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Study on the correlations between the structural colors of photonic crystals and the base colors of textile fabric substrates

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ABSTRACT

Three typical colloidal microspheres were synthesized to fabricate three-dimensional photonic crystals on the polyester fabrics in different base colors by vertical deposition self-assembly. The influences of different kinds of base colors on the final colors of the assembled fabric substrates and the related iridescent phenomena were deeply investigated. The results showed that the white base color could dilute the structural color of the photonic crystals to greatest extent, however, the black base color could highlight the structural color at the most extent. If the base color of fabric substrate has the similar hue to the structural color of photonic crystals, it has little influence on the final color of the assembled fabrics. However, the final color has the lower saturation if the base color of fabric substrate is the complementary color of the photonic crystals. In addition, the assembled fabrics in various base colors still have the iridescent phenomena.

1. Introduction

Dyes and pigments can produce the colors because they selectively absorb and reflect certain wavelengths of visible light [1]. Structural colors, in contrast to those produced by pigments or dyes, arise from the physical interaction of light with biological nano-structures [2,3]. In other words, structural colors are exclusively on the shape of the material and not its chemical properties [4,5]. We can observe the structural color in natural life forms, for example, in peacock feathers, outer shells of jewel beetles, wings of Morpho butterflies and many other insects [6–8]. While pigments and dyes degrade and their colors fade over time, some types of structural coloration can persist hundreds, thousands, and even millions of years after the death of the organism.

Photonic crystals (PCs) are regarded as a kind of dielectric material with a highly periodic structure, having the capacity to confine and control the propagation of light owing to the existence of a photonic band gap, a band of frequency where light propagation in photonic crystals is forbidden [9–11]. If the photonic band gap falls into the visible light range between 380 and 780 nm, visible light of specific wavelengths is not allowed to propagate in the photonic crystal structure, thus being selectively reflected. Structural colors are then produced on the surface of periodic photonic crystals, completely different from the traditional coloration principles of dyes and pigments in textiles.

In our previous study, we have fabricated a series of photonic crystals on textile fabrics by colloid self-assembly and verified that the structural colors originated from the related photonic crystals can readily be controlled by adjusting the size of the colloidal microspheres and the viewing angles [12–14]. However, in practical textile application, especially for dyed or printed fabrics with some patterns, if we plan to fabricate photonic crystals in some special positions on the fabrics, before the design steps we have to foresee the possible colors of the fabrics after the self-assembly. However, the correlations between structural colors and pigmentary colors on textile fabrics have been seldom reported.

In this paper, silica (SiO_2), silica/polystyrene (SiO_2@PS) and polystyrene/methacrylic acid (PS@MAA) photonic crystals were fabricated on the polyester fabrics by vertical deposition self-assembly. By controlling the structural colors of the photonic crystals and the base colors of the fabrics, the color changes and the related possible mechanisms between the structural colors of the photonic crystal and the base colors of the fabric substrates were deeply investigated. It is believed that the related research work will further promote the application prospects of structural colors in textile fields.

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2. Experimental

2.1. Reagents and materials

Tetraethylorthosilicate (TEOS, A.R. grade, Kermel Reagent Factory, Tianjin, China), ethanol (A.R. grade, Jiani Reagent Factory, Wuxi, China), ammonia (A.R. grade, Gaojing Chemical Reagent Factory, Hangzhou, China), 3-(Trimethoxysilyl) propyl methacrylate (MPS, A.R. grade, Aladdin Industrial Corporation, Shanghai, China), potassium persulfate (KPS, A.R. grade, Aijian Reagent Factory, Shanghai, China) and ammonium persulfate (APS, A.R. grade, Yongda Reagent Factory, Tianjin, China) were used without further purification. Styrene (St, A.R. grade, Yongda Reagent Factory, Tianjin, China) and methacrylic acid (MAA, A.R. grade, Kemiou Chemical Reagent Factory, Tianjin, China) were purified by distillation under reduced pressure. Nitrogen (98%, Jingong Specialty Gases Co., Ltd., Hangzhou, China) was used as received from laboratory. Plain weave polyester fabrics of the same texture in different base colors were bought from the local textile market. Deionized water (>18 MΩ cm, Millipore Milli-Q) was obtained from a Millipore-Q Plus water purifier and used throughout the experiments.

2.2. Synthesis of monodisperse colloidal microspheres

2.2.1. SiO_2 colloidal microspheres

The monodisperse SiO_2 colloidal microspheres were prepared by Stöber method through the hydrolysis and condensation-polymerization of tetraethylorthosilicate $Si(OEt)_4$ (98%, AR) in water-ethanol mixed solution with ammonia as a catalyst [15]. Firstly, 3 ml $NH_3 \cdot H_2O$, 8 ml H_2O and 100 ml C_2H_5OH were added to the three-necked round-bottom flask successively with a magnetic agitation (350 rpm) at 25 °C. After 10 min, 6 ml TEOS dissolved in 20 ml C_2H_5OH were introduced into the reactor within 15 min. Furthermore, in order to obtain monodisperse SiO_2 microspheres, it is important to keep a constant reaction temperature at 25 °C and the mixture should be stirred for 20 h with a magnetic stirrer (350 rpm).

2.2.2. SiO_2@PS colloidal microspheres

The monodisperse SiO_2@PS composite microspheres were synthesized by emulsion polymerization with grafted SiO_2 microspheres as seeds, St as monomer, SDBS as emulsifier, $NaHCO_3$ as buffer agent and KPS as an initiator [16]. The grafted SiO_2 microspheres were prepared by Stöber method mentioned above and modified by MPS at 40 °C for 24 h. Synthesis were carried out in a 250 ml four-necked round-bottom flask equipped with an inlet of nitrogen gas, a reflux condenser, thermometer and a paddle-type agitator. In a typical experiment, 0.1 g of grafted SiO_2 microspheres (95 nm in diameter) dispersed in 10 ml of ethanol by ultrasonication, 10 ml St, 0.1 g SDBS, 0.24 g $NaHCO_3$ and 95 ml H_2O were added to the four-necked round-bottom flask. When the mixture was heated to 80 °C, 0.1 g KPS dissolved in 5 ml H_2O was introduced into the reactor. The reaction mixture was kept at 80 °C for 10 h. The whole reaction was carried out in nitrogen atmosphere with mechanical stirring at around 350 rpm.

2.2.3. PS@MAA colloidal microspheres

The monodisperse PS@MAA microspheres were prepared by soap-free emulsion copolymerization [17]. With one sample as an example, 20 g of St, 3 g of MAA, and 195 g of H_2O were added to the four-neck round-bottom flask. When the mixture was heated to 70 °C, 0.1 g of APS dissolved in 5 g of H_2O was added to the reactor. The reaction was maintained at 70 °C for 8 h. The whole reaction was carried out in nitrogen atmosphere with mechanical stirring at around 350 rpm.

It is noted that if the reaction parameters can be varied and controlled well, we can obtain the above colloidal microspheres in different diameters.

2.3. Fabrication of photonic crystals on polyester fabrics by vertical deposition

In our study, SiO_2, SiO_2@PS and PS@MAA colloidal microspheres were used to fabricate photonic crystals by vertical deposition self-assembly on plain woven polyester fabrics. Firstly, colloidal microsphere suspensions were diluted to 1.0 wt% in deionized water, and vibrated by ultrasonic for about 5 min. Then, a piece of polyester woven fabric was vertically placed in a glass bottle which was subsequently filled with the dilute microsphere suspension. Finally, the polyester fabric with the dilute microsphere suspension was located in a vacuum drying oven at a constant temperature of 60 °C with a relative humidity of 40–60% for more than 72 h dependent on various deposition rates of colloidal microspheres [18]. After drying the sediment, water in the colloidal suspensions were evaporated and the structural colors of photonic crystals on polyester fabrics were obtained.

2.4. Characterization

2.4.1. Particle size and monodispersity

The average hydrodynamic diameter and particle dispersion index (PDI) of colloidal microspheres were determined by a Malvern laser particle sizes analyzer (Nano-S, Malvern, England). It is noted that the colloidal suspensions were diluted approximately 1000-fold with Milli Q water before measurement.

2.4.2. Surface morphology

The morphology of colloidal microspheres was observed by a field emission scanning electron microscopy (FESEM, ALTRA55, Germany) and a transmission electron microscope (TEM, JEM2100, Japan). Moreover, the surface morphology of photonic crystal was also observed by a field emission scanning electron microscopy (FESEM, ALTRA55, Germany).

2.4.3. Structural color and iridescence

The colors on the polyester fabrics were observed by a digital camera (EOS600D, Canon, Japan) and a 3D video microscope (KH-7700, HIROX, Japan). The reflectance spectra of the colors on polyester fabrics were recorded in the range of 400–700 nm on a UV–Vis Spectrometer (Lambda 900, PerkinElmer, USA). Note that the colors and the reflection spectra were measured at normal incidence. The color difference of the samples were measured by DigiEye Imaging System (Digifull, VeriVide, Britain) in according to a Commission International de L'Eclairage(CIE) LAB color scale. The iridescence of structural colors was recorded by a digital camera (EOS600D, Canon, Japan) and a multi-angle spectrophotometer (MA98, X-Rite, USA) with colorimetric illuminant of D65 and colorimetric standard observer of 10°. The MA98 multi-angle spectrophotometer is an intelligent, hand-held tool based on reflection measurements, and it can provide the images, L*a*b*values and reflectance spectra of the samples under various viewing directions. The measurement geometries were as follows: the sample was directionally illuminated at 45° from the normal, and the aspecular viewing angles in plane were at −15°, 15°, 25°, 45°, 75°, and 110°; the secondary illumination was at 15° from the normal, and the aspecular viewing angles in plane were at −15° and 15°. The intensity of reflectance spectra measured by this multi-angle spectrophotometer was in the range of 0–400% and the reflectance data were in agreement with the ASTM E2539-08 [19–22].