Photonic crystals: a unique partnership between light and matter

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Abstract
Photonic crystals are periodic dielectric structures with an index of refraction periodicity of the order of the wavelength of light. They are emerging as a key building block for many applications in nanotechnology that involve controlling the flow of light. In this paper, the basic physical principles and applications of photonic crystals are presented, as well as descriptions of some of the many chemical and physical strategies that have been used for their fabrication.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Semiconducting materials utilizing electrons as information carriers are the cornerstone of a revolution which continues to this day in solid-state electronics. Integrated circuit performance has been increasing exponentially at a rate of more than two orders of magnitude per decade as transistor gate widths have decreased [1]. This is in accordance with Moore’s law which states that the number of transistors that can be inexpensively placed on an integrated circuit is doubling approximately every 2 years [2]. At the same time, however, a bottleneck is arising between the switching speed of a transistor and the propagation delay between such components. Even the speed provided by using copper interconnects with a low dielectric cladding is not expected to match the rate of device shrinkage without introducing higher costs and manufacturing complexity. Although large bandwidth optical fibres using photons as information carriers can operate over large distances, the photonic signals presently require electronic processing at each circuit node. Therefore, ultimately, direct optical interconnects will be needed to be made from materials that can localize and guide light. This effect can be provided by photonic crystals (PC), also known as photonic band gap materials (PBG).

A PC is defined as a periodic dielectric structure with an index of refraction periodicity of the order of the wavelength of light being localized. These structures were first described by Yablonovitch [3] and John [4] in 1987. Since then the number of publications related to PCs has been explosive. Schematic pictures of one-, two- and three-dimensional (1D, 2D and
3D) PCs are presented in figure 1 where the high- and low-index materials are shown in red and yellow, respectively.

The most fascinating characteristic of materials on the nanoscale is that their electronic properties are size dependent. For example, iconic images can be readily found of quantum dots (QDs) in solution that exhibit a spectacular range of emission wavelengths due to quantum confinement effects obtained by changing their radii [5]. In simplistic terms, this effect is akin to the well-known particle-in-a-box model from elementary quantum mechanics. As explained below, PC properties are not based on absorption or emission transitions. Instead they are determined entirely by the index of refraction periodicity which can be scaled from submicron dimensions (to control UV/VUV light) to the centimetre scale (to control microwaves). Since the wavelengths being controlled are typically of the order of hundreds of nanometers or longer (visible to infrared) PCs need not be scaled down to the tens of nanometer range. Regardless, PCs are beginning to have a profound effect on the development of nanoscale devices because they can significantly enhance the interactions between light and matter. As just one example, ultra small lasers have been made by incorporating fluorescent QDs into a PC structure [6, 7].

In this paper, students are provided with the basic physical principles and applications of photonic crystals as well as the descriptions of some of the many chemical and physical strategies that have been used for their fabrication. References to relevant primary literature are also provided as a starting point for a more detailed exploration of this burgeoning field.

2. One-dimensional structures

Pedagogically, a 1D well structure where the optical wavelength of each segment corresponding to one optical quarter wavelength thick, $\lambda/4$, serves as a useful pedagogical starting point for understanding how a PC operates (figure 2) [9]. These types of structures were actually first discussed by Lord Rayleigh as early as 1887 [10].

The dielectric constant $\varepsilon(x)$ can be written as

$$\varepsilon(x) = \varepsilon_0 + \varepsilon(x)$$ (1)

where $\varepsilon_0$ is the average dielectric constant and $\varepsilon(x)$ represents the spatial variation of $\varepsilon(x)$. The index of refraction, $n$, in the absence of absorption, is related to the dielectric constant through the relation $n = \sqrt{\varepsilon}$. The total dielectric constant is assumed to be real and positive everywhere in space. Assume that the lattice periodicity has the dimension ‘$a$’, and that the low-index and high-index segment thicknesses are $L_{\text{low}}$ and $L_{\text{high}}$, respectively. Thus, the periodicity $a = L_{\text{low}} + L_{\text{high}}$. The optical thickness of each segment is given by the product of the geometrical distance involved and the index of refraction.
Two synergistic optical scattering phenomena can occur within such a periodic arrangement. The first is Bragg scattering which will occur when the overall geometric periodicity of the repeating structure is an integer multiple of half the optical wavelength, that is, when \( \frac{m}{2} \lambda = a \), where \( m \) is an integer, \( \pm 1, \pm 2, \pm 3, \ldots \). The second is reflection within each unit cell which will be a maximum when the segment optical thicknesses equal one quarter optical wavelength, that is, when \( n_{high}L_{high} = \frac{\lambda}{4} = n_{low}L_{low} \). A ‘stop band’ or ‘band gap’ will open when the dimensions of the periodicity and the segments are chosen so that both scattering conditions occur at the same wavelength. Constructive interference of the multiple reflected rays will then maximize the overall reflection of the material. Generally, the periodic arrangement of different dielectric materials opens a gap in one dimension. The width of the stop band or band gap is an increasing function of the index of refraction (or dielectric constant) ratio of the high and low-index materials. It can be shown that at normal incidence the edges of the stop gap centred at frequency \( \omega_0 \) occur at \( \omega_0 \pm \Delta \omega \) where

\[
\frac{\Delta \omega}{\omega_0} = \frac{2}{\pi} \arcsin \left( \frac{n_{high} - n_{low}}{n_{high} + n_{low}} \right)
\]

and are independent of light polarization [11]. At other angles the reflectivity becomes polarization dependent.

The effects described above also arise in other well-established techniques which involve Bragg scattering such as x-ray diffraction. One may then be tempted to ask why the concept of photonic crystals has achieved such prominence in recent years. Indeed, is the moniker ‘photonic crystal’ simply a new name for an old phenomenon? This question was recently addressed by Yablonovitch who suggested that the name photonic crystals should apply only to 2D and 3D periodic structures with a large dielectric contrast [12] (>2) which is defined as the ratio of the dielectric constants of the high and low \( \varepsilon \)-regions, that is, \( \varepsilon_{high}/\varepsilon_{low} \). That said, many publications appear yearly on the subject of 1D PCs.

Some of the approaches used to calculate band structures include the plane wave expansion method (PWEM) [13], the transfer matrix method (TMM) [14, 15] and the finite difference time domain method (FDTD) [16]. In this work, the MIT photonic bands (MPB) software based on the PWEM was used to simulate several examples of PCs [17]. MPB is a free software package developed for Unix systems by S. G. Johnson and the Joannopoulos Ab Initio Physics group at MIT, which can be downloaded at http://ab-initio.mit.edu/wiki/index.php/MIT_Photonic_Bands. This link provides access to a manual which includes a user tutorial as well as a data analysis tutorial.

A typical plot of normalized photon frequency (\( = \frac{m}{2} \lambda \)) versus wave vector (photonic band structure) for a high index contrast 1D dielectric stack is shown in figure 3 for a range of wave vector \( \mathbf{k} \)-values (\( \mathbf{k} = \frac{2\pi}{\lambda} \)) between \( -\pi/a \) and \( \pi/a \).
3. Natural photonic crystals

Although PC architectures appear to be artificial, they are actually found in naturally occurring opal gemstones, and in many living organisms [18–20]. Species that exhibit iridescent colours due to interference effects include the peacock, comb-jellyfish, the sea mouse, the rainforest beetle and the blue Morpho butterfly. Although widely cited as an example of a natural photonic crystal, the Morpho butterfly is perhaps not actually prototypical because its coloration is thought to involve both interference and diffraction effects, and dye pigmentation [20]. Biologically, it is believed that species have evolved colour through Bragg reflections as a means of thermal regulation and signalling [21].

Naturally occurring periodic structures have almost exclusively 2D and 3D geometries, but are not, by the Yablonovitch criteria, genuine PCs because their dielectric contrasts are not particularly large. Their activity however can be explained by the extremely large number of periods found in these structures. This allows them to behave as essentially infinite PCs which lead to perfect band gaps. The current goal experimentally is to fabricate in the lab what Nature has been doing for millions of years.

3.1. Theoretical underpinning of PC operation

A deeper understanding of photonic crystals in general can be obtained by using Maxwell equations to derive the following equation for the magnetic component $\vec{H}(\vec{r})$ in a periodic dielectric medium with dielectric constant $\varepsilon(\vec{r})$ [8]:

$$\left(\vec{\nabla} \times \frac{1}{\varepsilon(\vec{r})} \vec{\nabla} \times \right) \vec{H}(\vec{r}) = \left(\frac{\omega^2}{c^2}\right) \vec{H}(\vec{r})$$

(3)

Here, $\omega$ and $c$ are the angular frequency of the light beam and the speed of light, respectively. Furthermore, the linear operator $\left(\vec{\nabla} \times \frac{1}{\varepsilon(\vec{r})} \vec{\nabla} \times \right)$ is Hermitian when $\varepsilon(\vec{r})$ is real.
Table 1. Analogies between specific quantities in quantum mechanics and electrodynamics.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Electrodynamics</th>
<th>Quantum mechanics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eigenfunction</td>
<td>$\vec{H}(\vec{r}, t) = \vec{H}(\vec{r}) e^{i\omega t}$</td>
<td>$\psi(\vec{r}, t) = \psi(\vec{r}) e^{i\omega t}$</td>
</tr>
<tr>
<td>Hermitian operator</td>
<td>$(\vec{\nabla} \times \frac{1}{\epsilon(\vec{r})} \vec{\nabla} \times -\frac{\bar{\hbar}}{2m} \nabla^2 + V(\vec{r})$</td>
<td>$E = \frac{\bar{\hbar}^2}{2m}$</td>
</tr>
<tr>
<td>Eigenvalue</td>
<td>$E = \frac{\bar{\hbar}^2}{2m}$</td>
<td>$E = \hbar \omega$</td>
</tr>
</tbody>
</table>

(i.e. the material is nonabsorbing), which means that the eigenfunctions form a complete set, and their associated eigenvalues are real.

The electric field $\vec{E}(\vec{r})$ can then be found from $\vec{H}(\vec{r})$ using

$$\vec{E}(\vec{r}) = \left( -\frac{i\bar{\hbar}}{\omega \epsilon(\vec{r})} \right) \vec{\nabla} \times \vec{H}(\vec{r}).$$

(4)

As written equation (3) is an eigenvalue problem where $\vec{H}(\vec{r})$ is an eigenfunction with eigenvalue $\frac{\bar{\hbar}^2}{2m}$. Although an equation similar to equation (3) can be derived for the electric displacement $\vec{D}(\vec{r}) = \epsilon(\vec{r}) \vec{E}(\vec{r})$, it can be shown that the operator involved is not Hermitian.

A useful analogy is often drawn between equation (3) and the quantum mechanical time-independent Schrödinger wave equation, $\hat{H} \psi(\vec{r}) = E \psi(\vec{r})$, where $\hat{H}$ is a Hermitian Hamiltonian operator, $\psi(\vec{r})$ is the quantum mechanical wave or eigenfunction and $E$ is the energy eigenvalue. The Hamiltonian is given by $\hat{H} = -\frac{\bar{\hbar}^2}{2m} \nabla^2 + V(\vec{r})$ where the first term is the kinetic energy operator and second is the potential energy. This comparison is shown more closely in table 1 [8].

While the similarities are striking, there are nevertheless a number of critical differences between quantum mechanics and electrodynamics. The first is that a quantum mechanical $\psi(\vec{r})$ is a scalar function, while the $\vec{E}$- and $\vec{H}$-fields are vectors. This leads to additional restrictions on the geometry of the microstructure and the dielectric constant which can produce a photonic band gap. The second is that in those specific cases when the quantum mechanical potential $V(\vec{r})$ is separable, which for example, in Cartesian coordinates means $V(\vec{r}) = V_x(x)V_y(y)V_z(z)$, the Schrödinger equation can be separated into three simpler equations, one for each direction. The electrodynamical curl operator in table 1, however, couples the solutions for different directions even when $\epsilon(\vec{r})$ is separable. Third, the electromagnetic results are in principle scalable from the nanometer to macroscopic dimensions while quantum mechanics is only valid for ‘small’ sizes (nanometer and smaller). Lastly, in quantum mechanical systems the lowest energy eigenstates have their maximum amplitudes in regions of low potential energy. Conversely, the lowest energy electromagnetic modes are concentrated in regions of high dielectric constant, while high frequency modes tend to concentrate their energy in regions of lower dielectric constant.

3.2. Semiconductor crystals analogies

The presence of a photonic band gap in a PC is also often described as the optical analogue of the electronic band gap associated with a semiconductor crystal. The periodic potential of the semiconducting crystal introduces gaps into the energy band structure along certain directions where electron waves are forbidden to propagate because of Bragg reflection. This is shown qualitatively in a plot of the electron energy versus electron wave vector $k$ (figure 4). Note that the momentum of an electron is given by $\hbar k$ while its energy $= \hbar \omega$. In a 1D semiconductor the first Bragg reflection takes place in $k$- (reciprocal) space at $k = \pm \frac{\pi}{a}$, where $a$ is the periodicity.
of the lattice. The region in $k$-space between $-\pi/a$ and $+\pi/a$ is called the first Brillouin zone of the lattice, and stop gaps will occur at any positive or negative integer multiple of $\pi/a$. By symmetry, the curve for negative values of $\vec{k}$ is simply the mirror image of this plot through a plane containing the $E$-axis at $k = 0$.

These symmetry properties show that the dispersion plot for the 1D PC in figure 3 shows band gap effect similar to that in figure 4. In a semiconductor, Bragg reflections at the periodic potentials produce standing waves of the electron wave function at the periodicity of the positively charged ion cores. Two standing waves are produced: one with its peak wave function amplitude occurring at the periodic potential maximum and one with its peak at the minimum [22]. This corresponds to two distinct energy levels with no available states in between, that is, a band gap. The energy state below the band gap is called the valence band, while the upper level is the conduction band.

Similarly, the energy levels below and above a photonic band gap correspond to electromagnetic standing waves with their energy maxima located in either the high or low dielectric regions. The regions of low dielectric constant is often filled with air which has $\varepsilon = 1$. Thus, it is common to label the region of lower dielectric constant the air band, even if the material involved is not air. The dielectric and air bands are the photonic analogues of the valence and conduction bands, respectively (figure 5). When the dielectric contrast in a PC is large, both standing waves actually have their energy primarily in the high $\varepsilon$-layers, but with more energy concentrated in the bottom band. Gaps form due to this difference in field energy location.

Near the band edges, the slope of figures 3 and 4, $\frac{d\omega}{dk}$, and hence, the group velocity $v_g = \frac{d\omega}{dk}$, defined as the velocity at which the envelope of light propagates within the material, approaches zero; that is, ‘slow photons’ are generated. The group velocity $v_g$ is distinct from the phase velocity of a wave with frequency $\omega$, $v_p = \frac{\omega}{k}$, although the two are related: $v_g = v_p \left(1 - \frac{k}{n} \frac{dn}{d\omega}\right)$. Physically, at the band edges these photons are undergoing multiple reflections and therefore only propagate slowly through the photonic structure with a mean velocity, $v_g$. The analogue phenomenon at the band edge of a semiconductor corresponds to the case where the de Broglie electron wave is nearly standing (equal probability of moving in either direction) [23].

An equivalent explanation for slow photons is that they arise from a dramatic alteration of the local photon density of states (DOS) within the periodic material. The photon DOS
corresponds to the number of photon states per frequency interval. A vanishing DOS within the photonic band gap leads to strong localization of photons and suppressed spontaneous emission. It can be shown that the group velocity, $v_g$, is inversely proportional to the large local photon DOS found at the band edges [24].

The curvature of the band structure in figure 4, $\frac{d^2k}{d\omega^2}$, in a semiconductor is inversely related to the effective mass of the electron. In a PC, this curvature is related to the change in group velocity as a function of the frequency of light. Essentially, the index of refraction of a PC exhibits anomalous dispersion near the band gap but one which is not associated with absorption. This dispersion determines how a pulse of polychromatic light will broaden without absorption loss because different frequency components travel with different group velocities within the periodic structure. New effects have been predicted and observed experimentally that depend on this property such as the superprism phenomenon where different wavelengths can be separated over a much wider angle, and ultra-refraction, where small changes in incident angles result in extraordinarily large angles of refraction (two orders of magnitude larger than a conventional prism), including negative bending [25].

These effects can lead to a large increase in the optical path length and an enhanced interaction between light and matter [26], and as such, can be readily exploited in many applications, including those that require nonlinear optical effects [27, 28]. For example, lasing can occur at a photonic band edge without the need of a standard laser cavity [6].

4. Two-dimensional photonic crystals

2D PCs are periodic in two directions and homogenous in the third. By symmetry, an electromagnetic wave propagating, for example, in the $xy$-plane of a 2D PC can be classified as transverse electric (TE) or transverse magnetic (TM) depending on their reflection symmetry through the $xy$-plane. TE modes have their $\vec{H}$-vector perpendicular to the plane in the $z$-direction and their $\vec{E}$-vector in the $xy$-plane. Conversely, TM modes have their $\vec{E}$-vector perpendicular to the plane, and their $\vec{H}$-vector in the $xy$-plane. 2D PCs are more complicated than 1D structures because their photonic responses are different for these two different polarizations. They can reflect light however from any direction in the plane unlike 1D PCs which only reflect light at normal incidence.

Highly symmetrical 2D PC geometries are usually either square or hexagonal [19]. It is common to label the direction of light propagation in a photonic band structure diagram
Table 2. Symbols and wave vector directions for square and hexagonal lattices.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Reciprocal space</th>
<th>Symbol</th>
<th>Reciprocal space</th>
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<tr>
<td>$\Gamma$</td>
<td>$\vec{k} = 0$</td>
<td>$\Gamma$</td>
<td>$\vec{k} = 0$</td>
</tr>
<tr>
<td>$X$</td>
<td>$\vec{k} = \frac{\pi}{a} \hat{x}$</td>
<td>$M$</td>
<td>$\vec{k} = \frac{2\pi}{3a} \hat{y}$</td>
</tr>
<tr>
<td>$M$</td>
<td>$\vec{k} = \frac{\pi}{a} \hat{x} + \frac{\pi}{\sqrt{3}} \hat{y}$</td>
<td>$K$</td>
<td>$\vec{k} = \frac{2\pi}{3a} \hat{x} + \frac{2\pi}{\sqrt{3}a} \hat{y}$</td>
</tr>
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</table>

According to the following standard reciprocal space notation which is listed in table 2 for the irreducible Brillouin zones of square and hexagonal lattices having periodicity, $a$, respectively. All other points in reciprocal space are related to these positions by rotational symmetry in the plane. Although the relationship between a square lattice and its Brillouin zone is straightforward, it is less so for a hexagonal lattice and its reciprocal primitive cell. Therefore this is shown diagrammatically in figure 6.

Analysis shows that for square column array of high-index dielectric islands a photonic band gap will open between the first (dielectric) band and the second (air) band for the TM modes but not for the TE modes (figure 7). Physically, this happens because the lowest TM mode is localized in the high dielectric regions while most of the electromagnetic power of the air band is found in the low-$\varepsilon$ regions. This result can be related to the fill factor which is a measure of the electric field intensity in the high dielectric region and is defined as

$$f = \frac{\int_{V_h} \varepsilon(r) \cdot |E^2(r)| \, d^3r}{\int_{V_t} \varepsilon(r) \cdot |E^2(r)| \, d^3r}$$

(5)

where $E$ is the macroscopic electric field, $\varepsilon(r)$ is the dielectric function of the structure, $V_h$ is the volume of high refractive index region and $V_t$ is the total volume of the photonic crystal. This parameter is relatively large for TM modes but not for TE modes in a square column array lattice. On the other hand, if the square lattice is a grid of dielectric veins versus isolated air islands, the fill factors are reversed and it is the TE modes which exhibit a band gap. These
observations can be taken as a general rule of thumb [8]: TM band gaps are favoured for isolated high 2D $\varepsilon$-regions while TE band gaps are favoured for connected lattices.

A ‘compromise’ lattice of a high dielectric material can be created that is nearly isolated yet also connected (figure 8(a)) [29]. Specifically, a hexagonal lattice of air holes placed inside the high-index material creates an array of triangular high $\varepsilon$-spots connected by narrow veins. Figure 8(b) shows the resultant photonic band diagram calculated for a structure with a dielectric contrast $\approx 6.7$. A photonic band gap and hence complete reflection is found for both the TE and TM modes. Conversely, a hexagonal array of isolated high-index columns exhibits a band gap for the TM modes only, in line with the rule of thumb mentioned above.

The size of the photonic band gap can be characterized by the gap–midgap ratio which is defined as $\frac{\Delta \omega}{\omega_0}$, where $\Delta \omega$ is the gap frequency width and $\omega_0$ is the frequency at the middle of the gap. This parameter which is typically of the order of 0.2 is more meaningful than $\Delta \omega$ alone as a measure of the size of the band gap since it is invariant to size scaling.

The size of band gap is affected by many parameters including the structural symmetry of the crystal, the dielectric constant ratio, the air-filling ratio and so on. Although it is difficult to provide a quantitative formula to describe the relationships between these parameters, the size of the gap can be calculated provided the structure is symmetrical. For example, it can be shown that the photonic band gap disappears for the structure shown in figure 8(a) when the dielectric constant ratio $= 4$. While the band gap can be increased to $\approx 5.2\%$ when the
Figure 8. (a) A 2D triangular photonic crystal with a complete band gap for both TE and TM modes. The structure is a column array of air holes ($\varepsilon_{\text{low}} = 1$) in a dielectric substrate ($\varepsilon_{\text{high}} = 6.7$), with $r/a = 0.45$. A dielectric triangular spot and vein are indicated. (b) Photonic band diagram for the structure shown in (a). The open circles correspond to TM modes while the closed circles to TE modes. The grey box shows the photonic band gap.

dielectric constant ratio reaches 12:1 (Si/air), its value will = 0 when the ratio $r/a = 0.2$ even when the dielectric constant ratio = 12.

Recently, work has been done on creating unsymmetrical arrays because they can be used to introduce novel optical properties. For example, Zheludev and co-workers recently fabricated a quasi-crystal array of nanoholes (figure 9) [30, 31] in a metal screen that can mimic the function of a lens. Planar chiral photonic meta-materials (figure 10) are also receiving attention because of their ability to manipulate the polarization state of light in the near- and far-fields [32].

One advantage of 2D PCs is that they can be fabricated using relatively standard ‘top-down’ methods [33]. One common approach is to use electron-beam (e-beam) lithography to write structures with defined dimensions into a photoresist (mask) which is subsequently placed on the surface of a high index of refraction substrate such as silicon or gallium arsenide. This step is followed by reactive ion etching (RIE) [34] which removes the unmasked regions of the substrate resulting in a periodic structure of air voids. While e-beam lithography and RIE together provide excellent spatial resolution, high volume production on a large area substrate is limited by the mask dimensions that can be written using e-beam lithography, and its high expense.

A second approach capitalizes on the idea that since band gaps at a particular wavelength require periodicities with a length scale comparable to the wavelength of light itself, that light itself should be an ideal tool for generating submicron structures in a photosensitive material (photoresist). This approach, called ‘holographic lithography’ or ‘interference lithography’,
Figure 9. (a) Regular and (b) quasi-crystal arrays of holes. (c) and (d) are $20 \times 20 \, \mu\text{m}^2$ fragments of their diffraction patterns, respectively. (e) and (f) are the intensity scans across the pattern centres [30].

Figure 10. SEM images of (a) right-handed and (b) left-handed chiral 2D planar arrays [32].

uses either a diffraction element or several laser beams directly as a substitute for e-beam lithography [35]. The resultant periodic structures can serve as templates in subsequent steps to obtain high index contrast PCs.
5. Three-dimensional photonic crystals

The first experimental realization of a 3D PC was achieved by Yablonovitch et al who fabricated a face centred cubic (fcc or opal-like) crystal in a low-loss dielectric medium, with a band gap operating in the microwave, by mechanically drilling tens of thousands of holes with radii slightly larger than close packing so that the voids joined up to form a connected network [36]. That system is known as the three cylinder structure or simply Yablonovite in recognition of this achievement.

The drilling angles along the three equivalent (110) directions used to generate Yablonovite are shown in figure 11(a) [37]. Both Yablonovite and its inverse structures are found to possess a complete band gap in three dimensions. The micron-scale Yablonovite crystal shown in figure 11(b) was made by chemically assisted ion beam etching through a triangular hole array mask, defined by e-beam lithography on GaAs. The inverse structure was fabricated using multiple-exposure x-ray lithography. See figure 1 of [38].

One structure which is predicted to have a large complete band gap is a 3D diamond lattice of spheres [13]. Band gaps have been found for other structures including the simple cubic [39] and the rhombohedral A7 lattice [40] lattices. It was shown that the largest gap–midgap ratio (0.46) can be achieved for an inverse diamond lattice of overlapping air holes.
in a dielectric with a filling fraction $= 0.81$. Physically, this corresponds to 3D PC made essentially of air voids with an ultrathin dielectric skeleton framework. Coupled with the fact that visible reflections require submicron periodicities, it is hardly surprising that fabrication of this lattice for operation at these high frequencies continues to be extremely challenging.

One ‘bottom-up’ synthetic approach is the use of colloidal suspensions of SiO$_2$ spheres in a viscous fluid that spontaneously form bulk 3D opal-like crystals with submicron periodicities. However, the dielectric constant ratio using this material is too low to yield a full band gap. The index contrast however was increased in one study, for example, by first sintering the opal structure to connect the SiO$_2$ spheres where they touch, and then infiltrating the pore structure with silicon which wets the surfaces of the glass spheres. An inverse opal structure with a complete band gap spanning $\sim 5\text{–}9\%$ of the centre frequency at the telecommunication wavelength of $\sim 1.5\,\mu\text{m}$ was formed after the glass spheres were removed by chemical etching [41]. Despite this achievement the process is quite involved and time consuming, and the photonic band gap is sensitive to structural disorder effects.

New structures possessing full 3D photonic band gaps have been proposed which are easier to fabricate by conventional microfabrication techniques. Examples include the so-called ‘woodpile structure’ [42, 43] which can be made by micromachining [44], a square-spiral geometry PC [45, 46] which can be fabricated using glancing angle deposition (GLAD) [47], and a tetragonal lattice of slanted pores [48] which can be generated by direct laser writing [49].

6. Defects and applications

Some of the most interesting applications of PCs arise when defects that locally break the spatial periodicity are introduced in a controlled manner. Defects introduce states that lie in the photonic band gap which allows light to propagate but only in those regions defined by the defect structure. While space precludes a comprehensive discussion, a few examples are described here which best illustrate the potential PCs holds in photonics applications.

Many applications involving 2D photonic crystals take advantage of their excellent wave guiding properties. A specific light path can be formed by introducing a line defect into the photonic structure. As shown in figures 12(a) and (b), wave guides with 90$^\circ$ bends [50] or beam splitters [51] can be made which can provide compact interconnect between photonic elements. Their main limitations however include high coupling losses and poor confinement in the third dimension.

PC fibres can have hollow air cores or be made of a dielectric material such as silica. The light channel is clad by a regular matrix of air holes lying parallel to the fibre axis which acts as a 2D PC [52]. When the guided wavelength falls into the photonic band gap, the light is constrained to propagate along the core. Optical losses can be very low because beam propagation is not based on total internal reflection. In addition to the obvious telecommunications applications, PC fibres are expected to be particularly effective for gas-phase nonlinear optical effects such as stimulated Raman scattering which requires high intensity, low power input beams with excellent transverse mode quality and long interaction lengths [53].

A point defect introduced into an otherwise perfect 2D photonic crystal can serve as a high quality ($Q$)-factor cavity for ultra-low threshold laser action because it would trap a narrow range of wavelengths with low loss while exhibiting extraordinarily high local field due to the band gap effect [23, 54]. When an optically active medium is placed inside a microwcavity, its spontaneous emission can be dramatically changed because the spontaneous emission rate depends on the optical mode density at the emission wavelength [55]. For example, media in
cavities having a fundamental mode frequency which is resonant with its emission frequency will exhibit an enhanced emission rate. This is the so-called Purcell effect [56]. Conversely a cavity can be designed to suppress spontaneous emission. Similarly, media can experience an enhanced or reduced absorption depending on whether or not the medium’s absorption frequency is resonant with a mode of the cavity. Multiplexers and demultiplexers based on these principles have been made to add or drop different energy photons to or from optical communication traffic [57].

While some success has been achieved in engineering defect structures within 3D PCs, fabrication remains challenging, expensive and time-consuming [59–61].

7. Conclusions and future developments

The goal of this paper was to provide an introduction into the fascinating physics of photonic crystals and to illustrate some of the exciting applications that have already been realized. Two future directions based around materials consideration merit a mention. The first is that the drive for true all-optical signal processing will rely on nonlinear optics as a means of influencing light by light. As noted above, the slow photons associated with propagation near the band edge of a PC increase the interaction time with the material thereby enhancing possible nonlinear effects [28].

Second, as promising as Si is as a medium for PC fabrication, the infrastructure required for this purpose is very expensive. Chalcogenide glasses are emerging as a promising replacement material because they are transparent in the infrared, have an index of refraction between 2.4 and 2.7, a large third order nonlinearity (100–1000× that of Si), a low two-photon absorption and can be processed by conventional lithographic techniques [62].

Acknowledgments

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