Photonic band gap materials: Technology, applications and challenges

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Photonic band gap (PBG) materials are periodic dielectric structures that forbid propagation of electromagnetic waves in a certain frequency range. They are able to engineer the most fundamental properties of electromagnetic waves, such as the laws of refraction, diffraction and emission of light from atoms. Such PBG materials not only open up a variety of possible applications, but also give rise to new physics. Unlike electronic micro-cavity, optical waveguides in a PBG microchip can simultaneously conduct hundreds of wavelength channels of information in a three-dimensional circuit path. In this article we discuss some aspects of PBG materials and their unusual properties, which provide a foundation for novel practical applications ranging from clinical medicine to information technology.

Keywords: Negative refraction, photonic band gap, photonic crystal, PBG fibre.

THE last century has been the age of artificial materials. One material that stands out in this regard is the semiconductor. Revolution in the electronics industry in the 20th century was made possible by the ability of semiconductors to microscopically manipulate the flow of electrons. Further advancement in the field prompted scientists to suggest that the new millennium will be the age of photonics in which artificial materials will be synthesized to microscopically manipulate the flow of light. One of these will be photonic band gap (PBG) materials having periodic dielectric structure. The study of distributed feedback lasers has been reported[1] on the basis of the fact that propagation of electromagnetic waves as well as that of light is forbidden for a small range of wave vectors and the index contrast is typically of the order of n_a/n_b = 0.01. However, the contrast is too low for fabrication of photonic crystals[2], which are new materials where photons are used instead of electrons as the information carrier. Some hybrid optoelectronic circuits have produced significant improvements over the performance of electronic circuits. However, there is a need for multipurpose photonic integrated circuits analogous to electronic integrated circuits to work at micrometre wavelength scale (1–10 μm), because light has many advantages over electricity; for instance, it can travel in dielectric materials at much greater speeds and carry larger amounts of information per second. The bandwidth of dielectric materials (of the order of one terahertz for fibre optics communication) provides space for larger amount of information as compared to a few hundred kHz for present telephone.

The photonic phenomenon has relied, in general, on the mechanism of total internal reflection. Light propagating in materials of high refractive index is reflected at the interface in materials of low refractive index, and requires an optically smoother interface with respect to wavelength. This requirement limits the degree of miniaturization of optical components, which necessitates a different mechanism from total internal reflection to fabrication of photonic crystals. The underlying concept is based on the existence of the PBG. In a nutshell, the idea is to design materials which can affect the properties of photons similar to the way ordinary semiconductor crystals affect the properties of electrons, and to discuss their physics and novel practical applications ranging from clinical medicine to information technology (IT).

Overview of the PBG technology

The earliest ideas to control radiative properties of materials by introducing a random refractive index variation, were theoretically proposed by Yablonovitch[2] and John[3] almost simultaneously in 1987. Yablonovitch suggested that photonic crystals could change the properties of the radiation field in such a way that there would be no electromagnetic modes available in the dielectric structure. It has been predicted[4] and experimentally verified[5,6] that the removal of dielectric materials in a PBG structure will generate a single mode in the gap, while addition of extra

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materials will give rise to several modes. Chan *et al.*[7] have given the smallest 3D complete photonic band gap (CPBG) and Yablonovitch *et al.*[8] have fabricated photonic crystals (PX) (Figure 1) for the microwave region; other designs are also available for CPBG[9–12]. Ozbay *et al.*[13] have used a technique of stacking thin micromachined (100) silicon wafers to fabricate PX for a wavelength of about 600 μm. The ultimate goal is the fabrication of PX for telecommunication purposes (1.5 μm). Cheng and Scherer[14] used electron beam lithography to drill (100) air channel type of 1.0 μm size. Fan *et al.*[15] have fabricated PX of submicrometre wavelength scale. Using a dielectric constant of 12.096 for Si at 1.5 μm and 2.084 for silica at the same wavelength gives an optimized CPBG[15] of about 14.0%, which could be improved to 23%.

A new and exciting approach to the design and fabrication of submicron 3D PX involves the creation of a periodic lattice of isolated metallic regions within a dielectric host[16]. The 3D metallic–dielectric PX have been studied theoretically[17–20] and have been shown[20] to have enormous omni directional PBG approaching 80%. An important application of the suppression of the spontaneous emission has been suggested[21–25]. It has also been suggested that an individual atom would be capable of binding a local mode similar to that generated by a defect in a PBG crystal[26–28]. The disordered dielectric microstructure could probably be fabricated more easily than the ordered structure and experimental verification has been done elsewhere[29]. Disordered dielectric structures have also been used to observe a reduction in the rate spontaneous emission at optical frequencies[30,31]. Johri and co-workers[32–37] have studied the 3D PX structure. Various groups too have proposed photonic crystals. Apart from the artificially engineered PBG materials, there are also naturally occurring PBG materials such as butterfly and opal. Theoretical methods are basically categorized as plane wave expansion method, transfer matrix method and finite difference time domain technique, while experimental methods are etching technique, layer-by-layer fabrication, woodpile structure and colloids.

Physics of PBG materials

Consider a monochromatic electromagnetic wave of frequency ω propagating through a medium whose dielectric constant varies from point to point in space as:

$$\varepsilon(x) = \varepsilon_0 + \varepsilon_{\text{fluct}}(x), \tag{1}$$

where ε_0 is the average part of the dielectric constant, and $\varepsilon_{\text{fluct}}$ the part of the dielectric constant that varies from point to point in space.

Assuming that the microstructures of the materials do not absorb light and the total dielectric constant is everywhere real and positive, the wave equation for the optical field is given by[3]

$$-\nabla^2 \cdot \vec{E} + \nabla(\vec{\nabla} \cdot \vec{E}) - \frac{\omega^2}{c^2}\varepsilon_{\text{fluct}}(x)\vec{E} = \frac{\omega^2}{c^2}\varepsilon_0 \vec{E}. \tag{2}$$

Maxwell's wave equation (eq. (2)) is written in the form of Schrödinger equation. The kinetic energy and scattering potential energy are the first and second terms respectively, with their energy eigenvalue $(\omega^2/c^2)\varepsilon_0$. The equation shows the refinement of light localization. The overall positivity of the dielectric constant (eq. (1)) leads to the constraint that the energy eigenvalue is always greater than the highest of the potential barrier presented by $(\omega^2/c^2)\varepsilon_{\text{fluct}}(x)$. Occurrence of bound states of the electromagnetic wave field requires specialized material in this spectral range[38].

PBG structures (Figure 2) use the principle of interference to reflect radiation. Reflection from PBG structures has been demonstrated in one, two and three dimensions and various applications have been proposed[39–42].

In recent years, the interaction between electromagnetic radiation and structures with one dimensional periodic perturbation has resulted in the appearance of new devices in microwave electronics, photonics and optics[43]. These structures are used to form distributed feedback in free electron masers[44,45] and quantum cascade lasers[46] or to obtain narrow-band filters, mode transformers and pulse compression[47,48]. The topic is fundamental and widely applicable. At microwave frequencies these structures are known as 1D Bragg structures[44,45]; whereas in integrated

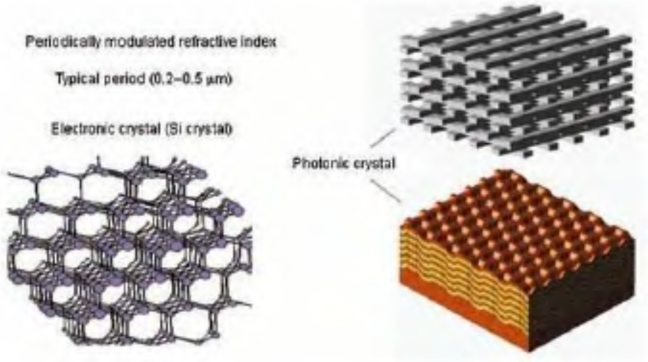

Figure 1. Photonic crystals.

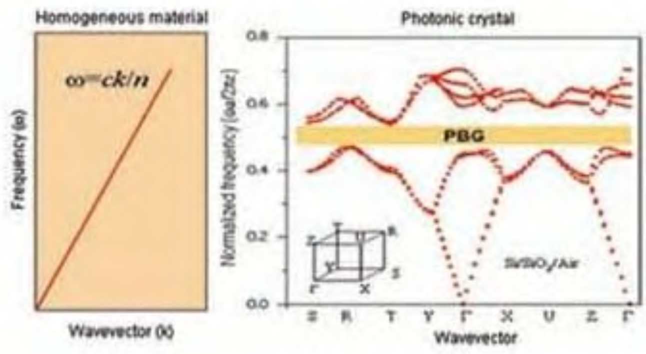

Figure 2. Illustration of PBG in a crystal.

optics and in Bose–Einstein condensate scattering they are called either 1D PBG structures or optical lattices[49].

The propagation speed of particles through tunnelling regions has been studied theoretically since the early days of quantum mechanics, and optical analogues of tunnelling have been explored in recent years because of their experimental accessibility. The physical meaning of group velocities greater than the vacuum speed of light *c* has been investigated in experimental work on the propagation of photons through layered dielectric materials with PBG at the frequency of light[50–52]. The measured delays of individual photons in these experiments were consistent with the group delay calculated as the derivative of the phase of the transmission amplitude with respect to angular frequency. The group delay can be negative, seemingly consistent with propagation at a speed greater than *c*. As has been pointed out earlier, these anomalous delays are the result of pulse reshaping and they do not imply a violation of Einstein causality[50–52].

It is hard to imagine a better way of transporting light than using an optical fibre. By surrounding a transparent fibre core with a second material that has a lower refractive index, light in the inner core is trapped by total internal reflection. In silica-based optical fibres, light can propagate in this way with low losses over global distances.

An alternative way of transmitting light was suggested in 1996 by Philip Russell and co-workers[53], who proposed trapping light in a fibre with a hollow core using a PBG. Such fibres may outperform normal optical fibres because light trapped in their hollow core travels through a tenuous gas, rather than a solid glass. Charlene Smith and co-workers[54] have reported a dramatic decrease in the observed optical losses in this new form of fibre.

PBG fibres (Figure 3)[55] are completely different from conventional fibres because they make use of the unusual properties of 2D periodic micro-structured materials. When the period of the lattice is comparable to the wave length of light, these photonic crystals can display a remarkable effect that does not occur in any natural material. The waves that are scattered from all the different interfaces can completely destroy any propagating modes within certain parameter ranges. Such band gaps are the photonic analogue of the electronic band gaps displayed by conventional crystals, but here they prevent photons – rather than electrons – from propagating.

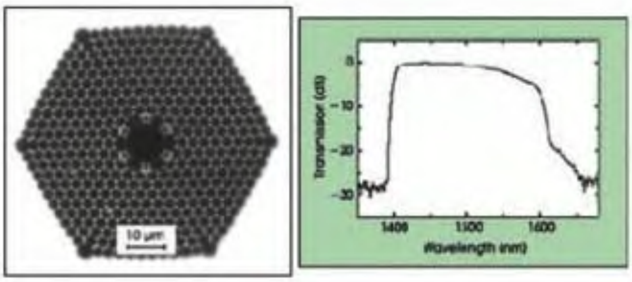

Figure 3. ***a***, PBG fibre. ***b***, PBG in the fibre's cladding guided light from ~1400 to ~1600 nm.

Applications

A growing array of imaging systems allows for the emergence of a set of less-invasive diagnostic procedures. Lasers are increasingly used in surgery that is more precise and less destructive than the scalpel. Unlike magnetic resonance imaging, which relies on very long wavelength radiations, or X-ray based tomography which depends on very short wavelength radiations, the optical matter utilizes intermediate wavelength windows. This window is sensitive to the concentration of oxygenated haemoglobin in the tissue and thereby provides an early diagnostic image of the metabolic process leading to cancer prior to structural damage caused by a tumour. Since these medical applications may yield health benefits, the need to promote the technology becomes more desirable. Some common applications include[56]:

(i) Zero-threshold microlasers with high modulation speed.
(ii) Low-threshold optical switches and all optical transistors for optical telecommunication.
(iii) High-speed optical computers.
(iv) Microlasers operating near a photonic band edge will exhibit ultra-fast modulation and switching speeds for application in high-speed data transfer and computing.
(v) Applications such as telecommunications, transfer and computing will be greatly enhanced through all optical processing in which bits of information, encoded in the form of a photon number distribution, can be transmitted and processed without conversion to and from electrical signals.
(vi) The PBG material provides dopant atom with a high degree of protection from damping effects of spontaneous emission and dipole de-phasing. In this case the two-level atoms may act as a two-level quantum mechanical register or single photon logic gate for all optical quantum computing.
(vii) Multiple scattering of light in biological tissue provides a safe, inexpensive and non-insidious probe of brain, breast and skin tumours.

The field of photonics covers the techniques and scientific knowledge which can be applied to the generation, propagation, control, amplification, detection, storage and processing of signals of the optical spectrum, as well as the technologies and derived uses. Photonics can be divided into several areas in which optical communication and photonic sensing technology are included. The constant pursuit of more efficient telecommunications has resulted in a major research push aimed at creating communication systems that are lighter, faster, more reliable and cheaper. This has resulted in advances in devices, subsystems and in particular, fibre optic technology, which in turn contribute to advances in fibre sensing technology[57].

Because electromagnetic waves in the frequency band from 100 GHz to 10 THz interact strongly with various molecules and gases, there is an interest in environmental and medical applications. Milimetre-wave photonic technology is the foundation for such measurements, and will probably also serve as a tool for elucidating phenomena that involve the interaction of radio waves and matter. The undeveloped frequency band, once harnessed, will lead to new technologies where, for example, antennas could be placed against the human body for medical sensing and as a kind of human interface.

Omnipresent IT services are just beginning to emerge, and may soon revolutionize IT. Based on groundbreaking presentations at the International Symposium on New Frontiers for Omnipresent IT Services, this far-reaching resource provides engineers with a detailed look at the technological developments that are blazing the way to a new information age. It describes a wide range of state-of-the-art engineering advances in photonics, sensing, electronics, micro-mechatronics, networks and communication schemes along with promising applications from biomedical sensors and intra-body networks to 'smart' buildings and long-haul communications[58].

As the demand for advanced materials increases, there is a growing interest in new approaches for fabrication of novel optical devices based on hybrid materials. Organo-functional silsesquioxanes are highly condensed molecular composites which show interesting physical and optical properties and can be modified by varying the organic functionality in the molecular building blocks. As a result, these hybrid materials have potential applications in optics, physics, chemistry, materials science and medicine[59].

Challenges and targets

Since all materials in the beginning have been highly anisotropic, stress must be on the quality and control of materials in all domains, particularly the measuring techniques, fabrication and manufacturability of the materials and future research should be focused on magnetic properties in the visible range to make circulators and other microwave-style components in photonics.

Photonic crystals architecture can be of help to increase solar energy conversion. The novel and unusual optical phenomenon of negative refraction observed in PX may lead to optical applications such as flat lenses with sub-wavelength focusing abilities. Utilization of PX can be scaled down or up across the entire electromagnetic spectrum, thus making them potentially available for a wide range of applications. PX structures (Figure 2) are anticipated to be an essential component of photonic integrated circuits in the near future.

Imaging devices, that will be safe, inexpensive and suitable for use in clinics and hospitals can be developed. Devices which are able to diagnose skin tumours without recourse to a biopsy can be developed as well as the ability to perform a blood test without having to draw blood from a patient.

Discussion and conclusion

The present study provides a technical overview of the rapidly emerging photonic IT. The article discusses the theory and principles of PBG materials and practical applications of PX devices. Emphasis is placed on key developing technologies that will enable the replacement of electrons by photons in the nano-sized information-processing devices. The technology has potential applications, especially in medicine. Fibre-optic strands can be made into far thinner and more supple catheters than has been previously feasible. Photonic materials have the potential to be a technological revolution of this century similar to the electronic revolution of the last century.

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