

Photonic Crystal Fabrication

1. Photonic Crystals

Since the 1980s, it has been realized that light can be controlled in an intricate way by nanostructures, hence the term “nanophotonics.” For instance, two groups demonstrated that multiple scattering of light can lead to intricate interference phenomena. Of particular interest are three-dimensional photonic crystals. In the ultimate three-dimensional photonic crystal with a band gap, certain frequencies of light are completely forbidden from existence, which makes them the supreme devices to control light. Originally, it was predicted that spontaneous emission of light is forbidden in these nanostructures or that light is localized. Another intriguing aspect of photonic crystals is that by adding an embedded microcavity, photons can be stored or slowed down. Therefore, photonic crystals truly function to “mold the flow of light.”

A photonic crystal is a periodic nanostructure made from two different materials that are periodically alternated over length scales on the order of the wavelength of light. Typically, one material is air and the other has a high index of refraction, e.g., a semiconductor. Light with certain wavelengths and wave vectors cannot propagate in such a structure because of Bragg diffraction. This is the condition where light that is reflected off the lattice planes in the crystal interferes constructively. The Bragg condition was first described for X-rays but is also valid for light. In case of a broadband (white light) reflectivity measurement on a photonic crystal, the Bragg condition appears as a peak in the spectrum, also referred to as stop band. No stop band exists when the difference in the refractive index of the constituent materials of the photonic crystal is zero. The stop band gets broader when the difference in refractive indices increases.

An important parameter of photonic crystals is the photonic strength, S , defined as the polarizability per unit cell volume. The photonic strength, S , is a measure of the interaction strength of photonic crystals with light. A higher S means that the crystal is more strongly interacting with light. Two frequencies form the edges of the stopgap of the photonic crystal $\Delta\omega_{\text{gap}}$. The center of the stopgap is the central frequency ω_{gap} . By measuring ω_{gap} and $\Delta\omega_{\text{gap}}$, the photonic strength S can be determined experimentally:

$$S = \frac{\Delta\omega_{\text{gap}}}{\omega_{\text{gap}}} \quad (1)$$

Whereas a stopgap is defined in one direction only, in a photonic band gap crystal a range of forbidden

frequencies exists for all directions in three dimensions. In order for a photonic band gap to appear, stopgaps from different lattice planes in the crystal overlap and couple. For this to occur, the photonic strength S of the crystal, and thus the difference in refractive indices of the two photonic crystal materials, must be high enough. The rule of thumb is that the photonic strength should exceed $S \geq 0.20$ for a photonic band gap to appear. In nanophotonics, one of the targets is to obtain three-dimensional photonic crystals with band gaps that are as broad as possible. Some examples of applications pursued with photonic crystals are the following:

- Thresholdless cavity lasers that are interesting in, e.g., miniaturized devices because of their high efficiency and low noise.
- Optical components to control the propagation of light, especially fibers, polarizing beamsplitters, and waveguides.
- Devices for detection and sensing, including detection of gas molecules, highly sensitive fluorescence detection and the detection of single particles.
- To change the color or the spontaneous emission rate at which light sources embedded inside the photonic crystals emit.
- (Optically) switching three-dimensional photonic crystals allows, for example, dynamic control of the emission of light sources that are inside the photonic crystal, e.g., the emission can be turned on or off.
- Ultimately, photonic crystals are predicted to contribute to all-optical computers where bits are encoded as light. Compared to traditional electronic computers, all-optical systems should be more energy efficient, faster, and have larger bandwidths.

2. Inverse Opals

Many different types of three-dimensional photonic crystals have been conceived but of particular interest are those that potentially provide three-dimensional photonic band gaps, as these offer ultimate control of light in all three dimensions simultaneously. Among the first structures considered as promising photonic crystals were face-centered cubic (fcc) crystals of colloidal spheres. These crystals are routinely obtained by different methods of self-assembly. Two types of fcc crystals of spheres are distinguished: (a) colloidal crystals that consist of separate spheres that perform Brownian motion while suspended in a liquid and (b) artificial opals where the spheres are immobilized as they are in close-packed contact and surrounded by air, as shown in Fig. 1.

Artificial opals made from self-assembled colloidal spheres are of considerable scientific and technological interest as photonic crystals, as components of light sources, solar cells, and chemical sensors, as well as in the field of plasmonics. Although colloidal

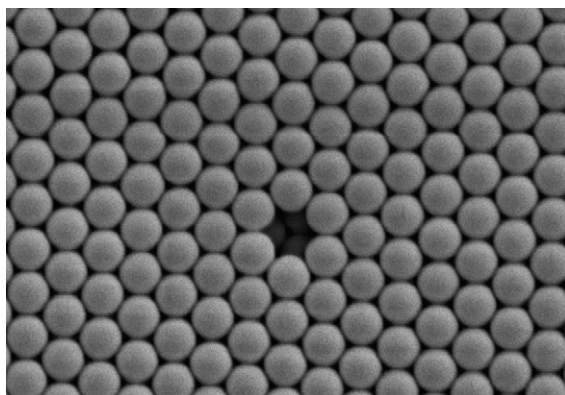


Figure 1

Scanning electron micrograph of the surface of a polystyrene artificial opal. Artificial opals are generally obtained by different methods of self-assembly. The spheres have a radius of 439 nm. A surface cavity consisting of a vacancy is apparent that is observed by chance in a self-organizing opal. A method has been demonstrated to make point defects by design.

crystals and artificial opals are interesting as photonic structures in their own right, they cannot form a photonic band gap due to the limited photonic strength of these crystals; for an artificial opal of polystyrene spheres, the photonic strength is approximately $S = 0.06$, whereas for photonic band gap formation, the photonic strength should be higher than 0.2.

Although it was originally suggested that it is impossible to obtain a band gap in fcc photonic crystals, it was realized in 1992 that in inverse opals it is possible to obtain a photonic band gap. Inverse opals consist of fcc-stacked spheres of air, embedded in a backbone of a higher index of refraction material (see Fig. 2). These inverse artificial opals can be obtained by using fcc colloidal sphere crystals as a template and filling them with a high index of refraction material, followed by removal of the opal template. Examples include inverse opals of metal oxides such as titanium dioxide, carbon, cadmium selenide, and even of metals. Alternative templates for inversion can be obtained by, e.g., holographic lithography.

In inverse opals, the index of refraction contrast must exceed 2.8 in order to obtain a photonic band gap. A material that meets this requirement is silicon with a refractive index of 3.5. Consequently, inverse opals of silicon are promising candidates to display a photonic band gap. Unfortunately, even for silicon, the calculated maximum width of the band gap in fcc inverse opals remains limited to 12%. The photonic band gap in fcc inverse opals is very sensitive to fabrication-induced disorder, which limits the usefulness of these structures when large band gaps are required.

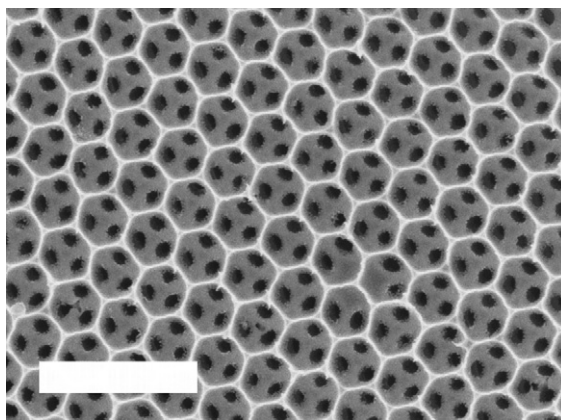


Figure 2

Scanning electron micrograph of the surface of an inverse opal. Inverse opals are obtained by using fcc colloidal sphere crystals as a template and filling them with a high index of refraction material, in this case titanium dioxide, followed by removal of the template. The scale bar equals 1 μm . Reproduced with permission from Lodahl P, van Driel A F, Nikolaev I S, Imman A, Overgaag K, Vanmaekelbergh D, Vos W L 2004 Controlling the dynamics of spontaneous emission from quantum dots by photonic crystals. *Nature* **430**, 654–7. Copyright Wiley.

3. Simple Cubic Photonic Crystals

Different varieties of three-dimensional photonic crystals with a simple cubic lattice have been suggested. Among the proposed building blocks are spheres, air spheres, square rods, circular rods, and many other motifs. Examples of simple cubic crystals are beautiful air sphere and square rod crystals. Unfortunately, the maximum width of the band gap of simple cubic photonic crystals remains limited: a maximum width of the (second-order) band gap of 13% is predicted for an optimized geometry. Moreover, one can expect these second-order band gaps to be sensitive to fabrication-induced disorder, similar to the band gap in fcc air sphere crystals.

4. Diamond-Like Photonic Crystals

The so-called diamond-like crystal structure has received a great deal of attention because of its large calculated width of the band gap, and the property that the photonic band gap already opens at an index of refraction contrast of 1.9 compared to 2.8 for fcc air sphere crystals. The use of diamond lattices in photonic crystals was introduced by Ho *et al.* and was comprehensively reviewed. Some examples of fabricated photonic crystals with a diamond-like structure are the following:

- An early type of diamond-structured photonic crystal is obtained by milling or etching pores in

separate steps in three directions. In 1995, such crystals were fabricated in GaAs and GaAsP. In a subsequent study, similar crystals were shown to be photonic, but a band gap remains to be demonstrated. For such a crystal made from silicon, the calculated band gaps have a relative width of up to 19%. Later, such a structure was fabricated using a combination of chemical etching and focused ion beam milling. This photonic crystal shows promising reflectivity peaks around $\lambda = 3 \mu\text{m}$.

- Diamond-like woodpile structures were introduced by Ho *et al.* in 1994. They are fabricated by stacking layers of dielectric rods on top of each other in sequential steps (see Fig. 3). The fabricated structures consist of stacked and rectangular touching rods. The maximum band gap width is limited to approximately 18% for structures in silicon.

- Two groups have described “spiral diamond” crystals, consisting of circular spirals. One of the techniques proposed to fabricate the structures is glancing angle deposition. Subsequent inversion of the square spirals with silicon yields a crystal with a calculated relative width of the band gap of approximately 24%.

- It has been attempted to fabricate diamond-like photonic crystals with dielectric spheres. For example, nanorobotic manipulation was used to obtain a pretty but small five-layer crystal.

- Three-dimensional woodpile crystals were fabricated by a double-angled etching technique. By two consecutive cryogenic reactive ion etch steps of 45°

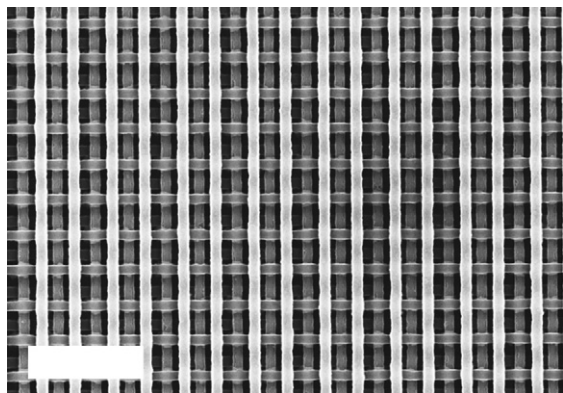


Figure 3. Scanning electron micrograph of the surface of a woodpile photonic crystal fabricated by Fleming and Lin (1999). These crystals are obtained by stacking layers of dielectric rods on top of each other in sequential steps using conventional semiconductor processes. The scale bar equals $2 \mu\text{m}$. Reproduced with permission from Harding P J, Euser T G, Vos W L 2009 Identification of competing ultrafast all-optical switching mechanisms in Si woodpile photonic crystals. *J. Opt. Soc. Am. B* **26**, 610–19. Copyright OSR.

with respect to the wafer surface, at an angle of 90° between the two etch directions, a thin photonic crystal was obtained.

5. Inverse Woodpile Photonic Crystals

The most promising type of diamond-like photonic crystals was introduced by Ho *et al.* These structures are referred to as inverse woodpile photonic crystals and consist of two geometrically identical arrays of pores perpendicular to each other in a high refractive index material (see Fig. 4). They differ from woodpile crystals in the sense that the filling fraction of high refractive index material is optimized and that the pores may overlap, which is required to obtain a maximum band gap. Inverse woodpile photonic crystals are very interesting because of their conceptual ease of fabrication by only etching in two directions and their high photonic strength, resulting in a broad band gap with a relative width of more than 25%.

A method was proposed to fabricate such inverse woodpile structures by using macroporous silicon and subsequently focused ion beam milling. Later, by using the proposed method, a crystal was obtained, which was one of the first fabricated inverse woodpiles. It was pointed out that the structure was misaligned, which results in a reduced calculated width of the band gap. A reflectivity spectrum was shown with a $>40\%$ reflectivity peak. This peak corresponds to a calculated stopgap in the direction that was measured. This result shows that these crystals are reasonably strongly photonic. Inverse woodpiles can also be obtained by solely using focused ion beam milling.

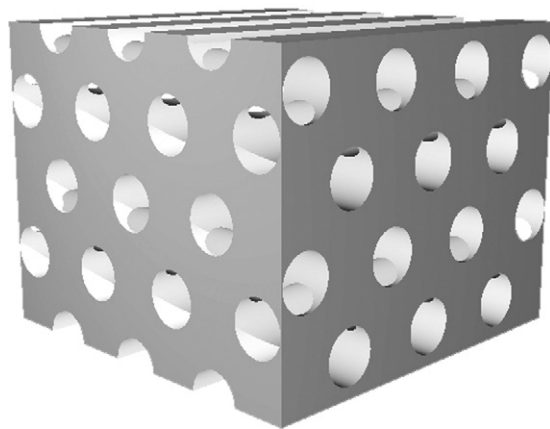


Figure 4 Three-dimensional representation of a cubic inverse woodpile photonic crystal. These structures consist of two geometrically identical arrays of pores perpendicular to each other in a high refractive index material.

Recently, an alternative method was described to fabricate similar crystals with pores that have an elliptical cross section. This method involves direct laser writing and silicon dioxide-assisted deposition of polycrystalline silicon. Optical transmittance and reflectivity experiments show that this structure is indeed strongly photonic. However, the optical experiments were performed along only one direction and hence do not confirm whether a photonic band gap exists in this structure. With further calculations, it is predicted that the structure can be improved to obtain relative widths of the band gap of 18%.

These examples show that several inverse woodpile crystals have successfully been fabricated. However, in none of these cases was a photonic band gap convincingly demonstrated, which remains an inspiring goal for the (near) future.

6. Optical Cavities in a Three-Dimensional Photonic Crystal

One of the great promises of nanophotonics is the possibility that light is trapped in optical cavities inside three-dimensional photonic band gap crystals. An optical cavity in a photonic crystal can be manufactured by either adding or removing high refractive index material, which yields a donor or an acceptor, respectively. The mirrors of the optical cavities are formed by the surrounding photonic crystal with a band gap. It has been predicted that light is trapped in such a photonic crystal cavity within a tiny volume as small as $1/100^{\text{th}}$ of a wavelength cubed. It is a challenge to embed such controlled point defects inside three-dimensional photonic band gap crystals to achieve functional systems.

The first experimental observations of donor and acceptor modes in fcc crystals were reported for microwave frequencies. Examples of fabricated defects on a micrometer scale include the incorporation of point defects in woodpile structures. Also, a method was proposed to obtain point defects in artificial opals using focused ion beam milling. Thus, photonic band gap crystals are on a fast lane toward a bright future.

See also: Photonic Crystals: Principles and Applications; Photonic-lattice Filament

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