zhao [a,b,*], Yu Ying [a], Qi Wang [a,b]

[a] College of Information Science and Engineering, Northeastern University, Shenyang 110819, China
[b] State Key Laboratory of Synthetical Automation for Process Industries, Shenyang 110819, China

ARTICLE INFO

Article history:
Received 19 November 2013
Received in revised form
6 May 2014
Accepted 27 May 2014

Keywords:
Tunable photonic crystal
Magnetic tuning
Thermal tuning

ABSTRACT

Tunable photonic crystal plays an important role for the fabrication of optical device. The photonic bandgap of it can be tuned by changing its crystal structural parameters or material dielectric properties. Research and development of the tunable photonic crystals will not only enrich the types of photonic crystal but also provide novel ideas and new methods for the development of optical devices. In the paper, the latest research progress on methods and technologies for tunable photonic crystal was reviewed. The relevant tuning principles were explained. The tunable photonic crystal was reviewed from five aspects including magnetic tuning, mechanical tuning, thermal tuning, electrical tuning and biochemical tuning. The representative examples were listed in detail, and advantages and applications of different tunable means were discussed. In the end, its development trend was predicted. The contents of this paper could provide assistance for the study and research of tunable photonic crystal, especially for the optical devices.

1. Introduction

Photonic crystals, which is also called optical semiconductor, are new artificial materials with a periodically modulated dielectric constant (seen in Fig. 1). The concept was first presented by Yablonovitch [1] and John [2]. The literature reported that photonic bandgap appeared in a certain wavelength range due to Bragg scattering of optical wave in the periodical dielectric structure. The photonic bandgap was relative to the periodical structure, based on the characteristic, tunable photonic crystal was first presented by Figotin [3]. In his paper, it was pointed that if the position or width of photonic bandgap could be tuned by external excitation, the photonic crystal was defined as tunable photonic crystal. There were a lot of advantages compared to traditional photonic crystal. The most obvious advantage was that the periodical dielectric constant and lattice constant of the traditional photonic crystals would keep stable after preparation, as for tunable photonic crystal, the periodical dielectric constant or lattice constant was flexible and easy tuned in a wide wavelength range even after preparation. This property had attracted more and more attentions from afterward researchers. Sure enough, after more than ten years of exploration and research, scientists had made significant advances on the theories and applications of tunable photonic crystal. Yoshino [4] presented a flexible tunable photonic crystal which was made of nanoscale polymer. When the force acting on the photonic crystal was more than 10 MPa, the periodical structure happened to deform, the central wavelength of reflectance spectra was red-shifted from 580 nm to 600 nm. Hiroyuki [5] presented a kind of two-dimensional tunable photonic crystal composed of copper oxide (a kind of high temperature superconductor). When the external temperature was increased from 5 K to 107 K, the dielectric constant change, the normalized frequency range of bandwidth would shift to high frequency from $0.2(a/\lambda)-0.39(a/\lambda)$ to $0.28(a/\lambda)-0.41(a/\lambda)$. Tian [6] presented a kind of one-dimensional tunable photonic crystal based on InSb. When the magnetic field along the direction of incident light was increased from 0 T to 0.42 T, the dielectric constant decreased, the eight photonic bandgaps located between 1.6×10^3 Hz and 4.0×10^3 Hz all transferred to low frequency about 10^3 Hz. Fei [7] presented a metallic tunable photonic crystal based on ferric oxide. When applied magnetic field was decreased from 36.2 T to 35.7 T, the effective refractivity would increase from 2.4 to 3.2.

The paper was reviewed from four parts. In the first part, the research background and significance of tunable photonic crystals was presented and the process of development was introduced simply. In the second part, the tuning principles of tunable photonic crystal were explained. The reason why optical properties changed was analyzed. In the third part, concrete tuning methods of tunable photonic crystal (magnetic tuning, mechanical tuning, thermal tuning, electric tuning and biochemical tuning) was introduced. Typical examples were given

* Corresponding author at: College of Information Science and Engineering, Northeastern University, Shenyang 110819, China.
E-mail addresses: zhaoyong@ise.neu.edu.cn, zhaoyong@tsinghua.org.cn (Y. Zhao).

http://dx.doi.org/10.1016/j.optlastec.2014.05.027
0030-3992/

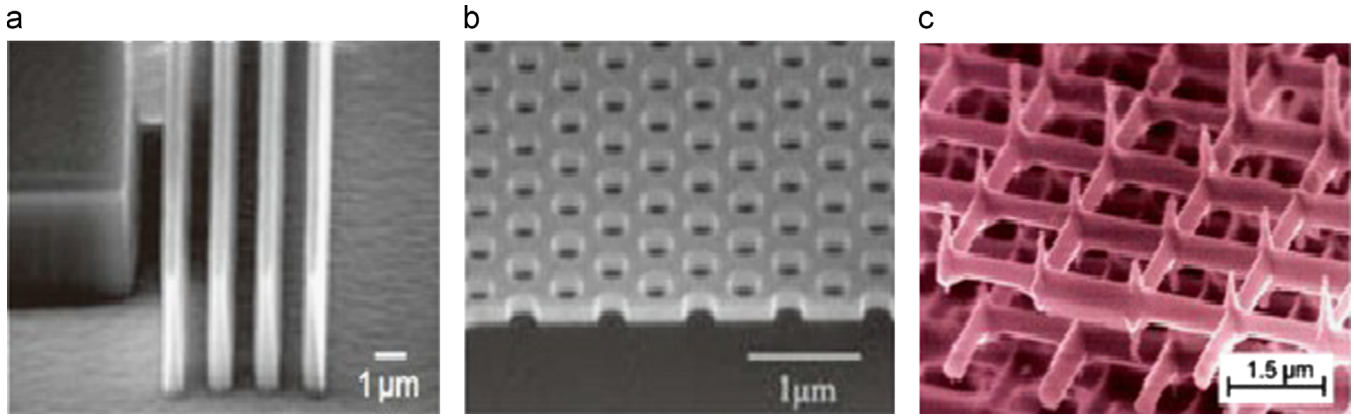

Fig. 1. Schematic illustrations of (a) one, (b) two, (c) three-dimensional photonic crystals.

to describe the tuning processes. It was pointed that there were wide applications on optical devices. In the last part, the content was summarized and the forecasts and outlook of tunable photonic crystal was made.

2. Tuning principles of tunable photonic crystals

Tunable photonic crystal is divided into two types, one is the tunable photonic crystal with tunability itself and the other is the tunable photonic crystal without tunability itself. For the former, structural parameters or material properties of it can be effectively tuned under the external excitation. For the latter, it will keep stable even under the external excitation. Because of the difference, the tunability can be realized mainly through two different principles. The first principle is to change both device geometry (lattice constant or medium pillar size) and material properties (dielectric constant or permeability). The second principle is to insert active material (solid or liquid, colloid and so on) which is sensitive to external excitation. The change of the effective refractive index is the final aim of the two tuning principles. The photonic bandgap can be calculated by plane wave expansion (PWE) [8], transfer matrix (TM) [9] and finite difference time domain (FDTD) [10].

2.1. Tuning by changing device geometry or material property

For the photonic crystal with tunability itself, the photonic bandgap of it is mainly relative to the device geometry or material property. Take a two-dimensional structure as an example in Fig. 2, it is composed of two periodical dielectric materials (dielectric cylinder and background medium). The dielectric constant of them are respectively ε_1 and ε_2. For some magnetic photonic crystals, it have permeability μ_1 and μ_2. The lattice constant and cylinder diameter are a and d.

The effective refractive index n_e can be expressed as:

$$n_e = f(a, d, \varepsilon_1,\ \mu_1) \quad or \quad n_e = f(a, d, \varepsilon_2,\ \mu_2) \tag{1}$$

from the formula, it is seen that the effective refractive index n_e is relative to crystal structure parameter (a,d), dielectric constant (ε_1, ε_2) and permeability (μ_1,μ_2). The tunability of the photonic bandgap is realized by changing the effective refractive index n_e, so it is concluded that the photonic bandgap can be tuned by changing periodic device geometry or material property.

2.2. Tuning by inserting active material

For most photonic crystals, crystal structure parameter or material dielectric property will keep stable after fabrication. If the effective refractive index is tuned, active material which is sensitive to external excitation should be introduced. As shown in Fig. 3, if several cylinders of two dimensional photonic crystals are removed, the defect mode will be formed. In the defect mode, active material is inserted into it, and the refractive index of active material can be tuned by the external excitation (magnetic field, temperature or pressure and so on).

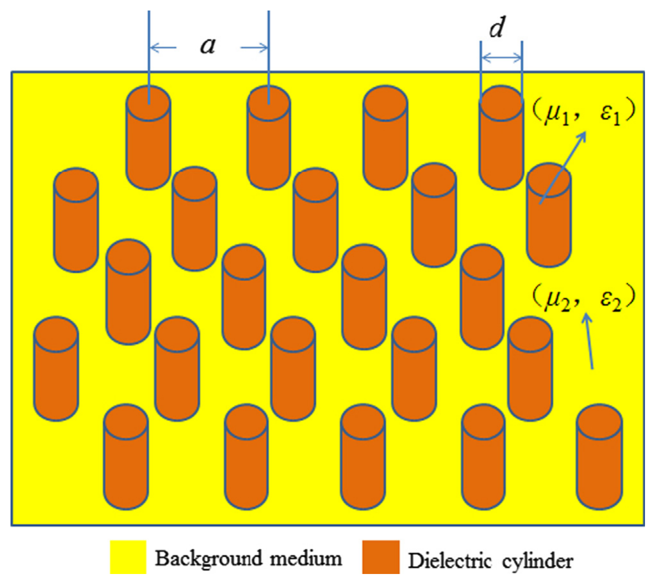

Fig. 2. Schematic of tunable photonic crystals with tunability itself.

The effective refractive index n_e is expressed as:

$$n_e = f(n_f), \tag{2}$$

in the formula, it can be seen that the refractive index of active material n_f is changed with the change of external excitation, so the effective refractive index of the integral structures can be tuned by external excitation. The principle is widely used in the research of tunable photonic crystals. The result shows that photonic crystal without tunability itself can also be tuned by external excitation.

3. Tunable photonic crystals

3.1. Magnetically tunable photonic crystals

3.1.1. Tunable photonic crystals based on magnetic fluid

Yang [11] presented a magnetically tunable photonic crystal based on magnetic fluid. As shown in Fig. 4, in his experiment, a three-dimensional of silicon cell with the thickness of 2 μm was