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Complex interaction of polarized light with three-dimensional opal-based photonic crystals: Diffraction and transmission studies☆

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Abstract

Polarization characteristics of light interaction with the photonic crystal of a-SiO_2 synthetic opals were studied under the conditions of low dielectric contrast. We analyzed 3D diffraction patterns of monochromatic light and calculated optical transmission spectra of oriented samples. The diffraction patterns are found to change with the polarization of incident light, indicating a strong polarization dependence of photonic stop bands in synthetic opals. It is shown theoretically there exists a critical angle, θ_c, of the p-polarized light incident on the $(h\,k\,l)$ crystal plane, at which the resonance contribution to Bragg diffraction vanishes.

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1. Introduction

The presence of forbidden spectral bands (stop bands) along certain paths of electromagnetic wave propagation or of a full forbidden band is the major feature of periodic dielectric structures known as photonic crystals [1–3]. Stop bands arise when the spatial modulation period of the dielectric constant and the light wavelength are comparable. For a full forbidden band to arise, the energy overlap of the stop bands must occur in all directions, and what is more important is this should happen in any polarization. The properties of photonic stop bands dependent upon light propagation directions were studied extensively [3–8], while the polarization characteristics have been discussed only in a few papers [9–12].

Principal aspects of light interaction with the three-dimensional (3D) lattice of a photonic crystal can be better understood if one studies crystals in experiments with polarized light. Among 3D model crystals suitable for investigations in the visible spectrum are synthetic opals, in which silica (a-SiO_2) spheres of submicron diameter are self-organized into a face-centered cubic (fcc) lattice [4,13,14].

The photonic band structure of synthetic opals has been discussed in many publications [4–21]. Its theoretical treatment was offered quite a few years ago (see, e.g., Refs. [16,17]), and for some time there was a certain gap between the experimental work and theory due to a poor quality of opal samples used in experiments. Light scattering by lattice defects in

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strongly disordered samples leads to great energy losses when electromagnetic radiation passes through the sample, such that the experimentalist fails to get an adequate picture of the photonic band structure. Modern technology is capable of producing high quality opal films with a thickness of about 20 growth layers [22], so recent work has been done on extremely thin film samples using transmission and reflection spectroscopy [5,18]. This is good, but one cannot study the photonic behavior of an opal film in all directions in the Brillouin zone, so, again, one fails to get an exhaustive picture of light interaction with a 3D crystal.

Recently, we have made a detailed characterization of opal samples using a combination of optical and microscopic techniques, which have revealed high quality opals [15,23,24]. These can be successfully used in diffraction and transmission experiments with any mutual orientation of the light beam and the opal crystal lattice. The photonic band structure of synthetic opals was studied in spectroscopic experiments, neglecting polarization effects in Refs. [15,25]. The spectral positions and half widths of the transmission bands were measured along the axes containing all high symmetry points on the surface of the Brillouin zone of the fcc lattice. It would be more natural, however, to study stop bands in photonic crystals by analyzing Bragg diffraction patterns.

Diffraction experiments on the structure of synthetic opals were first carried out by the authors of Refs. [23,25]. They analyzed in detail the diffraction patterns when the light beam was incident in directions normal to the [1 1 1] growth direction, and additional studies were performed for specular Bragg reflection from the (1 1 1) crystal planes [25,26]. It was found that the diffraction technique provided visualization of stop bands and identification of crystal planes responsible for the formation of such bands. However, the diffraction technique based on the angular distribution of diffracted light intensity can be combined with transmission spectroscopy to achieve clearer results.

The present work was aimed at a detailed study of polarized light interaction with the opal crystal lattice. We examined transmission spectra theoretically and present these results in Section 2. We carried out experiments on the diffraction of non-polarized and polarized monochromatic light in synthetic opals, described in Sections 3 and 4, respectively.

2. The calculation of polarized transmission spectra

Transmission spectroscopy is a conventional method used in experiments on the photonic band structure. In Ref. [12], the polarized transmission spectra of opals were studied using white light. The samples had the (1 1 1) growth surface of 10 mm × 10 mm in size and about 1 mm in thickness; the diameter of the a-SiO_2 spheres was about 315 nm. This diameter allows obtaining the photonic band structure and observing the Bragg diffraction in the visible region. An opal sample was fixed at the center of a spherical cell of 5 cm in diameter and filled with a water ethylene glycol solution used as an immersion medium to suppress diffusive light scattering from the surfaces. The dielectric constant of the silica is $\varepsilon_{a\text{-SiO}_2} = 1.85$, a water ethylene glycol solution is $\varepsilon_{\text{gl-w}} = 1.93$, and the dielectric constant of the filled opal sample is $\varepsilon_0 = 0.74\varepsilon_{a\text{-SiO}_2} + 0.26\varepsilon_{\text{gl-w}} \approx 1.87$. The spectra were measured in the spectral range of 365–825 nm, using a Shimadzu UV-3100 spectrophotometer. Diameter of the scanning light beam was about 2 mm.

The transmission spectra were analyzed as a function of the incidence angle θ, when the scanning plane in

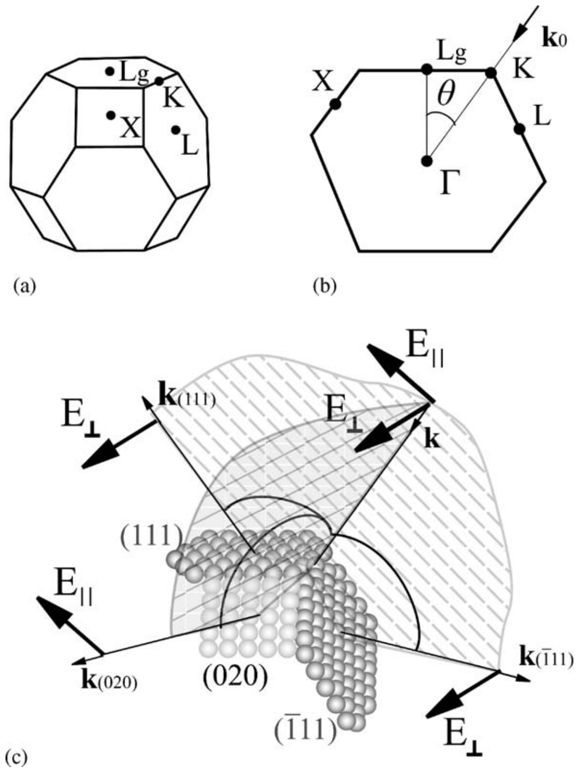

Fig. 1. (a) The Brillouin zone of the fcc lattice. L_g is a point, at which the $\Gamma \rightarrow L_g$ direction indicates the [1 1 1] growth axis in the fcc opal lattice. (b) The cross section of the Brillouin zone in the fcc lattice, corresponding to the scanning plane in the light transmission experiments. (c) Scheme of the polarized beam diffraction at the incidence angle $\theta = 35^\circ$. One can see beams reflected from the (1 1 1), $(\bar{1}\,1\,1)$ and (0 2 0) planes with the dominant polarization of the diffracted light.