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1. Polarization effects in optical spectra of photonic crystals

Good afternoon. I would like to introduce myself. My name is Anton Samusev. I'm a student of Saint Petersburg State Polytechnical University and I have scientific practice in department of Solid State Optics at Ioffe Physico-Technical Institute.
The field of my interest is experimental studies of photonic crystals. Here I would like to present some results of our scientific group from Ioffe Institute concerning experimental and theoretical studies of polarization effects in opal-based photonic crystals.

2. Overview

- I will start with some general remarks concerning photonic band gap structure of artificial opals.
- Then I will tell you about several particular experimental results of polarization-resolved study that were published two years ago.
- Further, I'll introduce (and compare with previous ones) our measurements of angular- and polarization-resolved transmission spectra, which provide more complete picture of polarized light coupling to three-dimensional photonic structure.
- Then I will show how these results can be discussed on terms of Fresnel theory and Brewster effect taken into account the relative orientation of different crystallographic planes in opal-based photonic structure.
- After that I'll present how the same effects were visualized and verified with diffraction technique.
- And I will finish my speech with some conclusion remarks.

So, let's get started.

3. Bragg Diffraction

The most important physical concept that we will discus now is concerned with Bragg diffraction of light. The Bragg diffraction of waves is responsible for the appearance of band gap in the energy spectra of various periodic structures. This picture illustrates well-known Bragg condition for reflected waves. For example we have a three dimensional photonic crystal with fcc lattice. In this case the incident wave partially (selectively) reflects on each of the crystallographic plane sets in accordance with the Bragg condition.

Here **h**, **k** and **l** are the Miller indexes of a specific crystalline plane set.

Theta is angel of incident.

Lambda is incident wavelength.

Pay attention to the fact that the Bragg diffraction takes place only if wavelength is of order of the modulation period.

4. Energy gap in electromagnetic spectrum

General task in photonic crystals fabrication is achieving complete photonic band gap. Using these figures I would like to show you how it is possible to obtain it. In case of three-dimensional photonic crystal in all the directions we archive so-called stop band, band gap in particular direction. The centers of these stop bands are situated on Brillouin Zone surface because of the wave phase relations. And there widths depend on the dielectric contrast according to the theoretical calculation. Overlapping of all the stop bands means complete photonic band gap achievement. Pay attention to the fact that condition of most distant stop bands overlapping is sufficient. And the directions of these stop bands correspond to BZ surface points that are nearest and most distant from BZ center. Therefore there are two ways to obtain complete band gap. The first one is dielectric contrast increasing. (Технически не так просто...) And the second way is appropriate lattice type selection. You can imagine that if we have spherical Brillouin Zone then we will automatically have complete photonic band gap. Brillouin Zone of fcc lattice is quite similar to a sphere, so a favorite candidate-material should have this type of lattice. For the study and visualization of the PBS, we chose synthetic opals with there fcc structure.

5. Angular-resolved transmission spectra of artificial opals

Now let me introduce some polarization-independent measurements of artificial opals. This figure presents experimental transmission spectra for angular-resolved scanning through the path, represented in the upper-right corner of the slide. Each direction of the incident beam, lying in this scanning plane is represented by its incident angle **Θ**.

All of the spectra show characteristic deeps corresponding to the photonic band gaps. We can see that deeps are shifted strongly depending on the incident angle. From the next figure you will see that the angular dependence of deeps positions is in good agreement with the Bragg condition. Bragg reflection from the {111} plane sets is responsible for these gaps. The deeps corresponding to reflection from the growth (111) planes are marked by red triangles and the blue triangles indicate the deeps corresponding to reflection from non-growth (-1,11) plane set. These plane sets are non-equivalent in a twinned opal structure. Lets compare two directions that are quite similar in the perfect fcc structure. One corresponds to Gamma – L growth direction with incident angle of Zero degrees. Another corresponds to gamma – L direction with incident angle of about 70 degrees. These gap energies coincide. Whereas the deep measured at incident angle of 70 is much broader than deep relative to the angle of zero. This broadening is due to stacking faults that affect the gap for any non-growth direction. That's why some additional information can be obtained from linewidths (breadth) of these deeps.

6. Photonic Bandgap Structure of Artificial Opals

The figure summarizes all experimental data, which we have obtained from polarization-independent transmission spectra of Synthetic Opal samples with lattice constant about 270nm. At the right hand you can see the 3 scanning planes, that contain all the high-symmetry points of the fcc BZ. On the left figure circles, squares and triangles show the measured gap positions. The black curve represents theoretically calculated position of the center of band gaps by deriving Bragg equation for different crystallographic plane sets of fcc lattice. As you see, this calculation is in a good agreement with the experimental data. This comparison confirms the conclusion that Bragg diffraction is responsible for the measured deeps in transmission spectra indeed. Also this figure represents band gap widths. The resulting width area was painted with the respective colors. These colors show the real spectral position of band gap in the visible for particular sample. Although the colors are defined by specific sample with fixed parameters of lattice constant and dielectric contrast, the photonic band gap structure for any other fcc opal-like photonic crystal can be obtained from the presented one by scaling the only two parameters. These parameters are lattice constant and the dielectric contrast.

7. Experimental evidence of polarization dependence in reflectivity spectra of artificial opals.

So I have finished with the introduction part of my speech and would like to turn directly to its goal.

Here are presented polarization-resolved artificial opal's reflectivity measurements of Galisteo-Lopez group. These results were published over 2 years ago. The reflectivity spectra were studied in the vicinity of the BZ growth L-point. Let me describe some peculiarities of experiment. For experiments the ΓLU scanning plane is chosen. The authors use several Fresnel theory terms to specify the incident beam polarization. So the incident beam with electric field oscillation vector lying in the diffraction plane is called p-polarized and the one with electric field oscillation vector that is normal (oriented normally) to this plane is called s-polarized. The surface of the sample is parallel to the growth (111) plane set and the incident angle is the angle formed by the normal to the crystal surface and the incident beam. Reflectivity spectra for s- and p-polarized light as a function of angle are presented on the right side of the slide. Two spectra for *s*- and *p*-polarized light, for an external angle of incidence of 39°, are presented in figure **c**. Both spectra have been normalized in intensity for comparison. Here, we can already appreciate the difference in width between both peaks, indicating strong polarization sensitivity.

8. Light coupling to single and multiple sets of crystallographic planes.

On the left side of this slide one can see theoretically calculated band gap center positions represented by the black curve. The investigated region is highlighted. This limited angular range of the incident light allows investigating (to investigate) only the response of (111) planes and therefore a complete picture of polarized light coupling to three-dimensional photonic structures still remains to be studied. The goal of the work that will be discussed next, is to demonstrate how polarized light couples to different sets of crystallographic planes. To achieve this aim, we measured polarization- and angle-resolved transmission spectra of synthetic opals along $L_g \rightarrow K \rightarrow L$ path in the high-symmetry plane $L_g\Gamma L$ of the fcc BZ. On the right hand you can see that the selected scanning path allows us to investigate the light coupling to (111), (11,-1), (200), and (020) planes in the measured angular and spectral diapason.

9. Fresnel Formulas

The observed polarization-resolved optical spectra we will discuss in terms of the Fresnel theory and the Brewster effect. Although the Fresnel theory and the Brewster effect are basically applied in the case of light transmission and reflection at the boundary of semi-infinite homogeneous medium, it will be demonstrated that such approach is unexpectedly useful for analyzing the polarized light which couples to the photonic structures with periodically modulated refractive indices in three dimensions. *Let me launch into a small digression on the Fresnel theory.*

The plane, that contain the incident beam on one side and a normal to a medium boarder (on which a beam is exposed) on the other side, is called plane of incidence or the incident plane. The electric field of the incident beam can always be written as a linear combination of two base vectors contained in a plane perpendicular to the radiation beam wave vector. In particular, it is convenient to choose such vectors as parallel and perpendicular to the incident plane. So, in case, when oscillation plane of electric field coincides with the plane of incidence, the beam is said to be p-polarized. And when the planes are perpendicular, the beam is s-polarized. On this slide the well known angular-resolved reflection index dependence for s- and p-polarization is shown. As you remember, according to the Fresnel theory, only the s-component is reflected if the incident angle is equal or about the Brewster angle. Make a note, that in case of small dielectric contrast the Brewster angle is about 45 degrees.

10. LgKL scanning plane

Now let us return to the experiment and consider incident light with wave vector (**k**) contained in the LKL scanning plane. Here the parallel electric field vector component lies in the scanning plane and the perpendicular one is normal to it. As you can see from the slide the scanning plane is perpendicular to both (111) and (11,-1) crystalline plane sets. They correspond to hexagonal faces of BZ. Therefore it is convenient to introduce standard notations for s- and p-components of incident beam as it follows from the first pair of equations.

Now let's pay attention to (200) and (020) plane sets. They are corresponded with square faces of BZ. For the symmetric scattering geometry when the incident wave vector passes through the K-point (at θ about 35 degrees) the ΓKX is a plane of incidence relative to concerned plane sets in terms of Fresnel theory. In this geometry we can introduce notations for s- and p-components for both (200) and (020) planes as represented in the second pair of equations.

By comparing these two pairs of equation one can see that the relative orientation of the {111} and {200} planes in the fcc lattice is such that the *s*- and *p*-components of the incident light change over for the Γ–K direction. According to the Fresnel theory, only *s*-component is reflected if the incidence angle is equal or about the Brewster angle. Therefore, we can expect, that the PERPENDICULAR component should be reflected from the {111} planes, while another PARALLEL component of incident light should be reflected from {200} planes. It means that one can prove experimentally whether the approach in terms of the Fresnel theory holds in the case of photonic crystals. Note that the transmission spectra will be of the most informative because each spectrum is affected by the reflection from every crystallographic plane.

11. Polarization dependences of photonic gaps. Analogy with Fresnel theory. Brewster angle.

And that are the experimental results. On the left side of this slide the transmission spectra of perpendicular and parallel-polarized light for different incident angles are presented. On the right hand you can see the wavelength-resolved dependence of the difference between parallel and perpendicular transmissivity. These dependences reflect the most pronounced polarization effects. As you see the differential transmissivity becomes positive in spectral region of 500 up to 700 nanometers. This is a region of band gaps corresponding to (111) and (-111) planes. Quite the contrary in the spectral diapason of 350 up to 500 nanometers, corresponding to (200) and (020) band gaps, the differential transmissivity becomes negative and reaches minimum at the incident angle of 35 degrees. In this ΓK geometry the (200) and (020) planes reflect mainly parallel-polarized light, that leads to the predominant perpendicular-polarized light transmitting.

12. Polarization peculiarities in transmission spectra of opals (theoretical and experimental results)

13. Fabrication of artificial opals

So we are reaching the final part of my speech, concerned with the diffraction experiments. But before speaking about the diffraction technique I have to pay attention to some peculiarities in the structure of artificial opals. Opals are made up of uniformly sized amorphous silica spheres. During the growth process they pack in rather perfect hexagonal layers. There are three possible positions of a growth layer in a horizontal plain. Let them be A, B and C. The layer sequence may be random, producing a twinned fcc structure. That means that such sequence may be divided into subsequences, corresponding to each fcc-twin.

And that's why the growth (111) planes are non-equivalent with other {111} planes because of the stacking faults in such structure.

14. Diffraction experimental scheme.

So we have reached the final part of my report concerned with strong polarization dependences in diffraction experiments. So let's have a look at the experimental scheme. The oriented opal sample is exposed to laser beam effect. Between laser and the opal sample the matt screen is placed. Diffraction patterns can be observed on this screen and photos can be taken from it. In all the experiments, which are presented further on, the growth axis is placed vertically and probing beam propagates along the rows of the spheres in the growth crystallographic layer. It is (-110) direction that is also called "the geometry of four spots". Depending on sample region which laser beam is aimed on and polarization of the probing radiation we observe different diffraction pattern on the screen. All the bragg diffraction spots are associated with plane sets of {111} type.

15. During an experiment.

Here is a photo of experimental plant, on which all the results were achieved.

16. fcc-1.

Now let's consider the visualization of opal structure. You can see photos of the matt screen. Its center is marked with a dagger. The central spot which is formed by reflection from lens and retort is deleted for convinience. On the photos we see various configurations of spots, formed by the reflected beams. As you remember, artificial opals have got a twinned structure. So, in case, when area, which laser beam is aimed on, predominately consist of one of the fcc-lattices, we see one diagonal pair of spots. For convinience of perception the Brilluen zone for fcc is shown on the righthand side. The two hexagonal faces, that correspond to reflective plane sets are highlighted.

17. fcc-2.

In this region of the sample another twin is predominating.

18. fcc-1+fcc-2.

Here none of the twins is predominating. This situation is most suitable for polarization studies.

19. Diffraction pattern on strongly disordered opal structure.

A disordered area of the opal sample gives circle as a diffraction pattern. The diameter of this circle is similar to distance between two diagonal spots. This case reminds us X-ray diffraction images of powder.

20. Bragg diffraction in [-110] geometry.

On this slide the diffraction patterns of all possible types are given.

21. Processed images.

Here the three-dimensional diagrams of intensity corresponding to the previous diffraction patterns are shown.

22. Image analysis process.

Now I will briefly describe the functionality of a program, which we developed to help us analyzing the diffraction patterns. All the further results were achieved, using this program**.** The computer processing consists of several steps. First of all we select the corners of the quadrangle screenshape on the photo. And the program maps the vertex of the screen to the corners of a square with the whole image scaling. Now the angle between the optical axis and the straight line, containing the opal sample and any point of the screen can be counted, taking into account the distance between the screen center and the sample.

After that, all the possible profiles of diffraction spots can be drawn and according to dynamically updatable diagram (on the right), the profile, which contains the point with the maximum of intensity can be found. Finally, the graph of dependence of intensity along the profile as a function of the angle is exported to other programs for subsequent processing.

23-41. Polarization 0 degrees (and other 18 slides).

And now I would like to present the latest results. I will show you a set of slides, on which the photos of diffraction pattern are shown. All these patterns were achieved in fixed geometry of the beam exposure, intensity and wavelength of laser radiation, but with the varying polarization of radiation. On the right you can see the diagrams of intensity along the profile of upper right and lower right spots, respectively. And on the top the scale of rotation angle of polarizer is placed. This angle is counted clockwise from the vertical position. I would like to remind you, that each pair of diagonal spots corresponds to its fcc-lattice. You see, that at the definite rotation angles of polarizer spots, corresponding to one lattice are severely attenuated and become almost invisible. This means, that for this polarization and this twin we have the geometry close to the Brewster angle geometry. As you remember, P-polarized beam, propagating through the boundary of two mediums, is not reflected and almost entirely passes through. Exactly this result we are observing in our experiments.

42. Intensity as a function of **polarization angle: I**(Θ)

The main result of polarization-resolved diffraction measurements is shown on this slide. It is evident that intensities of previously mentioned diagonal pairs of spots show anti-phase dependence on the angle of polarization. Let me explain this result. In this geometry the planes of incidence corresponding to each twin are almost perpendicular to each other. For example, when the polarization angle is about 135 degrees the incident beam is p-polarized for one twin and s-polarized for the other one. That’s why the intensity of one pair of spots reaches it’s maximum and intensity of another one is about its minimum value.

43. Conclusions

Finally I would like to make some conclusions.

- The evidence of strong polarization dependencies in both optical spectroscopy and diffraction experiments was demonstrated.
- The polarization-resolved transmission measurements can be discussed in terms of Fresnel theory taking into account the relative orientation of different crystalline plane sets.
- With the diffraction technique it was shown, that polarization dependencies take place even far from the critical angle.
- These experimental results and conclusions bridge the phenomena of light interacting with photonic crystals and homogenious medium interface.

Thank you for your attention!
A would be very glad to answer your questions, if any.