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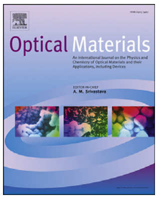

Method of determining dispersion dependence of refractive index of nanospheres building opals

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The method of determining dispersion dependence of refractive index of nanospheres building opals is presented. In this method basing on angular dependences of the spectral positions of Bragg diffraction minima on transmission spectra for opal series of known spheres diameter, the spectrum of effective refractive index for opals and then refractive index for material building opal's spheres is determined. The described procedure is used for determination of $n_{eff}(\lambda)$ for opals and $n_{sph}(\lambda)$ for material which spheres building investigated opals are made of. The obtained results are compared with literature data of $n_{SiO2}(\lambda)$ considered in the analysis and interpretation of extremes related to the light diffraction at (*hkl*) SiO_2 opal planes.

1. Introduction

The aim of this paper is to present a method for determining the dispersion dependence of the refractive index of nanospheres building synthetic opals. Such opals are a matrix for the production of photonic crystals of inverse opal structure. These structures can be used in fabrication of different devices which can be applied in many fields such as optoelectronics, telecommunications, thermophotovoltaics, sensors applications, electrochemical energy storage [1].

Photonic crystals are materials with a periodically modulated dielectric constant [2]. This is implemented technologically by the periodic arrangement of materials having different dielectric constants in a structure of designed symmetry. This results in the formation of the photonic band gap in the photonic band structure, which is affected by such parameters as the size of spheres building opal and the effective refractive index (n_{eff}). As it has been presented in Ref. [3], these parameters can be designated in the spectrogoniometric research. The correct interpretation of n_{eff} requires the knowledge of a refractive index of opal-building spheres (n_{sph}). So far in the literature there have been applied two approaches. One assumes [4,5] that the spectrum of the refractive index of opal-building silica spheres is the same as the spectrum of the refractive index of fused silica. The second one takes the refractive index value determined for the SiO_2 spheres that is independent of the wavelength (eg. Ref. [6]). Since both of these approaches can produce only approximate results [7], in the presented paper an entirely new method for determining the dispersion dependence of the refractive index of opal-building spheres is suggested. This method is based on the assumption that the refractive index of the material that builds spheres as well as the filling factor of opals with spheres (f_{sph}) are the same for opals made from spheres of different diameters produced in the same technological processes.

2. Experiment

Monodisperse silica spheres of different diameters have been prepared according to the procedure described in Refs. [3,8–10] based on Stöber method [11]. In the production of SiO_2 spheres with different size only quantity of ammonia has been changed and the others reagents have been used in the same quantities. The size (D_{SEM}) of produced spheres has been determined from electron micrographs as it was described in Ref. [3]. For the formation of opals, we have used the method of vertical deposition of the prepared colloid on the glass substrates [12]. In such a way we have obtained a series of eleven thin opal films of *fcc* structure. This is confirmed by the SEM image obtained using PHENOM scanning electron microscope. Typical SEM micrographs are presented in Fig. 1. One can see hexagonal network structure typical of the (111)

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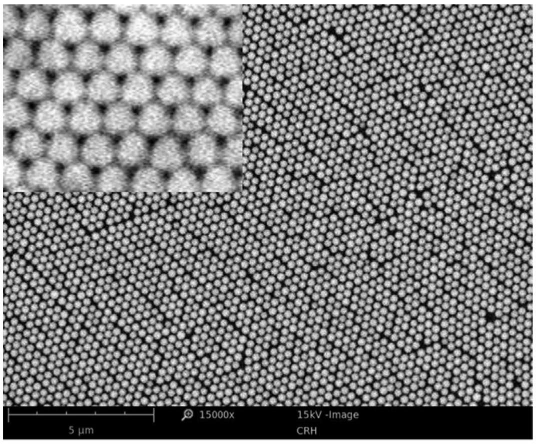

Fig. 1. SEM image of the (111) surface of a thin layer of SiO_2 opal prepared using self-assembly technic by the vertical deposition of prepared spheres; inset shows an enlarged part of the same surface.

layers in the terms of the *fcc* lattice.

Spectrogoniometric measurements of transmission have been performed for each opal of produced series. They were carried out at room temperature using linearly polarized light of the direction of electric field vector perpendicular (s) and parallel (p) to the plane of incidence in spectral range from 380 nm to 1050 nm for angles of incidence ranging from −80° to 80° with a sampling interval of 1° (see Supporting Information, Figs. S1 − S3). The details of used experimental set-up have been presented elsewhere [13,14]. An exemplary spectra of optical transmission registered for different angles of incidence s-polarized light upon the opal built from monodisperse spheres of diameter $D_{SEM} = 361$ nm and $D_{SEM} = 287$ nm are presented in Fig. 2. In each spectrum one can identify local minima ($\lambda_{c(hkl)}$) associated with the Bragg diffraction on (*hkl*) opal planes.

On this basis angular dependences of the spectral positions of Bragg diffraction minima on transmission spectra for opal series of known spheres diameter ranging from $D_{SEM} = 245$ nm to $D_{SEM} = 361$ nm have been obtained. In the presented analysis only minimum ($\lambda_{c(111)}$) associated with the Bragg diffraction on (*111*) opal planes is taken into account.

Dependences $\lambda_{c(111)}(\theta_i)$ determined for an exemplary opal for different polarization of light (*s* and *p*) are presented in Fig. 3. One can see that characteristics obtained for both polarizations are comparable within the measurement uncertainty. However for p-polarized light in some range of angles near Brewster angle, Bragg's minima are fuzzy, therefore there is no result in this range. So in the presented analysis only the results registered for s-polarized light have been used.

Positions of minima connected with diffraction on (111) opal planes are shifted to shorter wavelengths with the increase of the angle of light incidence according to the formula:

$$\lambda_{c(111)} = 2\cdot\sqrt{\frac{2}{3}}\cdot D\cdot\ \sqrt{n_{eff}^2\ - \sin^2\theta_i}, \tag{1}$$

where

$$n_{eff}^2 =\ n_{sph}^2\cdot f_{sph} + n_{medium}^2\cdot\left(1 - f_{sph}\right). \tag{2}$$

Values of n_{sph} and n_{medium} are the refractive indices of silica spheres and the surrounding medium (i.e. air), respectively. Analysis of this relationship allows to determine the morphology of photonic crystals. However, a prerequisite for obtaining a correct result is a knowledge of n_{sph} parameter.

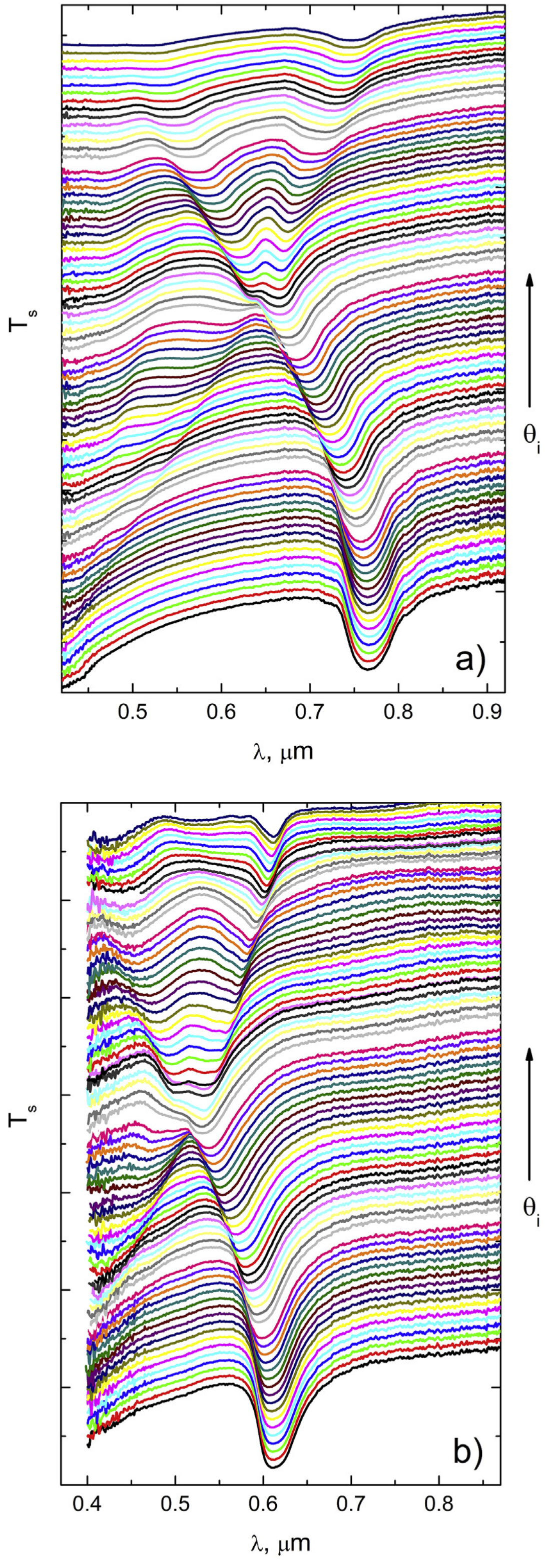

Fig. 2. Spectra of optical transmission registered for different angles of incidence s-polarized light upon the opal built from monodisperse spheres of diameter $D_{SEM} = 361$ nm (a) and $D_{SEM} = 287$ nm (b). Spectra have been vertically shifted for the sake of clarity.

It is well known that silica spheres produced by Stöber method are porous. It can be considered that they consist of two fractions: