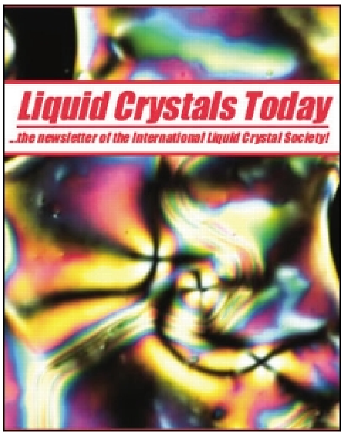


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# Tunable photonic crystals

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# Tunable photonic crystals

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## 1. Introduction

Nano-structured materials with a spatially periodic variation of the dielectric constant (figure 1) can show unique optical properties if their lattice constant is similar to the wavelength of light [1–6]. If the amplitude of the spatial variation of the dielectric constant is sufficiently large, the material can show a photonic band gap (figure 2), i.e. an interval of frequencies where no propagating modes of the electromagnetic radiation occur. A wave exhibiting a frequency within the photonic band gap will be reflected at the surface of the photonic crystal. However, even more interesting than this Bragg reflection is the possibility of wave-guiding along line defects within the photonic crystal or the trapping of light within point defects of the photonic crystals. Owing to the photonic band gap, the emission of light from an excited molecule embedded in the 'photonic crystal' can be inhibited [2, 3], or Anderson localization of photons may occur [4]. The possibility to fabricate optical waveguides, waveguide couplers, optical filters or other functional elements within very small areas makes photonic crystals very promising key materials in the field of integrated optics. However, their manufacturing is difficult and remains a great challenge. Soon after the prediction of a complete photonic band gap in spatially periodic dielectrics [5], Yablonovitch [6] produced a photonic crystal with a band gap in the microwave range by drilling holes in a silicon wafer, appropriately (figure 1). Since then, many different techniques of manufacturing have been used in order to create two-dimensional (2D) and three-dimensional (3D) structures in solid substrates or to make use of the self assembly of colloidal particles (figure 1) (see, for example, references [6–11]).

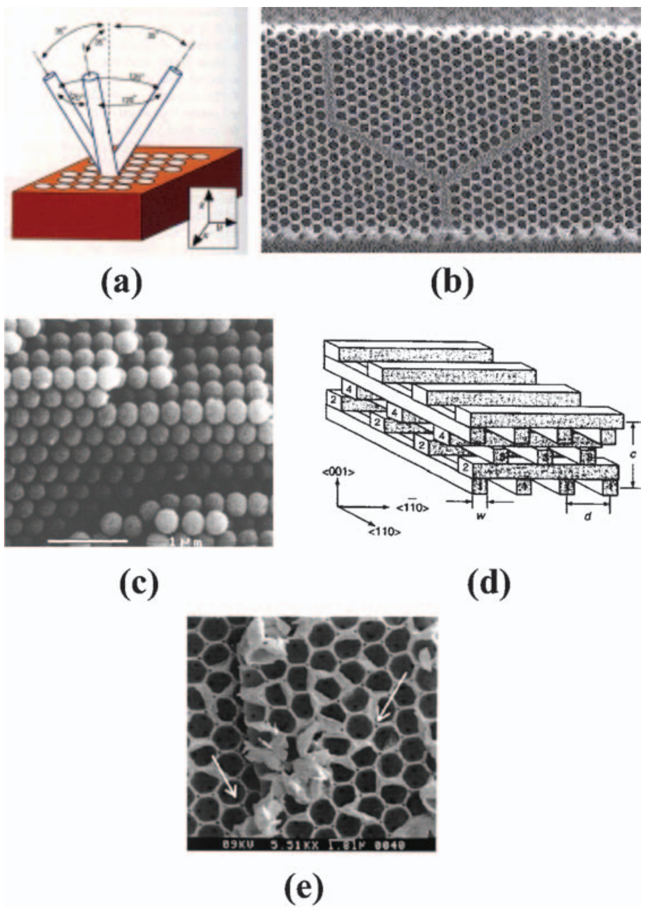


Figure 1. Examples of photonic crystals. (a) Yablonovite [6], (b) 2D array of cylindrical holes in a silicon wafer [7], (c) colloidal crystal ($SiO_2$, opal) [8], (d) 3D photonic crystal made of Si [9], (e) inverted opal, made of air spheres in titania [10].

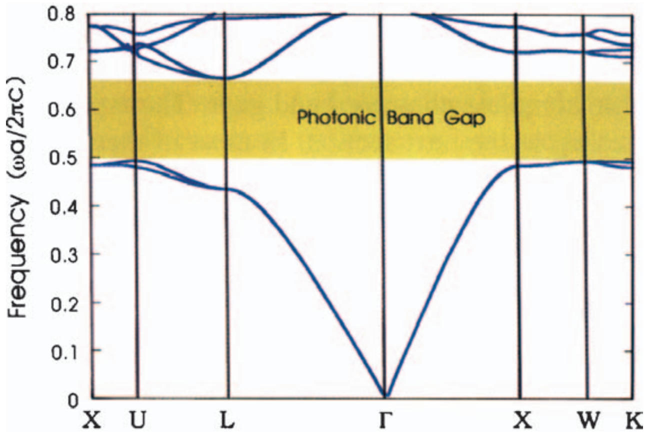


Figure 2. Dispersion relation of a diamond structure [1].

From a theoretical point of view, the solution of the electromagnetic wave equation for photons travelling in a periodic dielectric structure is similar to solving the Schrödinger equation for electrons in a semiconductor

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crystal [1]. Because of this analogy, the range of forbidden frequencies, the photonic band gap, can be considered as an analogue of the electronic band gap in semiconductors.

The appearance of a photonic band gap can be easily understood by considering a one-dimensional photonic crystal, i.e. an alternating stack of two kinds of dielectric layers. If the two dielectric constants of these layers are very similar ($\varepsilon_1 \approx \varepsilon_2 = \varepsilon$), the frequency $\omega$ of light propagating through the layers is proportional to the wavevector, $\omega = (c_0/\sqrt{\varepsilon})k$, throughout. However, for high dielectric contrast ($\varepsilon_1 \ll \varepsilon_2$), Bragg reflection can lead to standing waves. If the wavelength matches the layer spacing $a$ properly, $k = \pm\pi/a$, two modes with the same wavevector $k$ can appear: one standing wave with maximum intensity at the locations with high dielectric constant [$\Rightarrow \omega_1 = (c_0/\sqrt{\varepsilon_1})k$], and one with maximum intensity at the locations with low dielectric constant [$\Rightarrow \omega_2 = (c_0/\sqrt{\varepsilon_2})k$]. In this case, we have two different frequencies corresponding to the same wavevector $k$, while frequencies between $\omega_1$ and $\omega_2$ do not correspond to any propagating mode. For three-dimensional structures, the dispersion relation $\omega(k)$ has to be analyzed for any $k$ within the irreducible Brillouin zone (figure 2). A structure is said to exhibit a complete photonic band gap if an interval of frequencies without any corresponding propagating mode exists.

A defect within a photonic crystal can behave as a resonant cavity with a very sharp resonance frequency. For example, the structure shown in figure 3 acts like a Fabry–Perot filter which is integrated in an optical wave guide [12]. Formally speaking, the sharp resonance frequency within the photonic band gap corresponds to a localized state. Very interesting effects appear also at the frequency edge of the photonic band gap. Note that the group velocity $v_g = (d\omega/dk)$ goes to zero at the band edge. This leads to further interesting phenomena, like distributed feed back (DFB) lasing at the band edge [13].

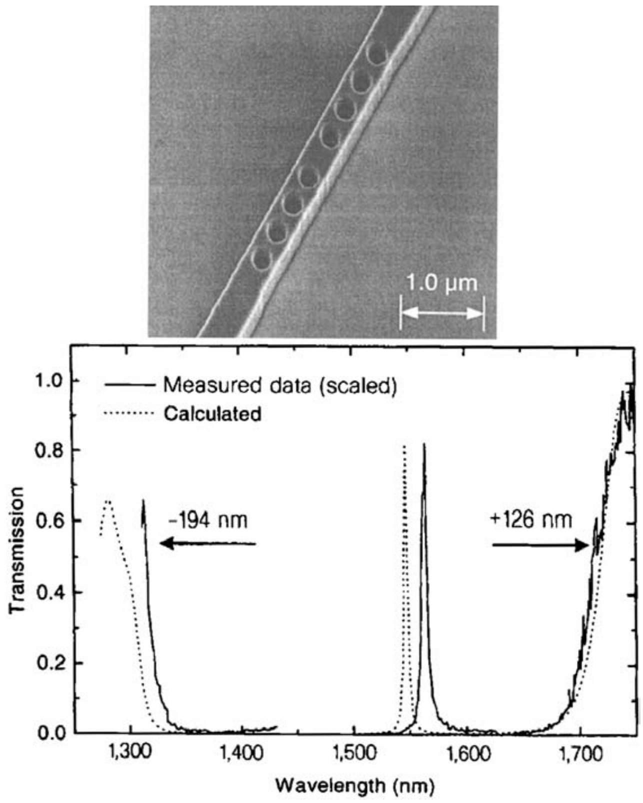


Figure 3. (a) Optical waveguide with an integrated PBG frequency filter. (b) Its spectrum, showing a photonic band gap and a resonance frequency within the gap [12].

## 2. Infiltration of photonic crystals by liquid crystals

Tuning of the photonic band gap, the band edge or a localized state within the band gap could be of great importance for applications. One possibility is the infiltration of photonic crystals by a liquid crystal [14–20]. 3D Colloidal crystals [14–18] and silicon wafers with a 2D structure [19] were filled with a liquid crystal, and either the temperature dependence or the field dependence of the refractive indices were used to shift the photonic band gap. For example, colloidal silica particles can form fcc structures (artificial opals). If the voids between the silica spheres are filled with a liquid crystal, the Bragg wavelengths can be shifted owing to changes in the temperature [14] or application of electric fields [17, 18]. Owing to the small difference between the refractive indices of silica and the liquid crystal, the wavelength shift is typically not larger than a few nm [14–18], and there is no complete photonic band gap. However, the appearance of a complete photonic band gap is predicted for inverted opal structures filled with a liquid crystal [21, 22]. Recently, inverted fcc structures were made from $SnS_2$, using a colloidal crystal as a template [23]. If the spherical voids are filled with a liquid crystal [24], the filling fraction (74%) is much larger than in normal opals (26%). Consequently a temperature-induced wavelength shift of 14 nm could be observed [24].

## 3. Cholesteric and blue phases

Due to their helical structure, cholesteric phases can show Bragg reflection of circularly polarized light and may be considered as a one-dimensional photonic crystal. The dispersion relation [25] shows a photonic band gap for circularly polarized light. A possible application is the distributed feedback (DFB) lasing that occurs when a cholesteric liquid crystal is doped with a LASER dye and optically pumped with suitable LASER pulses [26]. Collimated light with very high intensity and very

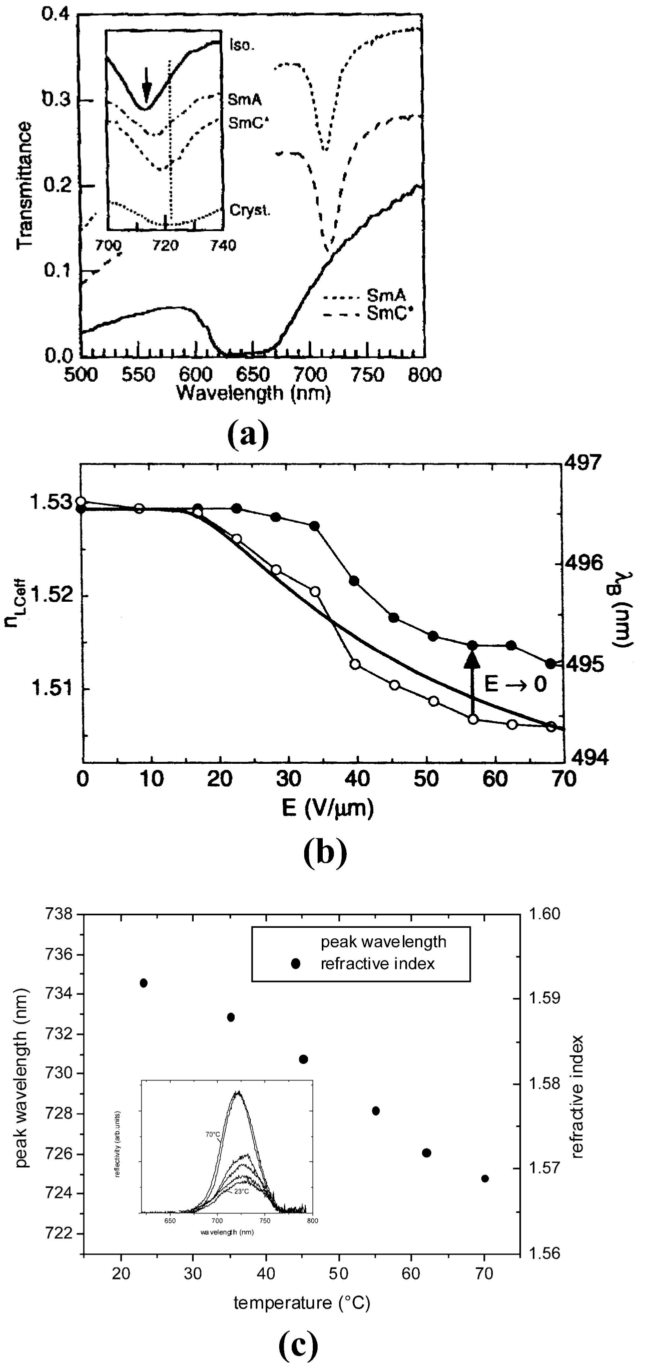


Figure 4. Change of the Bragg wavelength with (a) temperature [14] or (b) electric field [17] in artificial opal structures filled with a liquid crystal. (c) Shift in an inverted fcc structure filled with liquid crystal [24].

narrow spectral bandwidth can occur at the edge of the broad selective reflection bands (figure 5), if the gain spectrum of the LASER dye and the selective reflection band of the cholesteric structure are properly matched. Using the language of photonic crystals, this phenomenon can be described as band edge lasing. The very small

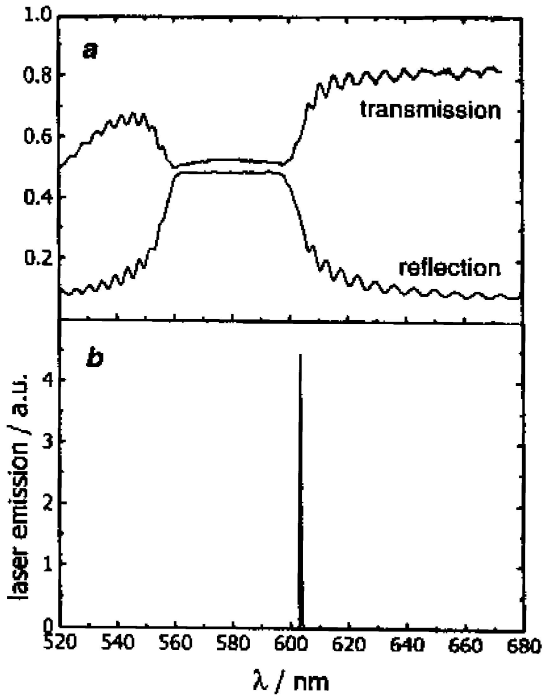


Figure 5. (a) Transmission and reflection spectra of a cholesteric phase. (b) Stimulated emission of the cholesteric phase doped with a LASER dye [28].

group velocity appearing at the frequency edges of the photonic band gap results in an enhanced interaction between matter and light.

This effect has been known for many years [26], but it was recently improved by using cholesteric elastomers [27] and highly cross-linked polymers [28]. In particular, elastomers offer a unique possibility to tune the LASER wavelength, by shifting the Bragg wavelength as a result of mechanical strain (figure 6). Also, tuning of the LASER wavelength by means of electric fields is possible, e.g. in ferroelectric SmC* phases with very small pitch, due to helical unwinding [29]. Very recently, a defect mode emission within the photonic band gap was realized in a dye-doped cholesteric polymer network [30].

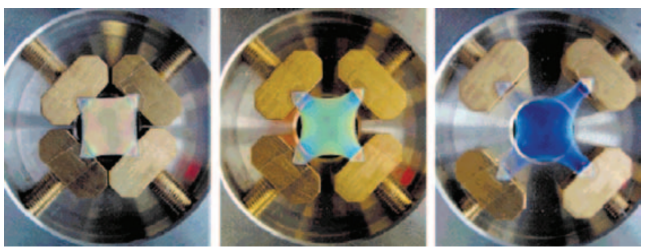

Figure 6. Cholesteric rubber, which changes the wavelength of selective reflection because of mechanical strain. Doping this material with a suitable laser dye leads to DFB lasing at the band edge. Thus, the wavelength of the narrow peak of stimulated emission can be mechanically tuned [27].

Not surprisingly, the three-dimensional structure of cholesteric blue phases (BP) appears in new splendour owing to the search for photonic crystal materials [31]. BP2 was successfully used to demonstrate the effect of DFB lasing [32]. Obviously, the very small dielectric contrast and the absence of a full photonic band gap are not obstacles to DFB lasing. However, as early as 1994, Hornreich and Shtrikman [33] recognized the importance of structures similar to blue phases for photonic band gap materials. They calculated the band structure for structures with the space group $O^8$, the same space group that describes the cubic blue phase BP1. If the double twist cylinders are replaced or decorated by either dielectric or conducting rods, the $O^8$ structure can show a photonic band gap (figure 7).

### 4. Holographic polymer-dispersed liquid crystals

A novel interesting approach towards photonic crystals is the holographic formation of polymer-dispersed liquid crystals (PDLC) [34, 35]. Photo-curable monomers, such as acrylates, are mixed with a liquid crystal and exposed to a holographic interference pattern of the radiation, which initiates the polymerization and cross-linking of the monomer. While the interference of two plane waves leads to a simple grating structure, three beams can be used to obtain a two-dimensional structure, and the interference of four or more non-coplanar beams results in three-dimensional structures. Depending on their direction and amplitude, all 14 Bravais lattices can be obtained [36]. So far, electric field induced switching of the diffraction efficiency on an orthorhombic *P* crystal made of a PDLC has been demonstrated [34]. However, systems with higher dielectric contrast are necessary in order to get a true photonic crystal.

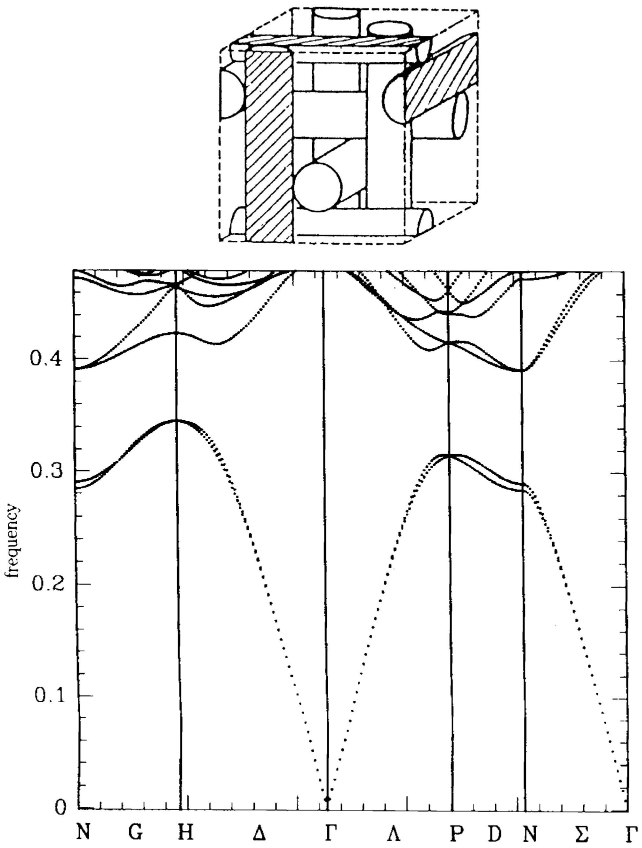


Figure 7. Top: arrangement of the double twist cylinders in the $O^8$ structure of BP1. Bottom: dispersion relation for a cubic $O^8$ structure composed of cylinders with a high dielectric constant in a matrix with low dielectric constant [33].

### Summary

In conclusion, photonic band gap nano-structures incorporating liquid crystals show a variety of interesting phenomena. Both the influence of electric fields on the effective refractive index and the spontaneous formation of spatially periodic structures are likely to make liquid crystals key materials in this topical field of research. However, many questions are yet to be answered. How to enhance the dielectric contrast? How to obtain well-defined anchoring in sub-micron-sized cavities and how to analyse the precise director field within these cavities? Can effective switching by external electric or magnetic fields be obtained in spite of the small cavity sizes? These are just some of the problems to be solved. A challenging new field of liquid crystal research has emerged.

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