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Invited review

Tunable one-dimensional photonic crystals from soft materials

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ABSTRACT

Photonic crystals are periodic dielectric nanostructures that can affect the propagation of light. Polymer-based photonic crystals have attracted great attentions for their potential application as sensors or optical switches due to their stimuli-responsive properties. This review summarizes the recent developments in one-dimensional (1-D) polymer-based photonic crystals, including the inspiration of the material from nature, principles for design and fabrication, mechanism of color tuning, and their tunable structural color in responsive to various stimuli. A number of fabrication methods, either by bottom–up or top–down approaches for 1-D polymeric photonic crystals have been overviewed.

Contents

1. Introduction

Photonic crystals are periodic dielectric nanomaterials that can affect the propagation characteristics of light. The propagation of certain wavelengths of light is forbidden in these materials due to the photonic band gaps that originate from the periodic modulation of the dielectric medium. Photonic crystals widely exist in

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nature, which can be recognized by the bright and beautiful structural colors, such as the feather of peacock, fins and scales of tropical fishes, and wings and scales of beetles. These structural colors come from the diffraction of light on the periodic nanostructures on the surface of the natural creatures. During the prolonged evolution, the natural creatures have developed these perfect photonic structures to adapt to environment for surviving [1–4]. Since the pioneering work on photonic crystals by Eli Yablonovitch and Sajeev John in 1987 [5,6], it has prompted a surge of intensive studies and huge interest in this field leading to many of the recent investigation into photonic crystal fabrication techniques. A number of artificial photonic crystals, including one-dimensional (1-D), 2-D and 3-D, have been designed and developed during the past more than two decades [7–20]. The simple examples of one-, two-, and three-dimensional photonic crystal structures are shown in Fig. 1. The classification of dimensionality is determined by periodicity of dielectric materials along one or more axes [21]. Among them, one-dimensional (1-D) photonic crystals, also known as Bragg stacks, consisting of layered alternating materials with different refractive indices along one direction, have attracted great attention because of their simple structure, high reflectivity, convenient fabrication process, and relatively easy prediction of their optical properties. Interference of light reflected at the interfaces of the 1-D dielectric layers leads to strong reflection in a specific wavelength range, resulting in structural colors [22]. The reflection peak wavelength can be described by the Bragg's law, which models the crystal as a set of discrete parallel planes separated by a constant parameter d, (Eq. (1)) [8,23]:

$$m\lambda = 2d\sin\theta, \tag{1}$$

where m is the order of diffraction, λ is the peak wavelength, d is the layer thickness or spacing between the planes in lattice, and θ is the glancing angle between the incident light and diffraction crystal planes. On the other hand, a more precise description of the reflection peaks can be made by combining Bragg's law and Snell's law. The wavelength position of the normal incidence for 1-D photonic structures is given by Bragg–Snell law (Eq. (2)) [24,25]:

$$m\lambda = 2(n_1 d_1 + n_h d_h) \tag{2}$$

where m is the diffraction order, λ is the peak wavelength, n_l,n_h are the refractive indices of the low-, and high-reflective index materials, respectively, and d_l, d_h are the thickness of the two alternating layers. From the equation, the wavelength of the reflected light from a multilayer material depends on the optical thickness ($n_i d_i$) of each layer. Each interface between layers reflects an amount of incident light dependent on the index contrast between the layers. Either an increase in the physical thickness or an increase in the effective refractive index of the alternating layers leads to a shift in the position of the Bragg diffraction peak [22].

The intensity of the diffraction wavelength, R, is given by the following equation (Eq. (3)) [26]

$$R = \left(\frac{1-Y}{1+Y}\right)^2 \times 100\%, Y = \frac{n_s}{n_0}\left(\frac{n_1}{n_h}\right)2N \tag{3}$$

where n_s is the refractive index of the substrate, n_0 is the refractive index of the surrounding medium, and N is the number of bilayers. It shows that the percentage reflectance, R, increases with increasing values of the reflective-index contrast ratio and with the number of layers. These equations tell the starting point for the design of 1-D photonic crystals and provide the guidelines for the development and applications of color tunable photonic crystals. The reflective index, n, can be tuned by chemical structure or composition change of the materials, and the layer distance, d, can be modified by controlling the fabrication parameters. The change of the layer distance could cause a more significant structural color tuning than the effects of the refractive index change. Most of the tunable 1-D photonic crystals are based on the modulation in layer thickness accompanied with change in the refractive index [22].

At the very beginning, the researches have mainly focused on photonic crystals fabricated from "hard materials", which have a limited or no color tuning. They are commercially used as high efficiency thin film optics like dielectric mirrors or optical filters, which reflect certain frequencies of light [27,28]. With the progress of photonic crystals, a strong demand for fabricating these materials from "soft materials" that the color can be changed under external stimuli is generated. Such materials, with significantly improved quality of the color, sensitivity, response rate, durability and selectivity, have great potential application in the sensors and optical switches. The best strategy to fabricate such materials is to embed the photonic band-gap structure in soft polymeric matrix, such as gels or elastomers. For instance, gel is a physically- or chemically-crosslinked polymer network containing sufficient amount of solvents. A gel is easily deformable and undergoes reversible volume change upon changes in the environmental condition, such as pH and temperature of the solvent [29–31]. The gels containing photonic structure, called as photonic gels, are then easy to change their color in response to the external stimuli due to modulation of the refractive index or lattice dimension. The hidden information, such as stress, pH or temperature change in the environment can be revealed by the optical signals of these materials and the photonic effect can be used as mechanism for developing chemical, physical or biological sensors.

In this review, we mainly discuss the recent developments in the 1-D polymer-based photonic crystals, including the inspiration of biomimetic approaches, design and fabrication principle, color tunable mechanism and their potential application as sensors or color switch indicators.

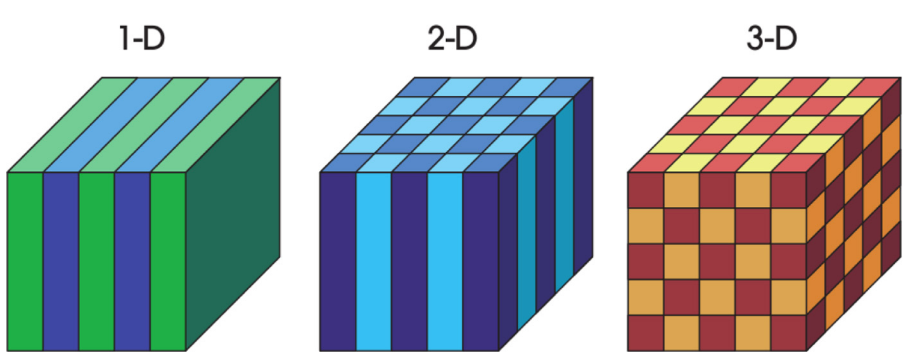

Fig. 1. Simple examples of one-, two-, three-dimensional photonic crystal structures. Reprinted with permission from Ref. [21].