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Review article

Recent advances in spherical photonic crystals: Generation and applications in optics

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ABSTRACT

Spherical photonic crystals (PCs), generated by assembly of monodisperse colloidal nanospheres in a spherical confined geometry, attract great attention recently owing to their potential applications in the fields of displays, sensors, optoelectronic devices, and others. Compared to their conventional film or bulk counterparts, the optical stop band of the spherical PCs is independent of the rotation under illumination of the surface of a fixed incident angle of the light, broadening their applications. In this paper, we will review recent advances in the field of spherical PCs including design, preparation and potential applications. Various preparation strategies for spherical PCs, including solvent-evaporation induced crystallization method, microfluidic-assisted approach, and others are outlined. Their applications based on the unique optical properties (such as photonic band gaps and structural colors) for sensing and displaying are then presented, followed by the perspective of this emerging field.

Contents

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1. Introduction

Photonic crystals (PCs) are structured materials where the refractive index is periodically modulated that can affect the propagation of light [1]. Interaction of the light waves and PCs (such as interference or scattering) leads to omnidirectional reflection or photonic band gaps (PBGs). In PBGs, light propagation will be forbidden and PCs will appear various brilliant colors, namely structural colors. Owing to their unique optical properties (PBGs and structural colors), PCs have attracted increasingly attention of the researchers in the last two decades, and have been widely applied in different fields such as optoelectronic devices, actuators, filters, sensors, and displays [2–10]. A number of methods, including top-down methods (such as interference lithography or deposition technique) and bottom-up methods (e.g., colloidal or block copolymer assembly) have been developed to fabricate PCs with varied structures and shapes at various length scales. Compared to the top-down techniques, the bottom-up methods, especially colloidal assembly, show more advantages such as low cost, easy operation, large-area fabrication. Up to now, colloid assembly has become the most promising technique for preparing three-dimensional colloidal PCs. To meet the requirements of practical applications, most of colloidal PCs have been made into thin film or bulk materials, which show different colors at various viewing angles that limit their extensive applications. To overcome the drawback of PC thin films, spherical PCs have been developed, whose optical stop band is independent of the rotation under illumination of the surface at a fixed incident angle of the light due to the spherical symmetry, broadening their perspective of applications. Some simple methods such as evaporation-induced crystallization or emulsification technique have been created to prepare spherical PCs; however, it is time-consuming and hard to obtain monodisperse spherical PCs with desired structures. Recently, great progress in the fabrication of monodisperse spherical PCs has been made by using the assisted methods such as electro-spraying or microfluidic-assisted approach. These newly developed methods not only can ensure the monodispersity of spherical PCs, but also can enable the fast preparation and structure tunability, paving the way for the development of advanced optoelectronic devices.

In this review, various synthesis strategies for generating spherical PCs will first be discussed, including solvent-evaporation induced crystallization method, the assisted methods such as electric, microfluidic-assisted method. Potential applications of spherical PCs in optics will then be outlined.

2. Strategies for the fabrication of spherical PCs

2.1. Spherical PCs fabricated by solvent-evaporation induced crystallization method

Solvent-evaporation induced crystallization method is first developed to prepare spherical PCs owing to its simplicity. In nature, colorful opals are natural PCs which originate from the self-assembly of silica nanospheres. To ensure the formation of the PCs, monodisperse colloidal nanospheres, including hard nanospheres (such as silica or polystyrene (PS) nanospheres) or soft nanospheres (e.g., microgels) are first synthesized through conventional synthesis methods such as stöber method or emulsion polymerization [11,12]. Monodisperse colloidal nanospheres can self-assemble into the crystal structure (e.g., face-centered cubic (fcc) structure) spontaneously during the evaporation of aqueous suspension of nanospheres. Thus, to realize the fabrication of spherical PC, spherical shape of the droplets containing nanospheres should be maintained during the whole process of solvent evaporation. The superhydrophobic substrate can offer a platform for the formation of spherical droplets. The suspension of monodisperse nanospheres can be sprayed or dropped on the superhydrophobic substrate by using the sprayer or micropipette, respectively; the droplets can be fixed on the substrate and form perfect spherical shape due to the interfacial tension among solid, liquid and air phases and the superhydrophobic effect of the substrate [13,14]. With the solvent (e.g., water) evaporation, the droplets occur to shrink and the nanospheres self-assemble at the interface of liquid and air. Finally, the solid spherical PCs can be obtained after fully evaporating the solvent. Also, the spherical droplets can be obtained by dropping the droplets on the surface of immiscible oil [15], as shown in Fig. 1a. To

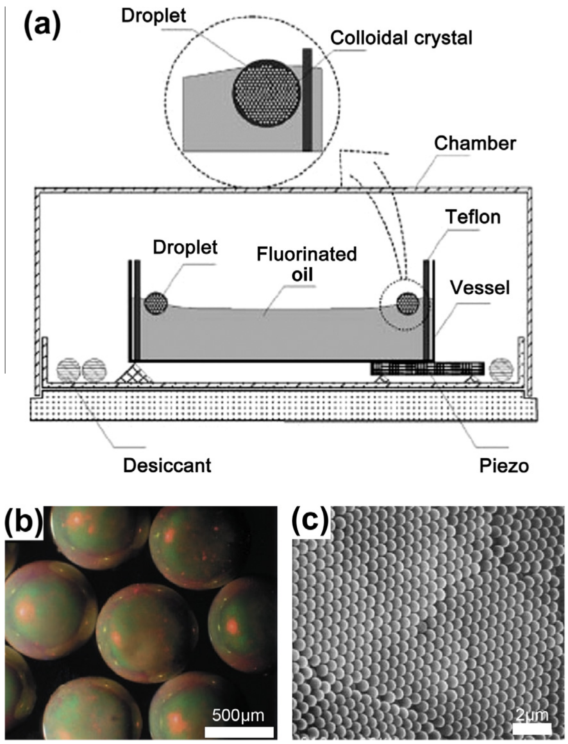

Fig. 1. (a) Schematic illustration showing the formation of spherical PCs through nanospheres assembly approach. The template aqueous droplets are suspended on the surface of fluorinated oil and colloid crystals are formed during the drying process. (b) Optical micrograph of spherical PCs obtained from 270 nm latex particles. (c) SEM image of the surface of a spherical PC. Adapted from Ref. [15].