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Impact of Alignment and Orientation in Photonic Crystal Devices

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Abstract

Photonic crystals are attractive optical materials for controlling and manipulating light flow. One dimensional photonic crystals are already in widespread use, in the form of thin-film optics, with applications from low and high reflection coatings on lenses and mirrors to colour changing paints and inks. Higher-dimensional photonic crystals are of great interest for both fundamental and applied research, and the two dimensional ones are beginning to find commercial applications. The first commercial products involving two-dimensionally periodic photonic crystals are already available in the form of photonic-crystal fibers, which use a microscale structure to confine light with radically different characteristics compared to conventional optical fiber for applications in nonlinear devices and guiding exotic wavelengths. The three-dimensional counterparts are still far from commercialization but may offer additional features such as optical nonlinearity required for the operation of optical transistors used in optical computers, when some technological aspects such as manufacturability and principal difficulties such as disorder are under control. the photonic crystal is not a single crystal that spreads over the entire scale, but it is separated into many small domains with different crystal orientations. As a photonic crystal generally has band gaps at different frequencies depending on the direction of light propagation, it seems mysterious that the scale is observed to be uniformly green under an optical microscope despite the multi-domain structure.

Keywords: Alignment, Impact of Alignment, Orientation, Photonic Crystal

Introduction

A three-dimensional periodic lattice known as a photonic crystal has attracted a considerable amount of attention for a few decades. Photonic crystals have been studied because of the fundamental interest in the physical properties of light inside such materials, and many studies have been carried out to apply their capability of controlling the propagation of light to various applications such as low-threshold lasers and photonic chips. However, it is still difficult to fabricate photonic crystals with a period that is comparable to the wavelength of light. By contrast, some insects are known to possess naturally occurring photonic crystals for their colorations; weevils are one such group of insects, and butterflies are another group that have been extensively studied. For example, some species of lycaenids (Callophrys rubi, Cyanophrys remus and Callophrys dumetorum) and papilionids (Parides sesostris and Teinopalpus imperialis) have been reported to have a photonic crystal structure inside their wing scales. These structures produce brilliant structural colours, which are presumably thought to serve as a tool for communication. It is quite interesting to learn how these natural photonic crystals develop and also to consider using them as a template for an inorganic photonic crystal that has a higher refractive index than biomaterials.

Exact identification of photonic crystal structures inside butterfly wing scales is a difficult task because of the complicated network topology. Recently, Michielsen & Stavenga carefully compared cross-sectional images of the wing scales observed by transmission electron microscopy (TEM) with computer-generated patterns assuming several structural models. They concluded from the reasonable matching in the patterns that the photonic crystals of a wing scale have a gyroid-type structure, which is a type of cubic-structure group that consists of two interconnecting channels comprising different materials. This structural identification has been later confirmed by small-angle X-ray scattering using synchrotron radiation and also by electron tomography.

The photonic crystals inside these wing scales are not a single crystal that spreads over the entire scale, but they are separated into many small domains with different crystal orientations. This multi-domain structure can largely affect the optical properties of the scale, because a photonic crystal generally has band gaps for different frequency ranges depending on the direction of propagating light. Hence, the wavelength of reflection can differ from domain to domain. It has been reported for gyroid-type photonic crystals that band gaps appear for the frequency ranges along the three primary directions of the cubic crystal, corresponding to blue, green and violet or ultraviolet colours, respectively, with the structural parameters obtained for a butterfly. In fact, the matte green scales of Cy. remus and Ca. dumetorum have been observed to consist of gleaming patches with different colours and intensities under an optical microscope. This appearance seems consistent with the multi-domain structure, where the exposed surfaces of domains are characterized by different Miller indices.

Fabrication challenges

Higher-dimensional photonic crystal fabrication faces two major challenges:

- Making them with enough precision to prevent scattering losses blurring the crystal properties
- Designing processes that can robustly mass-produce the crystals

One promising fabrication method for two-dimensionally periodic photonic crystals is a photonic-crystal fiber, such as a holey fiber. Using fiber draw techniques developed for communications fiber it meets these two requirements, and photonic crystal fibres are commercially available. Another promising method for developing two-dimensional photonic crystals is the so-called photonic crystal slab. These structures consist of a slab of material—such as silicon—that can be patterned using techniques from the semiconductor industry. Such chips offer the potential to combine photonic processing with electronic processing on a single chip.

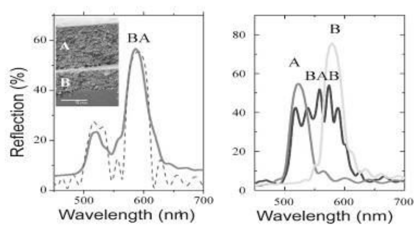
For three dimensional photonic crystals, various techniques have been used—including photolithography and etching techniques similar to those used for integrated circuits.Some of these techniques are already commercially available. To avoid the complex machinery of nanotechnological methods, some alternate approaches involve growing photonic crystals from colloidal crystals as self-assembled structures.

Mass-scale 3D photonic crystal films and fibres can now be produced using a shear-assembly technique that stacks 200–300 nm colloidal polymer spheres into perfect films of fcclattice. Because the particles have a softer transparent rubber coating, the films can be stretched and molded, tuning the photonic bandgaps and producing striking structural coloreffects.

Heterostructures on the base of single-crystal opal films

From the practical state point it is very important to produce the extended defects in PhC. Such defects give rise to propagating modes lying within the forbidden PBG. These modes are a crucial element in the development of PhCs as waveguides, resonant cavities for low-threshold lasers, or as other photonic devices.

The controlled formation of states within the forbidden gap is to use an extended periodicity, in the form of an optical superlattice. The general properties of such systems were first described theoretically by Russell. Examples have been experimentally realized in one-dimensional structures, in both semiconductor multilayers and in optical fiber gratings. The fabrication of a three-dimensional optical superlattice structure from sequential depositions of silica colloidal crystals by convective self-assembly was obtained in. There are single-crystal opal films to fabricate the colloidal crystal heterostructures. One of such structures made of composed of two different single-crystal films with various diameters of MSSP. The preferred vertical orientation of the crystalline axis is preserved. The reflection spectra AB of double-layer opal consisting of single-crystal films clearly demonstrated the presence of different stop-bands as a consequence of stop-band superposition of individual compositional colloidal crystals.



a) b)

Fig. 1. Reflection spectra of opal-based heterostructure assembling from two (solid line BA)

There are fabricated structures as thick as three layers BAB and ABA. The solid curve BAB shows the normal-incidence reflection spectrum of BAB three layer heterostructure. The two B sections consist of 16 lattice planes of a close-packed face-centered-cubic (fcc) colloidal single-crystal composed of 260-nm diameter spheres. The middle A section is 23 planes of an fcc crystal, with sphere diameter of 235 nm.

From comparison of spectrum BA it is possible to draw a conclusion that an additional layer reinforces the long-range periodicity of the superlattice, resulting in significant modifications to the observed stop bands. In the three layer sample BAB as well as for structure ABA, the broad photonic stop bands exhibit pronounced modulation. The experimental result provides convincing evidence that the observed structure does indeed arise from superlattice effects. Thus, the controlled formation of states within the forbidden gap has obtained due to an extended periodicity, in the form of an optical superlattice.

LOW THRESHOLD LASING IN SINGLE-CRYSTAL FILMS AND HETEROSTRUCTURES

Noble opal samples with crystal sizes greater than the beam diameter were obtained by the crystallization in suspensions of charged MSSPs. Structural defects inevitably present in artificial opals introduce disorder that leads to strong scattering and random lasing. In such case we have observed the appearance of multiple emission lines. These lines laid within the region of the maximum dye gain, are unrelated to the opal PBG and had high threshold intensity I ~ 13-15 MW/cm^2.

In contrast, the single-crystal films and three-layer opal heterostructures enable to obtain laser emission in a relatively narrow solid angle (~20^0) with a lower threshold intensity of I ~ 2,5 MW/cm^2 for a single-crystal film infiltrated with Rodamin 6G and I ~ 0,85 MW/cm^2 for an heterostructure on the base of single-crystal opal films. The heterostructures as thick as three layers BAB. The optical feedback in the case of single-crystal opal film lasers is provided via Bragg scattering of light from crystallographic planes at the first pseudogap edge in the direction of Γ-L. The two B sections provide additional optical feedback in the heterostructure laser.

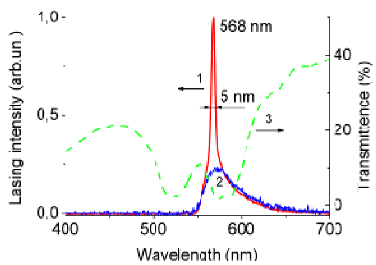


Fig. 2. Emission spectra of opal heterostructure infiltrated with Rhodamin 6G solution.

There is a new effect appearing in the displacement of the PBG on the background of the spectrum of backward diffracted and reflected Bragg waves at the grazing incident of white-light beam on the (glass - opal thin film) interface. The physical basis for observable effect is such characteristics of the PhCs as a strong angular dispersion and the dependence of the spectral position of PBG on the type of analyte. PhC films were grown by the movable meniscus method from the suspension of MSSPs on a glass prism. A white light beam from a halogen lamp was incident on a face of a glass prism and, then, on the (glass–PhC) interface. The inset in Fig.4 shows the interaction scheme. Here, we consider refracted and reflected Bragg waves for which the directions of tangential projections of wave vectors are opposite to the corresponding projection of the wave vector of the incident wave. Refracted (2) and backward reflected (3) waves were observed after the incidence of the white light beam (1) from the glass with the reflective index n_g = 1.51 at the interface between this medium and the three dimensional PhC film deposited on its surface.

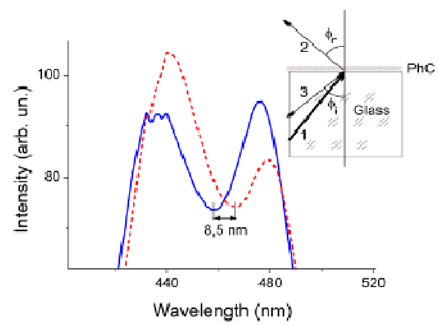


Fig. 3. Spectrum of the refracted Bragg wave with the stop band (solid line) before and (dashed line) after the action of ammonia vapors with a density of 2 mg/m^3.

It is revealed that the spectrum of the Bragg backward reflection and refraction manifested the PBG, which changes its position under insignificant change of the concentration of vapor of a range of substances (isopropyl alcohol, dibutyl amine, tributyl amine, water, ammonia), filling the PhC. The effect was reversible. After the termination of action of the analyte vapor under room conditions the PBG returned to original spectral position during 10-15 seconds. The spectral shift of the PBG depends on the polarity of the analyte and increases with their dipole momenta and the concentration of vapors. Specifically, we revealed that for the concentration of NH_3 (2 mg/m3 the PBG spectral shift of the diffracted light was about 8 nm.

Conclusion

The presence of a mobile hydrogen atom in polar hydroxyl groups gives rise to the effective interaction with the molecules of the gas and liquid phases. The estimates show that the ammonia molecular monolayer uniformly covering the surface of the opal balls gives rise to a change in neff in ammonia vapors by $\Delta n_{eff} \approx 0.004$, which corresponds to the spectral shift of the center of the stop band by about 1 nm. However, it should be taken into account that silica balls can consist of globules and their specific surface can be larger by an order of magnitude, which was not taken into account in the estimates.

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