

Photonic crystals: making a cage for light

by Willem Vos (1) and L. (Kobus) Kuipers (2)

(1) *van der Waals-Zeeman Instituut, Universiteit van Amsterdam, Valckenierstraat 65, 1018 XE Amsterdam, URL: www.thephotonicbandgaps.com*
(2) *Applied Optics Group, MESA⁺ Research Institute and Department of Applied Physics, Universiteit Twente, Postbus 217, 7500 AE Enschede, URL: tnweb.tn.utwente.nl/ot*

Photonic crystals are optical materials with an intricate three-dimensional structure that manipulates light in unusual ways thanks to multiple Bragg diffraction. The structure has the length scale of the order of the wavelength of light. In future, such crystals could steer light beams around tiny optical chips or be the heart of a new breed of efficient light emitters. An example of a photonic crystal is the gem opal, which consists of a regular array of tiny silicate spheres, ordered like the atoms in a crystal lattice, but on a scale thousand times larger. If the structure has a large variation in refractive index a "photonic bandgap" occurs. Under these special circumstances, Bragg diffraction prevents a certain range of wavelengths from propagating in *any* direction inside the crystal. As an important quantum-optical consequence, spontaneous emission of excited atoms or molecules inside the crystal is completely inhibited. Moreover, controlled defects in a photonic crystal will result in localized states in the band gap, as if light is trapped in a cage (see Figure 1).

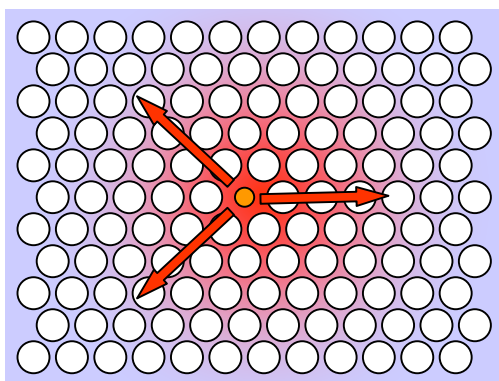


Figure 1. "Photons in a cage": light emitted by a source (central circle) is trapped in a photonic crystal cavity. The light is prevented from propagating through the bulk of the crystal because of a photonic band gap. By switching the crystal's properties, one effectively switches the photons.

This and other exciting phenomena were predicted in 1987 by Yablonovitch at Bell Communications Research (now at UCLA). Simultaneously, John at Princeton (now in Toronto) predicted that disorder in a photonic band gap crystal will cause localization of light, where photons become trapped and can no longer propagate. These pioneering papers illustrate the growing appreciation in the eighties and nineties of the close analogies between electrons and photons.

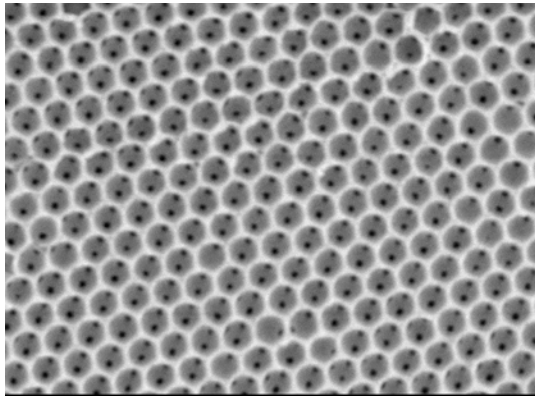
In 1991, Yablonovitch and his co-workers performed two landmark experiments. First, they observed a photonic bandgap at microwave frequencies in samples with a centimetre-scale structure made by drilling holes in stycast low-temperature glue. Next, they observed localized states in the forbidden band gap that result from intended crystal defects. These states are high-Q cavities that serve as miniature laser cavities at optical frequencies.

At around the same time, theorists started to become interested in the subject. Ho and colleagues in Iowa predicted a photonic band gap in a diamond structure and proposed a feasible construction method. Then in 1992, the group of Haus at Rensselaer Polytechnic in the US predicted that the ubiquitous face centered cubic (fcc) lattice could also possess a band gap.

The goal became how to fabricate crystals that would work at optical frequencies. This requires a structure that has a length scale about ten thousand times smaller than the microwave crystals.

In 1996 teams from Siemens in Germany and the University of Glasgow in Scotland independently made crystals with two-dimensional optical band gaps, that is a band gap for light confined to a plane. The Siemens team electrochemically etched silicon to get a gap at a wavelength of 5 micrometre while the Glasgow team performed lithography on AlGaAs to obtain a gap at 850 nm. Sandia National Laboratories in the US and a Japanese team based in Kyoto have taken the next logical step and stacked several microstructured semiconductor layers in pursuit of three-dimensional band gaps. They succeeded in creating structures with stop-gaps at telecom wavelengths in the near-infrared.

Stacking however, is not only way to make 3D photonic crystals. An easier method is to make photonic crystals from self-organizing systems such as colloidal suspensions. These naturally have the right structure size for the optical range, but unfortunately a small refractive index variation. In 1998, however, three groups in Minnesota, Amsterdam, and at Allied Signal developed strongly photonic crystals, by using artificial opals with an fcc structure as templates to pattern high-refractive index materials. Such air-sphere crystals or inverse opals present a clear route to photonic band gaps and are now being fabricated by many groups worldwide. This year (2000) the group in Toronto (van Driel) produced a beautiful air-sphere crystal based on Si. According to their calculations, the crystal could well have a bandgap around 1.5 μm .



*Figure 2. Scanning electron microscope image of the surface of an air sphere crystal (Science **281**, 802 (1998)), also known as “inverse opal”. A highly ordered (111) hexagonal arrangement of air spheres with a radius of 330 nm is observed in titania (TiO_2 , the white structure) that has a high refractive index of ~ 2.5 . The small black holes at the bottom of each air sphere are windows that connect to the next deeper layer of air spheres, which ensures the connectivity of both air and titania.*

To the unaided eye, optical Bragg reflections of air-sphere crystals (Figure 2) appear as colored reflections. We have recorded the reflectivity as a function of angle of incidence and polarization over a wide range of wavelengths. The data demonstrate that Bragg reflection prevents light from propagating in 55 % of all directions (Phys. Rev. Lett. **83**, 2730 (1999)). Such a drastic “encaging” of the light should also influence the spontaneous emission of light sources inside the crystals. Indeed, our recent results demonstrate a large modification of the directional spontaneous emission properties (Phys. Rev. A (accepted Oct. 2000)).

In experiments with ultrashort femtosecond light pulses, we have measured the group velocity and group velocity dispersion for light that travels through a crystal (Phys. Rev. Lett. **83**, 2942 (1999)). We find that light is considerably slowed down at wavelengths near a Bragg reflection, is a precursor to localization. If one draws the analogy between light and electrons, the dispersion can be identified with an “effective mass” of photons, that diverges near a gap.

To date, it remains an open question what the experimental signatures are of a photonic band gap. Both reflectivity and emission experiments reveal that in strongly photonic crystals, Bragg diffractions of different sets of crystal planes become coupled, giving rise to multiple Bragg diffraction, and flat dispersionless bands (Phys. Rev. B **62**, 9872 (2000)). In the range of the 2nd order Bragg reflection (nearly 1/2 times the wavelength of the usual Bragg reflection) where the band gap is predicted for *fcc* crystals, these couplings become highly complex (Phys. Lett. A **272**, 101 (2000)). Interestingly, a detailed analysis of the data reveals that reflectivity is not a telling probe of photonic crystals: even in the absence of a band gap does one observe features that could easily be interpreted as the much-anticipated photonic band gap. It has been proposed that a photonic band gap can be identified from the emission spectrum of e.g. dye that is placed inside a crystal (J. Opt. Soc. Am. B **16**, 1403 (1999)). While stop gaps have been observed in the emission spectra in weakly

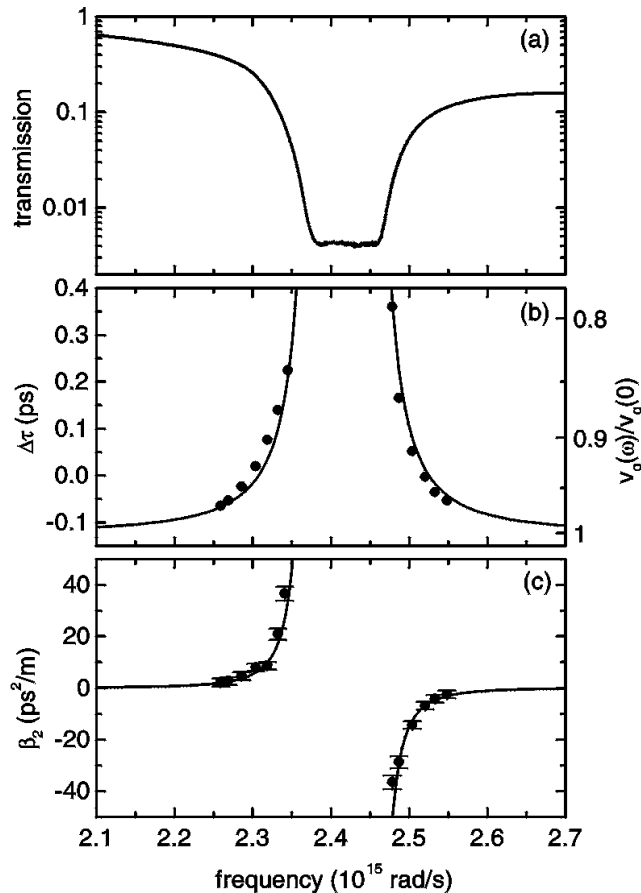


Figure 3. (a) Transmission spectrum of photonic crystal consisting of a self-organizing colloidal suspension. (b) Measured pulse delay times (full circles) near the L gap versus central frequency of the incoming pulses. (c) Measured group velocity dispersion parameter (full circles) as a function of frequency. The drawn lines in (b) and (c) represent calculation with dynamical diffraction theory. It is clear that the light slows down as the Bragg reflection is approached.

photonic colloidal crystals, no evidence has yet been observed of modified total spontaneous emission rates (Phys. Rev. A. **59**, 4727 (1999) and Phys. Rev. Lett. **83**, 5401 (1999)).

It is exhilarating that template-assisted growth of photonic crystals has become very popular - also for completely different, chemical applications - due to the relative ease of fabrication. Collaborations are going on with colleagues in Utrecht and St. Louis to develop crystals made from new materials to raise m to the regime (> 3) where photonic band gaps are predicted. Nevertheless, before envisioning the use of three-dimensional photonic crystals in optical circuits, one must be aware that light in photonic crystal travels a limited distance (the mean free path) before it becomes diffuse. In recent experiments we find mean free paths of about 15 microns for both opals and air-sphere crystals (Phys. Lett. A **268**, 104 (2000)).

Conventionally, the light propagation is investigated by relating the optical in- and output to a theoretical model. While good agreement between experiment and theory gives a satisfying sense of understanding, absence of agreement in these complex structures leads to an absence of understanding. With its capacity to measure local optical intensity distributions inside the top-layer of a structure, the photon scanning tunneling microscope (PSTM) is able to circumvent the need for input-output measurements. Of course, the local intensity distributions around small periodic structures still contain the information gathered with reflectivity and transmission experiments. However, here the microscope 'shines' as it also detects mode conversion into high-loss modes of the structures, which would have otherwise remained hidden (Appl. Phys. Lett. **77**, 142 (2000)).

Wavelength-dependent measurements of the intensity distributions unravel the various whispering gallery modes in a cylindrical microcavity (Opt. Lett. **24**, 1829 (2000), J. Opt. Soc. Am. B (accepted Oct. 2000)). It turns out that topographical features lead to (unwanted) polarization conversion (IEEE/Phot. Techn. Lett. (to appear Nov. 2000)). Here, the observations are aided by the somewhat counterintuitive fact that the PSTM picks up both TE- and TM-polarized modes propagating in a structure (Opt. Lett. **25**, 637 (2000)).

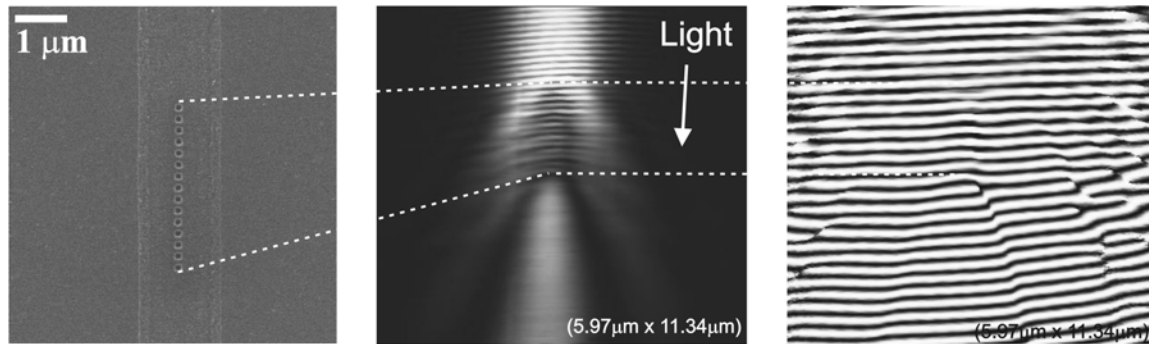


Figure 4. Focused ion beam image (left) of a small one-dimensional photonic crystal. The periodicity and the diameter of the holes are 220 nm and 110 nm, respectively. With the phase-sensitive PSTM the amplitude (middle) and the cosine of the phase (right) are measured as light scatters from the structure. A standing wave is visible in front of the array as are two diffracted waves behind the structure. Several phase singularities are visible in the wake of the array. (*J. Microsc. (to appear Jan. 2000)*)

Through the measurement of the phase evolution in addition to the amplitude distribution, all the ingredients are available to fully characterize the light propagation. Thus, we have unearthed unexpected optical phenomena like the creation of phase singularities (*Phys. Rev. Lett.* **85**, 294 (2000)) even in simple structures. Figure 4 shows light scattering from a periodic array of air rods fabricated by focused ion beam milling in a conventional waveguide. From the modulation depth of the standing wave on front of the array, the reflection coefficient can be determined. The attenuation coefficient of light inside the structure is directly available and can be related to the position and width of the stop gap. The local spacing of the phase fronts yields the effective index of the material in model-independent fashion. The phase maps also reveal the creation of single phase singularities and entire singularity networks.

A recent breakthrough allows us to fabricate large free-standing membranes containing a two-dimensional photonic crystal. Arbitrarily shaped defects, e.g. lines and small cavities, are easily introduced without the need for advanced lithography. Figure 5 depicts a free-standing membrane with a line defect. The defect was designed to guide light with a wavelength of 670 nm through the crystal.

Other scientists are already starting to uncover new physical and optical phenomena with photonic crystals. The group of Scherer at Caltech has just demonstrated lasing in a microscopic cavity of only 2.5 cubic half-wavelengths made from a single defect in a 2D photonic crystal, that contains quantum wells as the emitters. A group at Bath, UK, led by Russell has fabricated the first photonic fibres - optical fibres that guide a single mode of light due to a 2D bandgap rather than conventional method of a waveguide. Instead of a solid glass core and cladding the fibre has a hollow core and is riddled with tiny holes that run along its length.

From the start, applications have been an important driving force for photonic crystals, for instance in pursuit of efficient light sources. The group of Baets at the University of Ghent has fabricated microstructured LEDs which convert electricity to light with a record efficiency of 22 %. Another exciting possible use of photonic crystals is steering light beams around miniature integrated optical circuits. A team led by Joannopoulos at MIT in the US has suggested using line defects in a photonic gap to route light around sharp bends on a wavelength scale. Similar waveguiding has already been demonstrated in the microwave regime by Lin at Sandia National Labs. As an alternative, a group at NEC's research centre in Japan is exploiting the highly anisotropic dispersion surfaces of photonic crystals to achieve dramatic beam steering effects, dubbed "superprism".

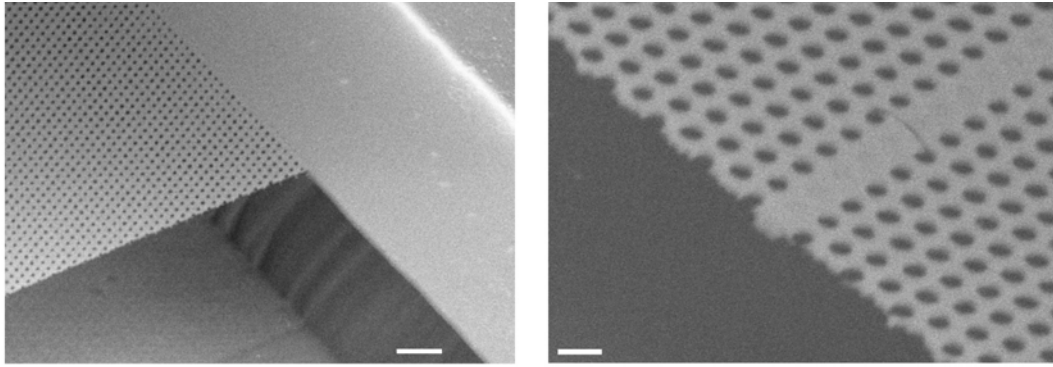


Figure 5. Scanning electron microscope images of a free-standing Si_3N_4 membrane (146 nm thick) containing a two-dimensional triangular array of air holes (periodicity 297 nm, hole diameter 200 nm). The membrane is 100 μm wide and 4 mm long and contains a linedefect with a width equal to twice the crystal period, the length is 1.1. mm. The scale bars in the left and right image are 1.5 μm and 400 nm, respectively.

A big step in the near future is the realization of a photonic band gap in a three-dimensional sample that operates at optical frequencies. Making this new state of matter is a major challenge for materials science and will require much interaction between experimentalists and theorists in optics. The reward will be access to exciting experiments on many quantum-optical phenomena, such as spontaneous emission inhibition or photon localization. Another crucial step is to produce photonic crystal structures that do more than just turn light around a corner. A careful utilization of interacting defect states enables the creation of optical switches and filters. More exciting and much more ambitious is the prospect to use the tiny lasers in two-dimensional crystals as elements in a quantum computer.

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