Structural Colored Fibers Based on Photonic Crystal Structures by Colloidal Assembly

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Abstract: In this paper the perspectives of structural colored fibers based on photonic crystal structures are discussed. These fibers display the distinctive colors, which are determined by the lattice constants of the photonic crystals. The color-changing capability of photonic fibers with potential applications in dynamic signage and environmentally adaptive coloration is demonstrated. The fibers are fabricated by the silica or polystyrene colloidal particles to the periodically ordered interconnecting structure in a cylindrical shape. The visible light is coherently diffracted on the surface of the fibers, which produces a shinning color in a narrow range of wavelength. Importantly, no dyes or colorants are used in fabrication of such fibers, thus making the fibers resistant to color fading. This method of making colorful fibers could be a promising way to reduce environmental pollution in the dying industry. Additionally, by changing the reflective index or lattice constant of a photonic fiber, its reflected colors change proportionally to the shift of reflective index or lattice constant, thus enabling visually interactive and sensing textiles responsive to the external stimuli.

Keywords: Structural color, photonic crystal, colloidal particle, fiber.

1. Introduction

Dyeing is one of the key steps in the textile industry. The purpose of dyeing is to let the fabrics appear in different colors for human's sensory enjoyment. The chemical colorant or pigment is attached onto the fabrics to produce the colour during the dyeing process. This process requires a huge amount of fresh water to dissolve the pigments and flush the fabrics. Eventually the unabsorbed remains of the pigments in the water form the industrial sewage. If it was discharged into the surrounding area, it will give rise to severe pollution issues to the environment. This kind of dyeing sewage contains highly-concentrated organic pollutants and is extremely difficult to be degraded by chemical or biological methods. Hence the dyeing sewage is impossible to be regenerated and recycled. Due to the above mentioned disadvantages, the dyeing sewage becomes one of the main sources of the industrial pollutions on earth.

To reduce the sewage discharge from the textile industries, many green and clear production processes are adopted by the textile manufacturers, e.g. pre-processing techniques and improved dyeing methods [1,2]. All these methods significantly reduce the pollution discharge and save the energy and mass consumption in the dyeing process; nevertheless, they are still based on the chemical molecular adsorption. Consequently the problems in the textile industries are hardly solved without a revolutionary way. Moreover, the global climate change caused by excessive greenhouse gas emissions results in mankind suffering from frequent disasters. The recent Copenhagen conference conveys a clear message that the reduction of the pollution, hazardous gases and resource-consumption is a vital action for stopping the global warming [3].

In this work a coloring strategy through a structural color method is proposed by incorporating the photonic crystal structures onto the thin fibers. In the second section, the basic concepts on the photonic crystals are introduced. In the third part, the primary results of the experiments are presented. Finally, a brief conclusion is derived and explained.

When the visible light is incidenting onto certain periodic structures, only the light with a specific wavelength will be diffracted. Thereby, the objects with the periodic structures are exhibiting a specific color. Since this coloring is due primarily to the lattice spacing owned by the periodic structures, it is called as "structural color" [4]. Whereas, the dielectrics with a spatial periodic structure are given by the name of "photonic crystals" [5]. The concept of photonic crystal is proposed by E.Yablonovitch and S. John in 1987 [6,7].

2. Photonic crystal and structural color

In this section, the mechanism of the structural color produced by the photonic crystals will be introduced.

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The current trends on the structural colors will be reviewed. Consequently, the fabrication method on the photonic crystals will be discussed.

2.1 Photonic crystal

Photonic crystals are regular arrays of materials with different refractive indices. The simplest case is that two materials with the distinctive reflective indices are stacked alternately in one dimension. The spatial period of the stack is called the lattice constant, since it corresponds to the lattice constant of ordinary crystals composed of a regular array of atoms. Actually, many basic ideas are common to both crystals and they will be utilized to build fundamental theories of the photonic crystals. However, one big difference between them is the scale of the lattice constant. In the case of ordinary atomic crystals, the lattice constant is on the order of angstroms. On the other hand, it is on the order of the wavelength of the relevant electromagnetic waves for the photonic crystals. For example, it is about 1 μm or less for visible light, and is about 1 cm for microwaves.

If a 3D photonic crystal is designed appropriately, there appears a frequency range where no electromagnetic eigenmode exists. Frequency ranges of this kind are called photonic band gaps, since they correspond to band gaps of electronic eigenstates in ordinary crystals.

The transmission spectra of photonic crystals reflect their band structure directly. They are often used for the experimental characterization of real specimens. Generally, the numerical calculation, such as the plane-wave expansion method, is utilized to calculate the transmittance and the Bragg reflectivity of 2D crystals. It has been demonstrated that the band gaps and the uncoupled modes lead to opaque frequency ranges, which correspond to the reflective light. It will also be shown that the small group velocity peculiar to the 2D and 3D crystals, that is, the group-velocity anomaly, is equivalent to a large effective refractive index. However, the behavior of the light on the surface of cylindrical photonic crystals, especially the diameter of the fibers is close to the wavelength of light, is still puzzling.

2.2 Structural color

The structural color is a common phenomenon in nature, especially among living things. The study of structural color based on the biological microstructure is one of the most important research areas in biomimicry [8-10]. Microstructure plays many important roles in living things. For example, the charming blue color of the Morpho sulkowskyi butterfly originates from light diffraction and scattering, which results from the ordered microstructure of its scales. The animals and insects are usually utilizing the structural color both for protection and warning. Today, the study of structural color has been extended from biology to optics [11]. The structural color is caused by the Bragg diffraction of visible light from the ordered voids regarded as crystallites. The peak values of reflection spectra, $\lambda_{\max}$, for the periodic colloidal crystal are obtained by

$$\lambda_{\max} = 1.633\left(d/m\right)\left(n_a^2 - \sin^2\theta\right)^{1/2};$$

where d is the diameter of a colloidal particle, m is an integral representing the order of diffraction, n_a is the refractive index of the colloidal particles at a certain condition, and θ is the angle measured from the normal to the plane of the crystal.

Currently the tunable structural color devices based on the photonic crystals have been intensively investigated by the frontiers, such as Seung-Man Yang [12] and Yukikazu Takeoka[13] etc. The recent progress focuses on the application of the photonic structural colors in the areas of inkless printing, reflective flat display and gas sensing [14-16].

2.3 Fabrication of photonic crystal

Photonic crystals are classified mainly into three categories, that is, one-dimensional (1D), two-dimensional (2D), and three-dimensional (3D) crystals according to the dimensionality of the stack [17]. The natural photonic crystal is very rare. Therefore, the photonic crystals are artificially made by the dielectric materials owing to the periodic structures. The photonic crystals that work in the microwave and far-infrared regions are relatively easy to fabricate. Those that work in the visible region, especially 3D ones are difficult to fabricate because of their small lattice constants. However, various technologies have been developed and applied to their fabrication in the last ten years, and many good crystals with a lattice constant less than 1 μm are now available. There are three kinds of methods to fabricate the photonic crystals by utilizing nanostructure fabrication (e-beam lithography, etc.), laser holography and colloidal assembly etc. The method of lithographic fabrication has the disadvantages of sophisticated technical flows and high costs; the method of laser holography is limited by the types of photosensitive resin materials.