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Polarization Change in Face-Centered Cubic Opal Films

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Abstract. Artificial opals are a popular platform for investigating fundamental properties of Photonic Crystals (PhC). In this work, we provide a theoretical analysis of polarization-resolved transmission experiments through thin opal films. Despite the full cubic symmetry of the PhC, this system provides a very efficient mechanism for manipulating the polarization state of light. Based on band structure calculations and Bloch mode analysis, we find that this effect closely resembles classical birefringence. Due to the cubic symmetry, however, a description using tensorial quantities is not possible. This indicates fundamental limitations of effective material models for Photonic Crystals and demonstrates the importance of accurately modelling the microscopic geometry of such systems.

Keywords: photonic crystals, polarization, birefringence

PACS: 42.25.Ja, 42.25.Lc, 42.70.Qs

INTRODUCTION

Photonic Crystals (PhC) are dielectric structures with features on the length scale of light. They feature unusual optical properties such as low group velocities (slow light) or complete photonic band gaps [1]. Among them, artificial opals are one type of Photonic Crystals that consist of dielectric spheres arranged in a face-centered cubic lattice. Although such structures do not feature a complete photonic band gap, they have been established as a very widely used model system for investigating fundamental properties of photonic crystals in general. One particular advantage is the fabrication process by self-assembly of monodisperse dielectric spheres [2] that yields samples of excellent quality. In this work, we consider an opal film consisting of 25 layers of spheres made of poly-methyl metacrylate (PMMA) (diameter $D = 368\text{nm}$, refractive index $n = 1.489$), stacked along the (111)-direction of the crystal. The film is illuminated by a polarized light beam in the Γ -L-W plane of the first Brillouin zone (cf. Fig. 1).

Systematic studies of the polarization dynamics and in particular of the cross-polarization transmission spectra of three dimensional Photonic Crystals are relatively rare although they are of great relevance for designing functional optical materials. In the case of opals this might be due to the cubic symmetry which excludes the possibility of form birefringence [3] in the effective medium limit. However, experiments show significant polarization transfer from s-polarization to p-polarization upon transmission through a thin opal film.

FIGURE 1. Top view sketch of the opal film. The crystal is grown in the (111)-direction, i.e. three types of layers of hexagonally packed spheres (denoted 'A' corresponding to bold circles, 'B' corresponding to thin circles and 'C' corresponding to dotted circles) are stacked on top of each other. Polarized light impinges in the Γ -L-W plane of the first Brillouin zone (indicated by red line). We denote the angle between the interface normal and the incident wave vector with Θ (not shown).

THEORETICAL ANALYSIS

As a first step of analysis, we performed polarization-resolved transmittance calculations using the Fourier

FIGURE 2. Calculated bar-polarized transmittance (s-pol in, s-pol out) into the zeroth Bragg-order for an opal consisting of 25 layers of PMMA spheres. The lateral resolution of this FMM-calculation was 349 Fourier coefficients; in the normal direction, we used 40 slices per layer of spheres. The strong transmission minimum starting around $\lambda = 800\text{nm}$ at $\Theta = 0^\circ$ is the fundamental stop band of our opal. The smaller transmission minimum around $\lambda = 450\text{nm}$ and around $\Theta = 60^\circ$ occurs due to wave vector mismatch at the PhC interface. The strong polarization transfer takes place in the fuzzy transmission minimum around $\lambda = 600\text{nm}$ and $\Theta = 50^\circ$.

modal method (FMM) [4]. In Fig 2, we show the s-polarized part of the zeroth diffraction order for s-polarized incident light and various wavelengths λ and angles Θ . This spectrum features several transmission gaps, the most prominent one being the fundamental stop band. Most strong transmission gaps in bar-polarization are due to the inability of the incident light to couple to propagating modes. Thus, these parameter regions do not exhibit any transmission into the other polarization state (cf. Fig 3). However, for angles around 50° and wave lengths around $\lambda = 650\text{nm}$, we find a strong polarization transfer. This effect is highly resonant and very sensitive to variations of the plane of incidence.

Changing the film thickness in our simulations leads to a strong variation of the cross-polarized response, which indicates that the origin for this effect is a property of the PhC bulk. Thus, we performed band structure calculations using the MIT Photonic Bands (MPB) software package [5] at a resolution of $32 \times 32 \times 32$ discretization points per unit cell. We closely investigated the band structure for all wave vectors to which the incident light can couple based on conservation of momentum

$$\vec{k}_{||} = \frac{2\pi}{c} \sin \Theta + \vec{G}_{||}. \quad (1)$$

Here, $\vec{G}_{||}$ denotes a reciprocal lattice vector of the (periodic) interface between PhC and air and $\vec{k}_{||}$ is the projection of the Bloch mode's wave vector to the interface

plane. The lattice constant was normalized to one for convenience. We find a wave vector mismatch between two modes that perfectly fits the before mentioned variation of cross-polarized transmittance. This closely resembles the situation in a birefringent material. Due to the inherent chirality of the crystal consisting of three types of layers stacked on top of each, one might expect similarities between the crystal and a circularly birefringent material. However, a careful inspection of the involved Bloch modes indicates a close relation to linear birefringence.

Our theoretical findings are in good agreement with corresponding experiments (not shown). The agreement for the bar-polarized spectra is quantitative whereas the corresponding results for the cross-polarized differ roughly by one order of magnitude. However, all theoretically predicted features are qualitatively present in the latter case, as well. Increasing the size of the illuminated spot of the sample led to a decreased cross-polarized signal whereas the bar-polarized response was barely affected. This suggests that the opal film is subject to fabrication disorder and the unexpectedly low polarization conversion efficiency can be attributed to averaging over antagonizing contributions from different parts of the sample.

FIGURE 3. Calculated cross-polarized transmittance (s-pol in, p-pol out) into the zeroth Bragg-order for an opal consisting of 25 layers of PMMA spheres. The stop band and the secondary transmission minimum around $\lambda = 450\text{nm}$ (cf. Fig. 2) do not exhibit any cross-polarized transmission. Around $\lambda = 600\text{nm}$ and $\Theta = 50^\circ$, however, there is a regime of strong polarization transfer. This area coincides with the fuzzy transmission minimum in Fig. 2.

CONSEQUENCES

The birefringence-like cross-polarization transmittance seemingly contradict the fact that materials with cubic symmetry do not exhibit optical anisotropy. However, this statement only holds in the limit of an effective material, i.e. if the wave length of light is much larger than any relevant feature size of the structure. In fact, our polarization transfer effect is found beyond the stop band which could be regarded as a natural boundary where any effective material description ceases to be valid. On the other hand, we would also expect that the anisotropy of a cubic structure cannot be expressed by quantities which are used to characterize effective material properties, i.e. by second rank tensors. Indeed, the top layer of spheres exhibits a six-fold rotational symmetry that is reduced to three-fold symmetry by the subsequent layers. Upon closer inspection, one furthermore recognizes six-fold antisymmetry. This (both the three-fold symmetry as well as the six-fold antisymmetry) is incompatible with second rank tensorial quantities. This demonstrates that Photonic Crystals cannot be satisfactorily modelled by effective material parameters such as an effective permittivity, at least as soon as polarization is involved.

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