Available online at www.sciencedirect.com
ScienceDirect
Photonics and Nanostructures – Fundamentals and Applications 6 (2008) 194–199
PHOTONICS AND NANOSTRUCTURES Fundamentals and Applications
www.elsevier.com/locate/photonics

One-dimensional opal photonic crystals

A.M. Kapitonov *

Medical and Biological Physics, Grodno State Medical University, Gorkogo Str. 80, Grodno 230015, Belarus

Received 16 June 2008; received in revised form 18 August 2008; accepted 18 August 2008
Available online 22 August 2008

Abstract

One-dimensional opals are 1D self-assembled close packed colloidal crystals consisting of monodisperse colloidal globules. Polystyrene globules with sizes in the 1.9–10 μm range sit on a flat substrate and touch two neighbors in diametrally opposite contact points. These opals are quasi-1D photonic crystals. Optical modes, including whispering gallery modes of individual globules, coupled collective modes, and nanojet-induced modes, are visualized in 1D opals.

PACS : 42.70.Qs; 78.67.−n

Keywords: One-dimensional; Opal; Photonic crystal

1. Introduction

Highly ordered assemblies of colloidal particles, named colloidal crystals, have attracted much attention since they are accessible prototypes of photonic band gap materials [1,2]. Opals are solid state colloidal crystals composed of a sub-micron or micron-sized monodisperse [3] spherical particles. Natural opals consist of the silica globules while preparation of artificial opals is possible with various materials, such as polystyrene (PS) and polymethyl methacrylate (PMMA). Globules self-assemble in close-packed layers which, in turn, form 3D lattice. Porous internal structure enables doping of opals. Resulting photonic crystals exhibit peculiar luminescence [4] and lasing [5] due to the alteration of the photon density of states. The search for materials with complete (omnidirectional) photonic band gap led to development of opal replicas made of high refractive index materials, such as titania [6], zinc oxide [5], and silicon [7]. Further functionalization of opals opens up the range of applications besides photonics [8–10].

Reducing size of opal in one dimension has natural limit when only the single close-packed layer of globules remains. Such ordered layers of monodisperse particles are commonly referred to as 2D colloidal crystals [11,12]. This is the ultimate case of a two-dimensional opal, which holds characteristic 2D (more precisely, quasi-2D) optical modes [13–15]. Translational symmetry of the refractive index, which is the key feature of any photonic crystal structure, still exists along the plane of 2D colloidal crystal. However, 2D opals do not fit in a prevailing convention assuming photonic crystals infinitely large in those dimensions where refractive index is not periodic.

For one-dimensional structures same terminological discrepancy exists. Conventional embodiment of 1D photonic crystal is nothing but a periodic stack of optical films, a simple kind of interference mirror. The ease of corresponding ‘‘one-dimensional’’ equations is favored by those exploring abstract models. Experiments

* Tel.: +375 152 434642; fax: +375 152 435341.
E-mail addresses: kapitonov.andrey@grsmu.by, kapitonov_andrey@hotmail.com.

1569-4410/$ – see front matter
doi:10.1016/j.photonics.2008.08.004

with arrays of colloidal globules are usually discussed in terms of "photonic molecules" or coupled optical resonators (for recent comprehensive guide in this field see, *e.g.*, Ref. [16]) while 1D periodicity of the refractive index remains unattended. This article introduces one-dimensional opals, which are close-packed linear arrays of monodisperse colloidal globules. We discuss a possibility of considering 1D opals as quasi-1D photonic crystals based on a fact that translational symmetry is provided by reasonably large number ($\sim 10^2$) of globules in the line. Modified photon density of states is inherent to photonic crystal structures. A number of optical modes reported here, both localized and propagating, are visualized in 1D opals by means of spectral imaging technique.

2. Results and discussion

2.1. Sample preparation

Preparation of opals reported here is based on the self-assembly of PS ($n = 1.59$) globules suspended in aqueous environment. 3D and 2D colloidal crystals can be obtained already by means of free drying of the suspension on a flat substrate, provided that globules are monodisperse (see insets in Fig. 1(b) and (c)). Arranging of globules into 1D opal strings requires some more control over the colloidal crystal growth. In particular, self-assembly directed by micro-flows of a precursor suspension [17] was utilized. Pipe-like flows were organized with cover glass substrates ($n = 1.52$), "pinning" points are seeded by a larger size spheres (which statistically occur in ensembles of globules [18]). With exhausting suspension source such pipe-flows shrink, reaching the diameter of globules in cross-section. At this moment globules move in series along the pipe-flow and consecutively stack in a close-packed 1D opal, which becomes mechanically robust after drying. 1D opals have being made with globule size ranging from 1.9 to 10 μm, what enables both convenient *in situ* monitoring of the assembling process and subsequent characterization with far-field optics.

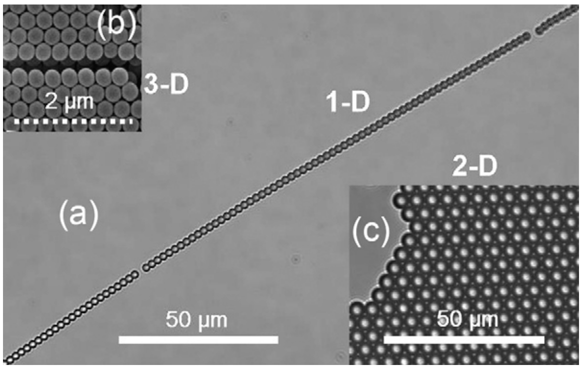

Fig. 1. (a) Optical image of one-dimensional opal (mark 1D) composed of 2.2 μm polystyrene globules. Opal-like PS structures of higher dimensionalities are given in the insets. (Upper-left, b) SEM image of three-dimensional opal (mark 3D) of 0.3 μm beads. (Lower-right, c) Optical image of two-dimensional (mark 2D) opal of 5 μm globules.

2.2. Morphology of 1D opals

Fig. 1(a) gives an example of one-dimensional polystyrene opal. The size of PS globules is 2.2 μm, thus internal structure of the sample is easily accessible with combination of optical microscope objective and CCD camera. About one hundred of microspheres fit into the field of view while individual globules are still distinguishable. There is defect-free domain of 1D colloidal crystal lattice (marked 1D in Fig. 1(a)) consisting of 66 globules. This domain is terminated with vacancies at both sides. Nevertheless 1D opals can be quite macroscopic in size, reaching millimeters in length. This is similar to the case of 3D and 2D opals, which are also polycrystalline [13,19]. Seemingly, the polycrystallinity of opals can be drastically reduced if synthesis routines involve seeded self-assembly. Such optimization needs to be done in future.

2D and 3D opals have also being prepared from similar PS globules for comparison. Upper-left inset in Fig. 1(b) shows SEM picture of 3D opal composed of 0.3 μm globules: Underlying layers of globules are visible in the crack. Lower-right inset (c) presents optical image of 2D monolayer of 5 μm globules. There is clear logical correspondence between 1D, 2D, and 3D opals: 1D samples possess the simplest linear close-packed structure with 1D periodicity conditioned by the monodispersity of globules. When such 1D lines adjoin to each other on a plane in the most compact manner, one arrives to the 2D opal layer with globules close-packed in a hexagonal 2D lattice. 3D opals obey apparently most sophisticated design rule, according to which 2D layers should be stacked together in order to form close-packed 3D lattice (fcc symmetry with stacking faults is often attributed).

Fig. 2(a) presents a 0.5-mm long portion of 1D opal obtained with lower magnification than in Fig. 1(a). The array is strictly linear along its whole length. Individual globules are still distinguishable due to their larger size, which is equal to 10 μm. Magnified image of smaller segment containing seven globules is shown in the upper-left inset in Fig. 2(b). It is resolved quite well that each sphere sits in a proper position: There is no gap