Scattering of light from disordered photonic structures

A D Sinelnik\(^{1, a}\), K B Samusev\(^{1,2}\), M V Rybin\(^{1,2}\), S Y Lukashenko\(^{1}\) and M F Limonov\(^{1,2}\)

\(^{1}\) ITMO University, St. Petersburg 197101, Russia
\(^{2}\) Ioffe Institute, St. Petersburg 194021, Russia

\(a\) E-mail: artem.sinelnik.95@mail.ru

Abstract. We study theoretically and experimentally the scattering of light from ordered and disordered photonic structures. As an example, we consider a thin slab of a woodpile-type photonic crystal and introduce random fluctuations in the rod orientation, revealing a crossover from the Laue diffraction to the formation of speckle patterns. We observe a nontrivial interplay between order and disorder when the orientational disorder is added only in one direction of the square woodpile structure. Namely, ordered sets of rods produce disordered patterns and, vice versa, disordered sets of rods produce ordered patterns. We explain this effect theoretically and experimentally by the fact that light scatters only from the intersection points of different rods.

1. Introduction
The macroscopic optical properties of a random medium essentially depend on the different length scales involved in the system on the microscopic level [1]. When both the size of the scatterers and the average distance between them are smaller than the wavelength, the random medium behaves as a homogeneous effective medium called as 3D metamaterials or 2D metasurfaces. When the refractive index of the medium displays fluctuations on length scales comparable or larger than the wavelength, undergoes a series of scattering events that randomizes the direction and phase of propagating waves. For the ordered photonic crystal, a laser light diffraction experiment demonstrates a Bragg diffraction pattern. For the disordered photonic structures including photonic glasses, a laser light diffraction experiment demonstrates a speckle pattern [2]. Laser speckle is an interference pattern produced by light scattered from different parts of the disordered object. The intensity at any point on the image is determined by the algebraic addition of all the wave amplitudes arriving at the point [3].

In this study, we measured experimentally optical diffraction from fabricated ordered and disordered woodpile-type structures and found unusual interplay between order and disorder. We found that the first-order diffraction patterns from ordered set of rods become randomized while diffraction patterns from disordered set of rods continue to be bright and sharp.

2. Samples preparation
The aim of this work was the synthesis of ordered and disordered woodpile-type photonic structures using the direct laser writing technique [4,5]. The structure was created using a hybrid organic-
inorganic material based on zirconium propoxide with an Irgacure 369 photo-initiator. The polymerization was performed with a 50 fs TiF-100F laser. The perfect woodpile structure is built \( xy \)-layer by \( xy \)-layer, four layers make up the lattice period \( c \) along the \( z \) axis. The building block that composes the structures is a square rod with the height \( c/4 \). In the first layer, the rods are parallel to each other with an \( a \) period along the \( x \) axis, in the second layer the same rods with the same \( a \) period are parallel to each other along the \( y \) axis.

The disordered woodpile structures were fabricated as follows. Each individual rod in the layer was turn about its center (along \( x \)- or \( y \)-axis) by random angle \( \alpha_i \) with respect to the ordered state (\( \alpha_i = 0 \) for the rods is the ordered structure). We employed function \( \sigma = p \frac{\pi}{4} \) (0 \( \leq \) \( p \) \( \leq \) 1) for the normal distribution and for the uniform distribution \(-\alpha_{\text{max}} \leq \alpha_i \leq \alpha_{\text{max}} \) with \( \alpha_{\text{max}} = p \frac{\pi}{4}, 0 \leq p \leq 1 \). All structures have the lattice parameters varied in the range of 0.5μm \( \leq a \leq 2.0 \mu m \), the number of layers along the \( z \)-axis \( N \) was ranging from two layers (a metasurface) to 10 layers (ordered or disordered thin film). The correspondence of the resulting materials to the designed structures was confirmed by scanning electron microscopy (SEM).

3. Light scattering from ordered photonic structures

![Figure 1](image)

**Figure 1.** (a) Schematic of the zero-order (\( n = 0 \)) and first-order (\( n = \pm 1 \)) Laue diffraction from the horizontally oriented chain of periodic scatterers. (b-c) Schematic of the zero- and first-order Laue diffraction from the ordered 2D structure with square symmetry in the case \( a_x = a_y \). Diffraction patterns on a flat screen are shown by thick lines. Scattered light is shown by different colors for clarity.

The ordered woodpile structure can be considered as a structure composed of two sets of mutually orthogonal chains along the \( x \)- and \( y \)-axes. We use the Born approximation for the analysis of light scattering from low-contrast ordered 2D structures. For the 2D structures with the square lattice symmetry, the position of each scatterer is determined by the 2D vector \( \mathbf{r}_i = \mathbf{a}_1 n_1 + \mathbf{a}_2 n_2 \), where \( \mathbf{a}_1 \) and \( \mathbf{a}_2 \) stand for the basis mutually perpendicular vectors (\( \mathbf{a}_1 \cdot \mathbf{a}_2 = 0 \)) of the square woodpile-like lattice (\( a_1=a_2=a \)). First, we consider the scattering from one-dimensional linear chain of scatterers.
The appearance of the Laue diffraction maxima in the case of the linear chain and normal incidence is described by the simple formula:

\[ \theta_s = \cos^{-1} \left( \frac{n\lambda}{a} \right) \]  

(1)

where \( a = |a_1| \), \( \lambda \) is the wavelength of incident light, and \( \theta_s \) is the angle of light scattering from the chain between vectors \( a_1 \) and the wave vector of the scattered waves \( k_s \). Note that the inverse cosine function is only defined in the interval from \(-1\) to \(1\). Therefore the equation (1) defines the diffraction selection rules in relation to the ratio between \( \lambda \) and \( a \).

The zero-order diffraction (\( n = 0 \)) is observed for any ratio between \( \lambda \) and \( a \) in the plane perpendicular to the axis \( a \) since the angle of light scattering becomes \( \theta_s = 90^\circ \), figure 1 (a). A pair of diffraction cones of the \( n \)-th order appears at \( a > n\lambda \). For \( \lambda < a < 2\lambda \), one can distinguish in the light scattering additionally to the plane (\( n=0 \)) a pair of cones (\( n=1 \)) that has the axes of symmetry coinciding with \( a \) and the apex angle of scattering \( \theta_{s1} = \cos^{-1} \left( \frac{\lambda}{a} \right) \), figure 1 (a). For \( 2\lambda < a < 3\lambda \), one can observe the plane and two pairs of cones with \( \theta_{s1} = \cos^{-1} \left( \frac{\lambda}{a} \right) \) (\( n=1 \)) and \( \theta_{s2} = \cos^{-1} \left( \frac{2\lambda}{a} \right) \) (\( n=2 \)) and so on.

4. Disorder-induced light scattering

![Image](image_url)

**Figure 2.** Diffraction pattern evolution for anisotropic woodpile thin slab depending on the disordered parameter \( p \) for the normal distribution. The anisotropic structures with disorder in rods oriented along vertical \( y \)-axis. \( p=0 \) (a), \( p=0.01 \) (b), \( p=0.04 \) (c), \( p=0.08 \) (d), \( p=0.1 \) (e), \( p=0.5 \) (f). All structures have external size in the \( xy \) plane of 100x100μm, the lattice parameters of the ordered sample \( a_x = a_y = 2\mu m \), the number of layers along the \( z \)-axis \( N=4 \). The patterns are observed on a flat screen positioned perpendicularly to the sample, as shown in figure 1 (a). \( \lambda = 0.53\mu m \).

Using scattering geometry show in figure 1 (a), we investigated the patterns observed on a flat screen positioned perpendicular to the sample. Figure 2 demonstrates the diffraction patterns from the anisotropic woodpile with disorder in rods oriented along vertical \( y \)-axis. The \( n \)-order diffraction patterns depend on the interscatterers distance accordingly to the Laue equation \( \theta_s = \cos^{-1} \left( \frac{n\lambda}{a} \right) \). Therefore for the randomized parameter \( a \), the angle \( \theta_{sn} \) becomes uncertain. With increasing of the
disordered parameter $p$, arcs and circles become more and more randomized and a granular distribution of light intensity appears at strong disorder $p = 0.5$.

To summarize, in woodpile disordered structures, the zero-order and higher-order diffraction patterns show different behavior as a function of the disorder parameter $p$. The zero-order diffraction is not significantly modified for small and intermediate disorder, but the higher-order diffraction can be affected strongly. For anisotropic woodpile structures when orientation disorder is introduced only in one direction of square woodpile, we found an interesting effect. When disorder increases, the higher-order patterns from ordered set of rods becomes randomized and finally hardly observed while higher-order patterns from disordered set of rods continue to be bright and sharp. The reason for such effect is that the light scatters not from the whole dielectric rod but from intersection points of different rods. This conclusion can be considered as general features of light scattering in dielectric photonic structures.

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