Photonic dualism of icosahedral quasicrystals

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Abstract. Here we report on fabrication of 3D submicron-size dielectric icosahedral quasicrystals and show a photonic dualism of these structures. Relying on far-field measurements, we found pronounced patterns of unconventional Bragg diffraction, which indicates the existence of multiple photonic pseudogaps.

1. Introduction

An ordinary crystal possesses periodicity and translational symmetry – when the basis vectors are translated to any distance, the lattice transforms into itself. The translation of the unit cell allows you to completely fill the space without gaps and overlaps, thereby creating an endless crystal lattice. In addition to translational symmetry, crystals are characterized by rotation and / or reflection symmetry. Because of translational symmetry, the crystal can have symmetry axes of the 2nd, 3rd, 4th and 6th orders and cannot have the rotation symmetry of the fifth and any order higher than the sixth, since such rotations do not bring the crystal lattice into itself.

Quasicrystals are a separate class of solids with quasiperiodicity, which does not imply filling the entire space during translation, as well as rotational symmetry axes of any order, in particular, those that are forbidden for ordinary periodic crystals. Quasicrystals, like ordinary crystals, can be one-dimensional, two-dimensional, and three-dimensional.

An example of two-dimensional quasicrystals are the Penrose mosaics, named after the mathematician Roger Penrose, who first considered such structures in his work "The Role of Aesthetics in Pure and Applied Mathematical Research."[1]. The Penrose mosaic family is built by sequentially adding building blocks consisting of a narrow and wide rhombus. The angle at the apex of a wide rhombus is $2\pi/5=72^\circ$, at the apex of a narrow rhombus $2\pi/10=36^\circ$.

An example of three-dimensional quasicrystals is the class of icosahedral structures. The family of icosahedrons is created by sequentially adding three-dimensional structural blocks according to a certain rule [2]. Icosahedrons have spatial axes of symmetry $C_{2v}$, $C_{3v}$, $C_{5v}$.
2. Discussion

For experimental studies of photonic dualism, icosahedral quasicrystals and a photonic crystal woodpile truncated along a sphere were created. A two-photon polymerization technique [3-4] was used to create these structures. Figure 1 shows SEM images of the generated structures.

![SEM images of the fabricated photonic crystal icosahedral quasicrystal. (a) SEM image photonic crystal woodpile. (b) SEM image quasicrystal.](image)

Figure 1. SEM images of the fabricated photonic crystal icosahedral quasicrystal. (a) SEM image photonic crystal woodpile. (b) SEM image quasicrystal.

Next, optical diffraction by a photonic crystal and a quasicrystal was investigated. An Nd laser with a wavelength of 532 nm was used as a light source [3]. Figure 2 shows the diffraction patterns for a photonic crystal and a quasicrystal.

![Experimental diffraction patterns from photonic crystal (a) and photonic quasicrystal (b).](image)

Figure 2. Experimental diffraction patterns from photonic crystal (a) and photonic quasicrystal (b).

The diffraction pattern from a photonic crystal exhibits C4v symmetry and is a superposition of two components: Bragg diffraction in the form of bright ordered maxima associated with the crystal structure, and a background in the form of speckle-type diffraction due to scattering from individual rods [5]. The second scattering component was determined by the eigenmodes of the rods of finite length [6]. Due to the different lengths of the rods, the scattering is random, which leads to the formation of a speckle pattern. It is known that the presence of bright diffraction maxima on ordered periodic photonic structures is associated with the presence of stop bands. Although quasicrystals do not have translational symmetry, the presence of diffraction maxima is associated with the existence of a quasi-stop band in
the band structure of a quasicrystal, since the diffraction pattern is closely related to reciprocal space [7]. The pronounced quasi-Bragg diffraction pattern in figure 2 indicate the existence of multiple photonic quasi-stop bands in quasicrystals.

Figure 3. (a) Image in the optical microscope showing a propagating beam through woodpile. (b) Optical microscope image of icosahedral quasicrystal that is completely filled with scattered light due to intrinsic localization. The white circle shows the boundaries of the samples.

Figure 3 shows images of a photonic crystal and a quasicrystal that are irradiated with 530 nm laser radiation. Figure 3a demonstrates that when light passes through a photonic crystal, there is only a ballistic component and a weak wave structure. However, no light scattering is observed on the rest of the photonic crystal. For clarity, the sample boundaries are marked with a white line. In the case of icosahedral quasicrystals, the images are fundamentally different. From figures 3b it can be seen that the quasicrystal is "filled" with scattered light and it is impossible to separate the ballistic component. On the one hand, due to quasiperiodicity, quasicrystals have structural elements, which can generate quasi-Bragg scattering and, accordingly, energy quasi-stop bands, which is the main property of periodic photonic crystals. On the other hand, due to the absence of ideal periodicity, in quasicrystals there is an uncompensated component of multiple scattering into the total solid angle of $4\pi$ steradians, similar to scattering by disordered structures. This is precisely the picture that is observed when studying the scattering of light by icosahedrons. On the one hand, on the screen located behind the sample, a rather pronounced picture of numerous Bragg reflections is observed, figure 2. On the other hand, there is an unstructured "glow" of the entire icosahedral sample – figure 3 due to multiple rescattering of light in a quasicrystal, similar to the scattering of light in a turbid disordered medium. Thus, it is because of this duality that photonic dualism is observed in quasicrystals. And such structures can behave both as ordered crystals and as disordered media, figure 4.
Figure 4. Schematic of light scattering in three states of solids. (a) Perfect crystals: Bragg scattering and a ballistic component of a transmitted laser beam. (b) Perfect 3D quasicrystals: Bragg scattering, multiple scattering of light within the structure, and a ballistic component. The light flux propagating in the direction of the incident laser beam can be separated into a ballistic component and a multiple scattering component, that is, light localized in a quasicrystal. (c) Disordered structures: multiple scattering of light localized within the structure, and the ballistic component, if observed.

3. Conclusions
In this work, we performed diffraction experiments characteristic of the study of crystalline samples. As a result, we demonstrated the photonic dualism of quasicrystals – both Bragg diffraction and multiple scattering owing to light localization in quasicrystals were observed. The photonic dualism of quasicrystals opens the way to variety applications in optics, from lasing and sensing to telecommunications.

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