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PHOTONIC BAND GAP MATERIALS: TECHNOLOGY, APPLICATIONS AND CHALLENGES

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Abstract

Last century has been the age of Artificial Materials. One material that stands out in this regard is the semiconductor. The revolution in electronic 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 made scientists 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 material (PBG). PBG are periodic dielectric structures that forbid propagation of electromagnetic waves in a certain frequency range. They are able to engineer most fundamental properties of electromagnetic waves such as the laws of refraction, diffraction, and emission of light from atoms. Such PBG material not only opens up variety of possible applications (in lasers, antennas, millimeter wave devices, efficient solar cells photo-catalytic processes, integrated optical communication etc.) but also give rise to new physics (cavity electrodynamics, localization, disorder, photon-number-state squeezing). 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 have discussed some aspects of PBG materials and their unusual properties, which provided a foundation for novel practical applications ranging from clinical medicine to information technology.

1. INTRODUCTION

The study of distributed feedback lasers has been reported [1] on the basis of the fact that propagation of electromagnetic waves and the propagation of light is forbidden for a small range of wave vectors and the index contrast are typically of the order of $n_a / n_b = 0.01$. But the contrast is too low to be suited for the 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. But there is a need of multipurpose photonic integrated circuits analogous to electronic integrated circuit to work at micrometer wavelength scale (1μm to 10μm) because light has many advantages over electricity for instance, it can travel in dielectric material at much greater speeds and carry larger amounts of information per second. The bandwidth of dielectric material (of the order of one terahertz for fiber optic communication) as compared to a few hundred KHz for present telephone it provides space for larger amount of information.

The photonic phenomenon has relied, in general, on the mechanism of total internal reflection. Light propagating in material of high refractive index is reflected at the interface in material of low refractive index and requires an optically smoother interface with respect to the wavelength. This requirement limits the degree of miniaturization of optical components, which necessitates a different mechanism from total internal reflection to fabrication of photonic crystal. The underlying concept is based on the existence of photonic band gap. 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.

2. OVERVIEW OF THE PBG TECHNOLOGY

The earliest ideas to control the radiative properties of the 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 crystal could change the properties of the radiation field in such a way that there would be no electromagnetic modes available in dielectric structure. It has been predicted [4] and experimentally verified [5,6] that the removal of the dielectric material in a PBG structure will generate a single mode in the gap while the addition of extra material will give rise to several modes. Ho et al [7] have given smallest 3D complete photonic band gap (CPBG) and Yablonovitch et al [8] have fabricated Photonic Crystal (PX) (figure 1) for the microwave region and other designs are available for CPBG have also been taken by other investigators [9-12]. Ozbay et al [13] have used a technique of stacking thin micromachined (100) silicon wafers to fabricate PX for wavelength of about 600μm. The ultimate goal for PX is its fabrication for telecommunication purposes (1.5μm). Schere and his co-worker [14] used electron beam lithography to drill (100) air channel type of 1.0μm size. Fan et al [15] have fabricated PX of sub-micrometer wavelength scale. Using a dielectric constant of Si as12.096 at 1.5μm and 2.084 for silica at the same wavelength λ = 1.5μm gives an optimized complete PBG of about14.0% which could be improved to 23% [15].

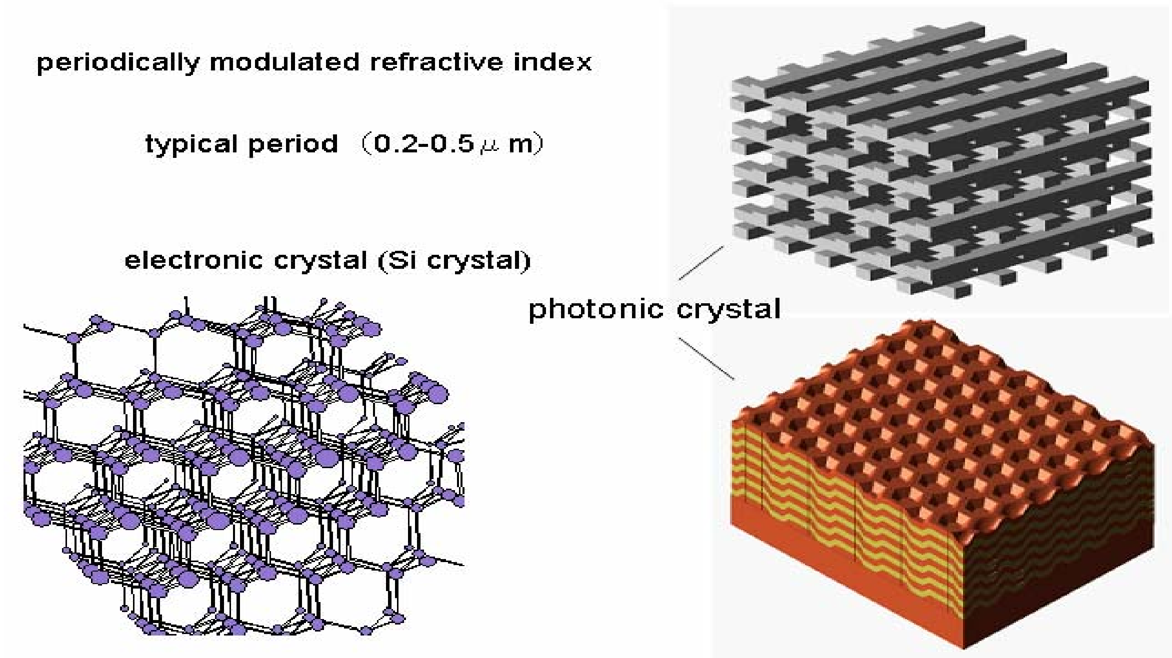


Figure 1: Photonic Crystal

A very 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] and 3D metallic–dielectric photonic crystals have been studied theoretically [17-20] and it has been shown [20] to have enormous Omni directional PBG approaching 80%. Yablonovitch [21-24] has suggested an important application of the suppression of the spontaneous emission. John and Wang [26-28] have suggested that an individual atom would also be capable of binding a local mode similar to those generated by a defect in a PBG crystal. The disordered dielectric microstructure could probably be fabricated more easily than ordered structure and experimental verification have been done elsewhere [29]. Disordered dielectric structures have also been used to observe a reduction of the rate spontaneous emission at optical frequencies [30,31]. Johri and his co-workers [32-37] have studied 3-D photonic crystal structure and various groups have proposed photonic crystal. Apart from the artificially engineered PBG material there are also naturally occurring PBG materials such as butterfly and opal. The theoretical methods are basically categorized as Plane Wave Expansion method (PWE), Transfer Matrix Method (TMM) and Finite Difference Time Domain technique (FDTD) while experimental methods are etching technique, layer-by-layer fabrication, woodpile-structure and colloids.

3. PHYSICS OF PHOTONIC BAND GAP MATERIALS

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

$$\varepsilon(x) = \varepsilon_0 + \varepsilon_{fluct}(x) \qquad (1)$$

where ε_0 = average part of the dielectric constant

ε_{fluct} = part of dielectric constant that varies from point to point in space.

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

$$-\nabla^2 \cdot \vec{E} + \nabla\left(\vec{\nabla}\cdot\vec{E}\right) - \frac{\omega^2}{c^2}\varepsilon_{fluct}(x)\,\vec{E} = \frac{\omega^2}{c^2}\varepsilon_0\,\vec{E} \qquad (2)$$

The Maxwell wave equation (Equation 2) was written in the form of Schrodinger equation. The Kinetic Energy (KE) and scattering Potential Energy (PE) are the first and second terms respectively with their energy eigen value $\frac{\omega^2}{c^2}\varepsilon_0$. The equation informs us of the refinement of light localization. The overall positivity of the dielectric constant (equation 1) leads to the constraint that the energy eigen value is always greater than the highest of the potential barrier presented by $\frac{\omega^2}{c^2}\varepsilon_{fluct}(x)$. The 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].

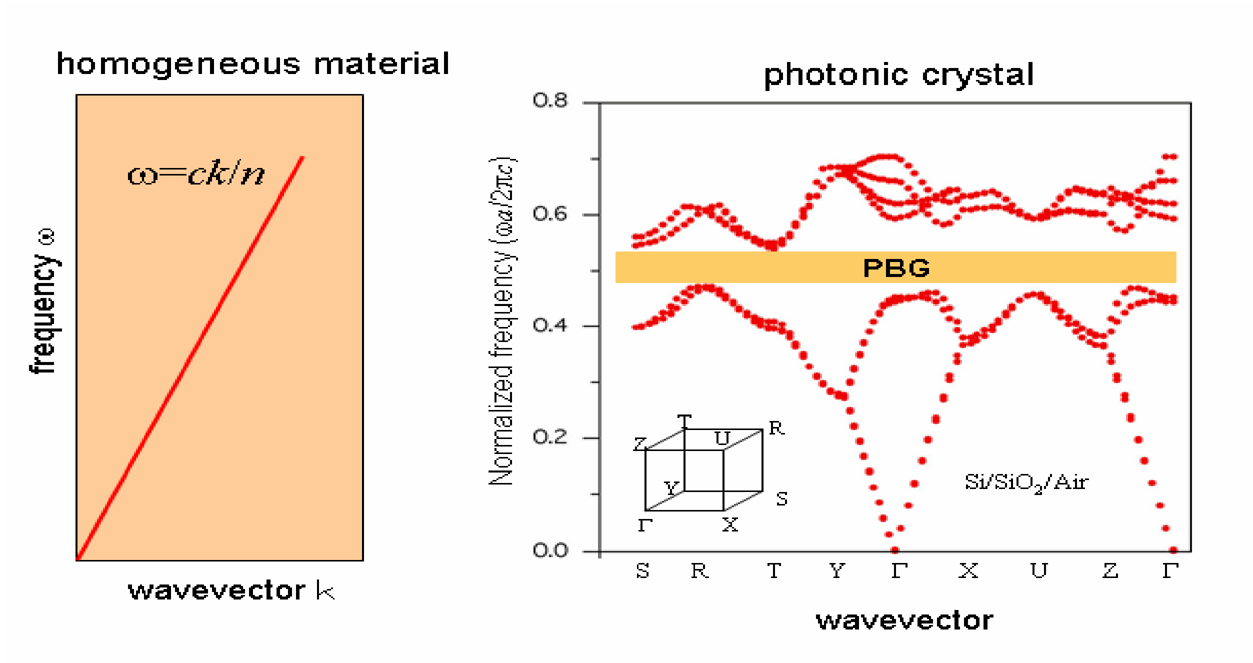


Figure 2: Illustration of photonic band gap in a crystal

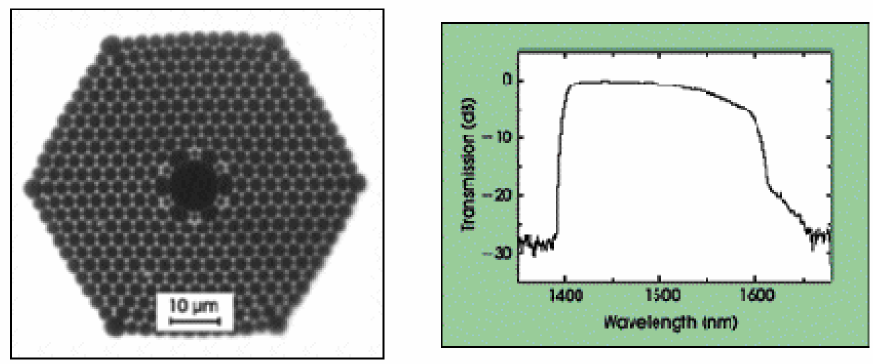
In recent years the interaction between electromagnetic radiation and structures with one dimensional (1D) periodic perturbation has resulted in the appearance of new devices in microwave electronics, photonics, and optics [43]. These structures are used to form distributed feedback in free electron 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. Indeed at microwave frequencies these structures are known as “1D Bragg structures” [44, 45] whereas in integrated optics and in Bose-Einstein condensate scattering they are called either “1D photonic bandgap (PBG) structures” or optical lattices [49].

The propagation speed of the particles through tunneling regions has been studied theoretically since the early days of quantum mechanics, and optical analogs of tunneling 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 photonic bandgaps 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 previously, these anomalous delays are the results 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 1995 by Philip Russell and co-workers (now at the University of Bath) that proposed trapping light in a fibre with a hollow core using a PBG. Such fibres might outperform normal optical fibres because light trapped in their hollow core travels through a tenuous gas, rather than a solid glass. Now Charlene Smith and co-workers at Corning Inc in New York have reported a dramatic decrease in the observed optical losses in this new form of fibre [53].

PBG fibres (figure 3 [54]) are completely different from conventional fibers because they make use of the unusual properties of 2D periodic micro-structured materials. When the period of the lattice is comparable to the wavelength 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 conspire to 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.



(a) **(b)**

Figure 3: (a) PBG fibre (b) PBG in the fiber's cladding guided light from ~1400 to ~1600 nm.

4. 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 (MRI), 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 hemoglobin in tissue and thereby provides an early diagnostic image of metabolic process leading to cancer prior to structural damage caused by the tumor. Since these medical applications of photonic may yield health benefits, the need to promote the technology becomes more desirable. Some common applications include [55]:

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 tumors.

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 their 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 great advances in devices, subsystems and in particular in fibre optic technology, which in turn contributes to advances in fibre sensing technology [56].

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 applications for environmental and medical measurements. Milimeter-wave photonic technology is the foundation for such measurements, and will probably also serve as a total 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 for a kind of human interface. Millimeter-wave photonic technology is a key to realizing the dream of omnipresent service to humanity.

Omnipresent Information Technology (IT) services are just beginning to emerge, yet the time is coming when they will truly revolutionize information technology. Based on groundbreaking papers presented 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 that run the gamut from biomedical sensors and intra-body networks to "smart" buildings and long haul communications [57].

As the demand of advanced materials increased, there is a growing interest in new approaches for fabrication of novel optical devices based on hybrid materials. Organofunctional silsesquioxanes are highly condensed molecular composites which show interesting physical and optical properties 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, material science, and medical areas [58].

5. CHALLENGES AND TARGETS

All materials in the beginning have been highly anisotropic. Therefore the stress must be on the quality and control of the materials on all domains, looking in particularly at the measuring techniques, fabrications and manufacturability of the materials. Future research should be focused on to get the magnetic properties in the visible to make circulators and other microwave style components in photonics.

Photonic crystals architecture can be of great help to increase solar energy conversion.

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

To develop imaging device, that will be safe, inexpensive and suitable for use in the clinics and hospitals.

To develop devices which are able to diagnose skin tumors without recourse to a biopsy and the ability to perform a blood test without having to draw blood from a patient.

6. DISCUSSION AND CONCLUSION

The present study is providing a technical overview of the rapidly emerging photonic information technology from different viewpoints. The paper laid down the theory and principles of PBG materials and practical applications of photonic crystal 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 is causing excitement in its potential for having applications, especially medical applications, whose benefits are more than commercial. Fiber-optic strands can be made into far thinner and more supple catheters than have previously been feasible. The photonic material has potentials to be a technological revolution of this century similar to the electronic revolution of the last century. Material scientists are giving priority to this field, as it is an emerging area that points to the next trillion-dollar industry.

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