PHOTONIC CRYSTAL: PRINCIPLES AND APLICATIONS IN NANOPHOTONICS

By

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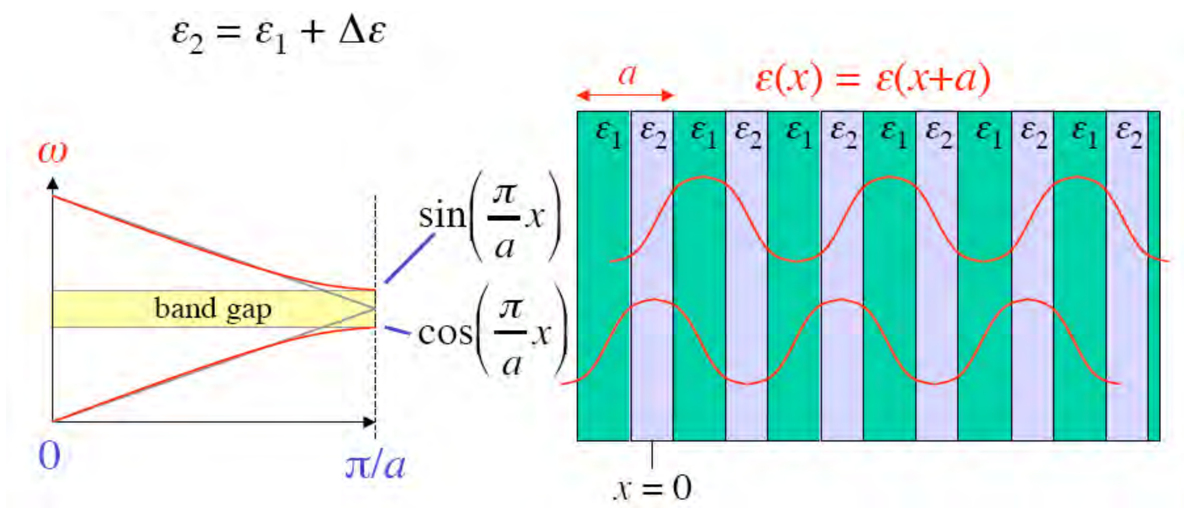
$\varepsilon_2 = \varepsilon_1 + \Delta\varepsilon$
a
$\varepsilon(x) = \varepsilon(x+a)$
ε_1 ε_2 ε_1 ε_2 ε_1 ε_2 ε_1 ε_2 ε_1 ε_2 ε_1 ε_2
ω
band gap
$\sin\left(\frac{\pi}{a}x\right)$
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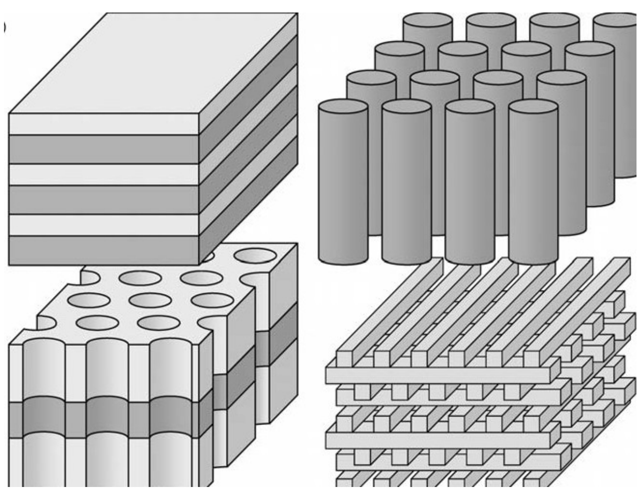

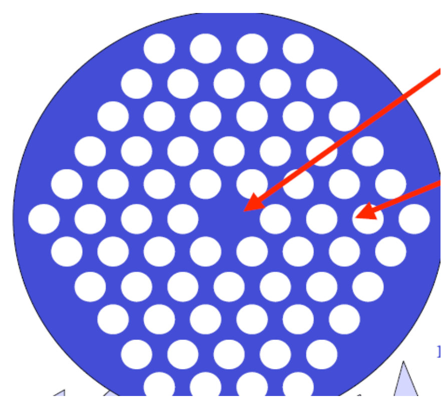

ADDIS ABABA UNIVERSITY

DEPARTMENT OF PHYSICS

The undersigned hereby certify that they have read and recommend to the Faculty of Graduate Studies for acceptance graduate a project entitled **" Photonic crystals: Principles and Aplications in Nanophotonics** " by **Dawit Assefa** in partial fulfillment of the requirements for the degree of Master of Science in physics.

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Abstract

Throughout the last two decades the studies on photonic crystal have made a tremendous developments in many aspects of physics, specifically in the field of nano-photonics. Moreover,many principles and applications of photonic crystal are appearing to be valid in different area of studies. Photonic crystals are microscopic dielectric materials by which light is to be trapped,confined or controlled as it tends to propagates through them. In this project, we review the historical development of photonic crystals, metalic photonic crystals and plasmoics, Maxwell equations and the inspirations of bandgap, the propagation of light in different media such as one , two and three dimensional media of photonic band gap materials(photonic crystals). Our study has fully, concentrated on the progresses, developments of principles and technological applications of photonic band gap material. Finally, we have predicted that electromagnetic waves(light modes) can be guided to a desired direction and in a desired manner carrying ample information by the help of different devices that appropriately exploit the properties of photonic crystals.

General Objective

- *To comprehend The Principles and Applications of Photonic Crystal.*

Specific Objectives

- *To Review Historical Development, Dopping and Operations of Photonic Crystals.*
- *To identify the best methods of Photonic Crystal Fabrications.*
- *To compare and contrast the validity of Quantum Mechanics for Electronic Wave. in Bulk Crystal and Maxwell Equations for Light wave in Photonic Crystal.*
- *To Analyze Photonic Band Gap in One ,Two and Three Dimensional Photonic Crystal.*
- *To Determine the Equivalent Eigen Values Problems for Electromagnetic Waves.*
- *To verify the Applications of Photonic Crystal in different fields.*

Acknowledgements

Foremost,I would like to express my sincere gratitude to Dr.S.K.Ghoshal,for just the right combination of freedom, inspiration, support and guidance, for his patience and understanding when deadlines were not met. Finaly I would like to express my dippiest appreciation to my families,relatives, friends and colleagues.

Chapter 1

Introduction

A crystal is a periodic arrangement of atoms or molecules. The pattern with which the atoms or molecules are repeated in space is the crystal lattice. The crystal presents a periodic potential to an electron propagating through it, and both the constituents of the crystal and the geometry of the lattice dictate the conduction properties of the crystal.

The theory of quantum mechanics in a periodic potential explains what was once a great mystery of physics: In a conducting crystal, why do electrons propagate like a diffuse gas of free particles? How do they avoid scattering from the constituents of the crystal lattice? The answer is that electrons propagate as waves, and waves that meet certain criteria can travel through a periodic potential without scattering (although they will be scattered by defects and impurities). Importantly, however, the lattice can also prohibit the propagation of certain waves. There may be gaps in the energy band structure of the crystal, meaning that electrons are forbidden to propagate with certain energies in certain directions. If the lattice potential is strong enough, the gap can extend to cover all possible propagation directions, resulting in a complete band gap. For example, a semiconductor has a complete band gap between the valence and conduction energy bands.

The optical analogue is the photonic crystal, in which the atoms or molecules are replaced by macroscopic media with differing dielectric constants, and the periodic potential is replaced by a periodic dielectric function (or, equivalently, a periodic index of refraction). If the dielectric constants of the materials in the crystal are sufficiently different, and if the absorption of light by the materials is minimal, then the refractions and reflections of light from all of the various interfaces can produce many of the same phenomena for photons (light modes) that the atomic potential produces for electrons. One solution to the problem of optical control and manipulation is thus a photonic crystal, a low-loss periodic dielectric medium[1].

1.1 Historical Development of Photonic Crystals

Throughout the last two decades, there has been significant activity in the development of photonic devices that can confine, control, and route light on a scale comparable to modern electronic devices,namely the nanometer scale. A key motivation for this is to realize photonic circuits having a density approaching that of modern electronic circuits. However, in order for this to be done, such devices would need the ability to confine light on a sub-wavelength scale and exist in a material compatible with the microelectronics manufacturing infrastructure.

Although the latter requirement was readily satisfied through a proper choice of materials, i.e silicon, the former one was more elusive. The reason for this arose from the fact that reflective, or conducting, devices are very lossy at optical wavelengths and refractive, or total internally reflective, devices do not offer mode confinement on a small enough scale.

Photonic crystals are optical materials that allow for controlling and manipulating the flow of light and are composed of a regular arrangement of a dielectric material that shows strong interaction with light; any material exhibiting spatial periodicity in refractive index is a photonic crystal. Photonic crystals are materials with repeating patterns spaced very close to one another, with separations between the patterns comparable to the wavelengths of light. When light falls on such a patterned material, the photons of light interact with it, and with proper design of the patterns, it is possible to control and manipulate the propagation of light within the material[9].

Thus, photonic crystals are periodically structured electromagnetic media, generally possessing photonic band gaps: ranges of frequency in which light cannot propagate through the structure. This periodicity, whose length scale is proportional to the wavelength of light in the band gap, is the electromagnetic analogue of a crystalline atomic lattice, where the latter acts on the electron wave function to produce the familiar band gaps, semiconductors, and so on, of solid-state physics. The study of photonic crystals is likewise governed by the Bloch-Floquet theorem, and intentionally introduced defects in the crystal (analogous to electronic dopant) give rise to localized electromagnetic states: linear waveguides and point-like cavities. The crystal can thus form a kind of perfect optical "insulator," which can confine light lossless around sharp bends,in lower-index media, and within wavelength-scale cavities, among other novel possibilities for control of electromagnetic phenomena. Below, we introduce the basic theoretical background of photonic crystals in one, two, and three dimensions , as well as hybrid structures that combine photonic-crystal effects in some directions with more-conventional index guiding in other directions. Electromagnetic wave propagation in periodic media was first studied by Lord Rayleigh in 1887, in connection with the peculiar reflective properties of a crystalline mineral with periodic "twinning" planes (across which the dielectric tensor undergoes a mirror flip). These correspond to one-dimensional photonic crystals, and he identified the fact that they have a narrow band gap prohibiting light propagation through the planes. This band gap is angle-dependent, due to the differing periodicities experienced by light propagating at non-normal incidences, producing a reflected color that varies sharply with angle. A similar effect is responsible for many other iridescent colors in nature, such as butterfly wings and abalone shells as we can see in fig 1.1. This generalization, which inspired the name "photonic crystal," led to many subsequent developments in their fabrication, theory, and application, from integrated optics to negative refraction to optical fibers that guide light in air.


Fig 1.1   Photonic crystal causing iridescent colors in nature(abalone and butterfly-wings) [13]

To a large extent, the field of PCs can be thought of as having its origins in the rather conventional 1-D thin-film stack, wherein a quarter wave thickness of alternating materials is arranged in a periodic fashion. In this device, it is well known that certain frequencies are transmitted whereas others are not. As the index contrast between the alternating layers is increased, the selectivity of the transmitted and reflected wavelengths is also increased. When extended to two and three dimensions, this selectivity is what gives rise to high-mode confinement. While 1-D thin-film stacks have been known for over a century, their generalization to higher dimensions was not proposed until the 1970s by Bykov,as a possible way of inhibiting spontaneous emission. In essence, Bykov proposed the use of a periodic structure that served to inhibit certain electromagnetic frequencies, thereby disallowing spontaneous emission. These devices ultimately became known as photonic bandgap (PBG) structures, as they suppressed a band of frequencies from existing, the so-called ‘‘photonic bandgap."

More recently (1987), Yablonovitch and John proposed the idea that a periodic arrangement of metallic or dielectric objects can possess the property of a bandgap for certain regions in the frequency spectrum, depending on the material they are constructed from, whether it be metallic for the microwave regime or dielectric for the optical regime. More over , Yablonovitch proposed a structure where an electronic and a photonic gap overlapped, thereby making it possible to enhance the performance of lasers, hetero-junction bipolar transistors, and solar cells. Subsequent to this work, John proposed using such structures for the localization of light in strongly scattering dielectric structures. In each of these cases,the basic idea was to tailor the properties of photons in a PC in a way directly analogous to how atomic crystals tailor the properties of electrons. That is to say, in the electronic case, the wave functions of electrons interact with the periodic potential of the atomic lattice, and for a certain range of energies(similar to frequencies for photons), electronic states cease to exist, thus giving rise to an electronic band gap. For PCs, the analogue of the electronic potential in an atomic crystal is the dielectric constants of the constituent materials of the PBG structure. And, due to the periodic interaction, certain PBGs appear wherein certain modes, or frequencies, are disallowed. In such a structure, one can then introduce a line or point defect, which amounts to the absence of the periodic lattice, wherein a mode is localized by virtue of being suppressed within the lattice. For this reason, these devices offer extreme mode confinement as well as the ability to control and route light very efficiently. With these advances, the field of PCs and in particular their realization in silicon-based materials has been a very active field of research over the last two decades. During this time, great success was achieved in identifying suitable periodic structures, dielectric materials, and both theoretical as well as experimental demonstration and characterization of 1-D, 2-D, and 3-D PC and bandgap structures.

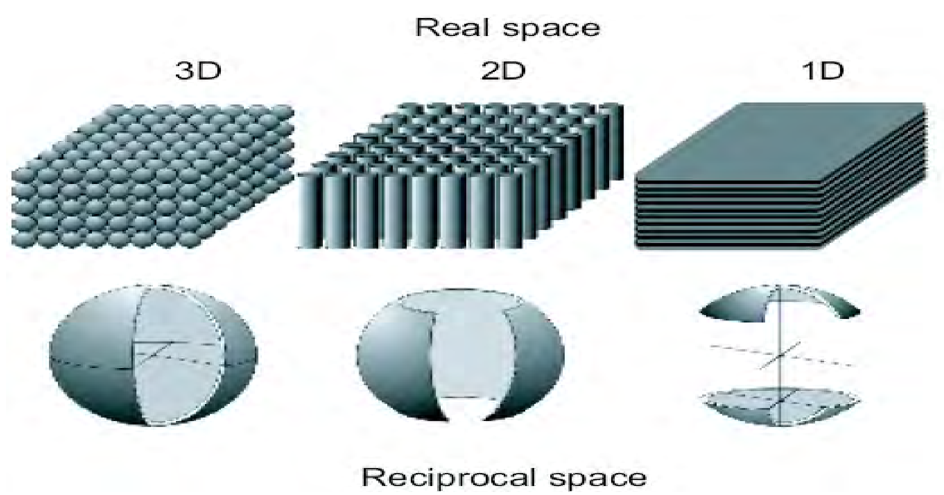


Fig 1.2 Real-space representation of a photonic crystal and reciprocal space regions for which propagation is not allowed [10]

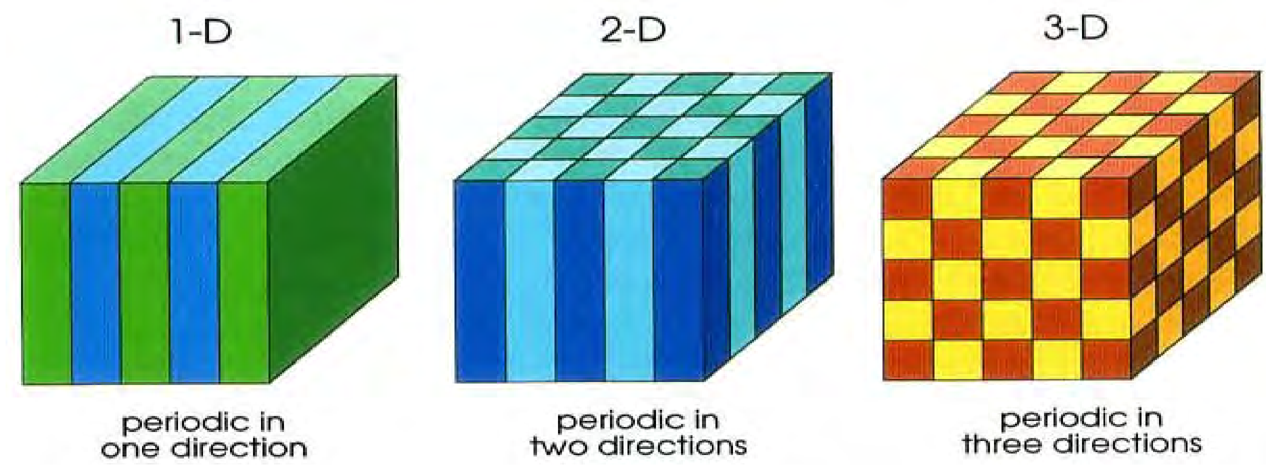


fig 1.3 Schematic depiction of photonic crystals periodic in one, two, and three directions,where the periodicity is in the material (typically dielectric) structure of the crystal [1]

However, developing suitable structures for novel device applications and systems that are economically feasible remains a challenge. This difficulty arises from the challenging aspects of their fabrication, which often requires high-resolution lithography and high-aspect-ratio etching. Although progress has been,and is being, made in these areas, significant market opportunities are yet to arise. Nonetheless, the field of PCs offers significant potential and is poised to find its place in the realm of high-technology applications[6].

In the following sections we are going to see some details of photonic crystals such as operation,doping, localization of light and fabrication mechanisms of photonic crystals

1.2 Operation of Photonic Crystal

The physical phenomenon that clearly describes the operation of a PC is the localization of light, which is achieved from the scattering and interference produced by a coherent wave in a periodic structure. Upon an incident radiation, the periodic scatterers constructing a PC could reflect an incident radiation at the same frequency in all directions. Then, wherever in space the radiation interferences occur constructively, sharp peaks would be observed. This portion of the radiation spectrum is then forbidden to propagate through the periodic structure and this band of frequencies is what was called a stop band, or a PBG. On the other hand, wherever in space an incident radiation destructively interferes with the periodic scatterers in a certain direction, this part of the radiation spectrum will propagate through the periodic structure with minimal attenuation, and this band of frequencies was called a pass band. For an electromagnetic wave propagating within a dielectric material, scattering takes place on a scale much larger than the wavelength of light. The localization of light occurs when the scale of the coherent multiple scatterers is reduced to the wavelength itself. In this case, a photon located in a lossless dielectric media provides an ideal realization of a single excited state in a static medium, at room temperature. Unlike electron localization, which requires an electron–electron interaction and electron–phonon interactions, photon localization offers the unique possibility of studying the angular, spatial, and temporal dependence of wave field intensities near localized transitions.

Light localization has fundamental consequences at the quantum level. This can be seen for a periodic array of high dielectrics that have dimensions comparable to the wavelength of light, by exhibiting a complete PBG in a certain range, analogous to the electronic energy band gap in a semiconductor material. In a PC, there are no allowed electromagnetic states in the forbidden frequency range.

1.3 Analogy Between Photonic and Semiconductor Crystals

In a semiconductor crystal, electron localization can be described using the Schrödinger equation for an electron with an effective mass m

$$\left[-\frac{\hbar^2}{2\mathrm{m}}\nabla^2+V(x)\right]\varphi(x)=E\varphi(x) \qquad 1.1$$

where h is Planck's constant, m the effective mass of electron, V(x) the potential function, φ(x) the wavefunction, and E the total energy. The probability of finding an electron at x is given by $|\varphi(x)|^2$.The electron can be trapped by a random potential V(x) in deep local potential fluctuations if the energy E is sufficiently negative. As the energy increases, the probability for the trapped electron to tunnel to a nearby potential fluctuation also increases. In the case of monochromatic electromagnetic waves of frequency ω propagating in an inhomogeneous, but non dissipative dielectric medium, Maxwell's equations are used to describe the wave propagation through space.

while keeping in mind that for a dielectric material μ(r) = 1.0

$$\nabla\times\left[\nabla\times\vec{E}(r)\right]=\omega^2\mu(r)\,\varepsilon(r)\,\vec{E}(r) \qquad 1.2$$

$$\nabla\times\left[\frac{1}{\varepsilon}\nabla(r)\times\vec{H}(r)\right]=-\,\omega^2\mu(r)\,\vec{H}(r) \qquad 1.3$$

The right-hand side of Eq. (1.2) can be further expanded using vector identities

$$-\nabla^2 \vec{E} + \nabla\left(\nabla . \vec{E}\right) = \omega\, 2\mu\left(r\right)\varepsilon\left(r\right)\vec{E}\left(r\right) \qquad 1.4$$

The total dielectric constant ε(r) can be separated into two parts as

$$\varepsilon\left(r\right) = \varepsilon_o + \varepsilon_{spatial}\left(r\right) \qquad 1.5$$

where ε_0 is the average value of the dielectric function and $\varepsilon_{spatial}(r)$ the spatial component of the dielectric function, which is analogous to the potential V(x) in the Schrödinger equation.

Eq. (1.3) then can be written as

$$-\nabla^2 \vec{E} + \nabla\left(\nabla \cdot \vec{E}\right) = \omega^2\left[\varepsilon_o + \varepsilon_{spatial}\left(r\right)\right]\mu\left(r\right)\vec{E}\left(r\right) \qquad 1.6$$

The quantity $\varepsilon_0\omega^2$ is similar to the total energy E in the Schrödinger equation. For an electronic system, lowering the electron energy usually enhances the electron localization. For a PC, lowering the photon energy leads to a complete disappearance of the scattering mechanism itself, where at a high photon energy, geometric and ray optic theory becomes more valid, and interference corrections to optical transport become less and less effective.

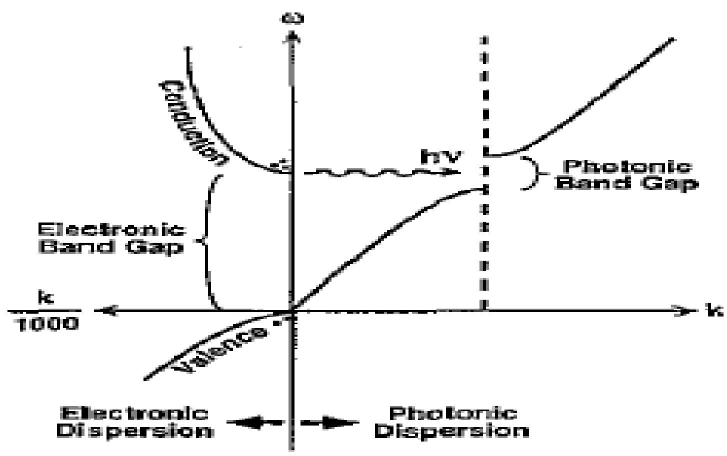


Fig1.4 Electronic and photonic dispersions [12]

We can also see from the above equation that, because the increase in dielectric strength is analogous to an increase in the potential well depth of a quantum mechanical system, the overall effect is to lower the frequency of all modes of the system; hence the band edges will move downward in frequency with a general frequency dependence of $1/\sqrt{\varepsilon_r}$. [6]

One way in which the electromagnetic case differs from the quantum-mechanical case is that photonic crystals do not generally have a fundamental scale, in either the spatial coordinate or in the potential strength (the dielectric constant). [1] This makes photonic crystals scalable in a way that traditional crystals are not .

1.4 Electromagnetic Localization in Photonic Crystals

The analogy between electron and photon localization has led to the scaling theory of localization, where the localization critical point is defined by a condition described by

$$\rho(\omega) D(\omega) \imath \simeq 1 \qquad 1.7$$

where $\rho(\omega)$ is the photon density of states (DOS), $D(\omega)$ the diffusion coefficient of light in a multiple scattering medium, and the transport mean free path. If the scattering microstructures do not significantly alter the photon DOS from its free space value

$$\rho_{vac}(\omega) = \frac{1}{c}\left(\frac{\omega}{c}\right)^2 \qquad 1.8$$

Then the localization criterion by assuming that $D(\omega) \approx c\ell$ becomes

$$\left(\frac{\omega \ell}{c}\right)^2 = 1 \qquad 1.9$$

In general, we can interpret the factor $4\pi(\omega/c)^2$ as the total phase space available for propagation of a photon of frequency ω. Thus, the localization criterion is given by

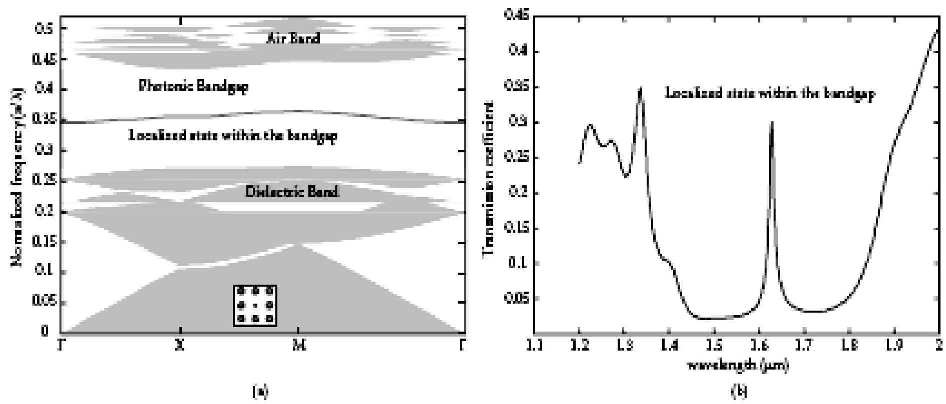
$$(phasespace) \times \ell^2 = 4\pi \qquad 1.10$$

The concepts of DOS, diffusion coefficient, mean free path, phase space, and their interrelationships provide the basis for further understanding PBGs. The spatial localization of light in a PC is achieved by introducing defects, which can take the form of a line defect, in which case the PC resembles a waveguide. Photons lying within the band gap from which they are not allowed to propagate through the crystal are confined to the defect region, as defined by the PC walls. Another kind of defect is that of a point defect, in which case the PC creates a cavity that confines a single or a multiple of closely separated modes to the spatial location of the point defect, centered within the cavity.[6]

The density of states of a one-dimensional channel is defined as the ratio dN/dωdl calculated per unit length of the channel, while in the case of a two-dimensional planar waveguide the density of states is the ratio dN/dωdS calculated per unit area of the waveguide. The presence of a waveguide results in the formation of nonzero density of states in the band gap of the confining material,i.e. in the cladding [2].

1.5 Doping of Photonic Crystals

In a PC, there exist a dielectric band and an air band, analogous to the valance and the conduction bands, respectively, in semiconductor material. Between the dielectric and air bands is the PBG, within which no energy state exists and as a result propagation is prohibited. Doping a semiconductor material can be achieved by either adding a donor or an acceptor atom. Both result in a change in the electrical properties of an atomic crystal by either having a p-type or an n-type material. In a similar fashion, the optical properties of a PC can be changed by introducing point defects, i.e either adding or removing a certain amount of dielectric material. When dielectric material is added to a unit cell, it behaves like a donor atom in an atomic crystal, which corresponds to a donor mode and has its origin at the bottom of the air band of the PC.



F*ig 1.5 A photonic crystal with a point defect will allow a single or multiple localized mode to exist within band gap as shown in (a) band diagram (b) attenuation diagram [6]*

Alternatively, removing dielectric material from a unit cell makes it behave like an acceptor atom in an atomic crystal, which corresponds to an acceptor mode and has its origin at the top of the dielectric band of the PC, as shown in Figure 1.5. Thus, acceptor modes are preferable for making single-mode laser microcavities, because they allow a single localized mode to oscillate in the cavity. By adding or removing a certain amount of dielectric material to the PC, we are disrupting the symmetry of the photonic lattice. By doing so, we are allowing either a single state or a multiple of closely separated states to exist within the band gap. This phenomenon of localizing states, by introducing point defects, can be useful in designing high-Q-value microcavities in Pcs [6].

1.6 Methods of Fabrication for Photonic crystals

The necessary precision in terms of fabrication is on the order of 10nm ; this manufacturing scale is some what of a challenge at this time, at least in terms of per unit costs and yields. Photonic crystals take advantage of the nano-fabrication processes that are available to pattern the dielectric function at the sub wavelength scale; this patterning ability presents the possibility of designing the electromagnetic modes of photonic devices in microscopic detail. The fabrication of 2D and 3D photonic crystals for near-infrared and visible frequencies remains a difficult undertaking at this time [9]. A wide variety of methods have been used to fabricate photonic crystals. Some of them are more suitable for the fabrication of 1D and 2D photonic crystals, whereas others are useful when one needs to localize photons in three dimensions. Some of these methods are discussed here.

1.6.1 Self-Assembly Methods

Colloidal self-assembly seems to be the most efficient method for fabrication of 3D photonic crystals. In this method, pre-designed building blocks (usually mono dispersed silica or polystyrene nano-spheres) spontaneously organize themselves into a stable structure. Although the currently available colloidal assemblies do not have a full photonic bandgap in the optical wave lengths because of their low index contrast, they do provide a template that can be infiltrated with material of higher refractive index. A number of techniques are available for colloidal assembly fabrication. A widely used technique for creating colloidal crystals is gravity sedimentation. Sedimentation is a process whereby particles, suspended in a solution, settle to the bottom of the container, as the solvent evaporates. The critical point here is finding the proper conditions for liquid evaporation so that the particles form a periodic lattice. Sedimentation under gravity is a slow process, taking as long as four weeks to get good crystals. If the process is accelerated to a few days, then crystallization produces a polycrystalline structure with many defects, as shown by the AFM image in Figure 1.6. The size of crystallites varies and depends on the quality of building blocks, time of crystallization, temperature, humidity, and so on.

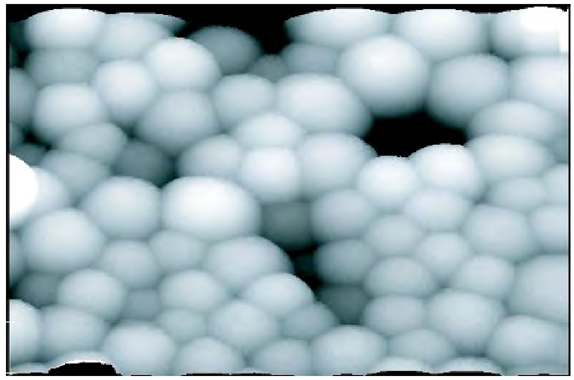


Fig1.6 The AFM image of 450-nm silica beads produced by sedimentation method,using crystal growth for 5 days [10].

Another self-assembly technique, introduced by Xia and co-workers (Park and Xia 1999; Gates et al., 1999), is called the cell method. The fabrication method is represented in Figure 1.7. An aqueous dispersion of spherical particles is injected into a cell formed by two glass substrates and a frame of photo resist or Mylar film, placed on the surface of the bottom substrate. One side of the frame has channels that can retain the particles, while allowing the solvent to flow through.

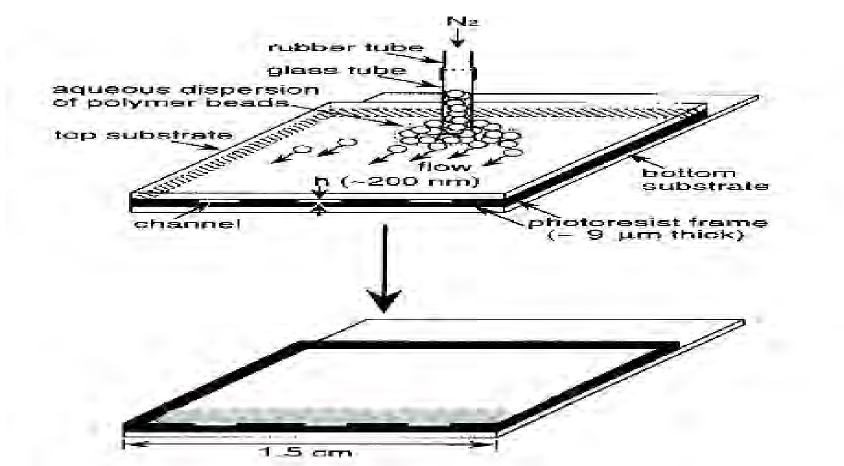


Fig1.7 The cell method for self-assembling of colloidal crystals [10].

The particles settle down in the cell to form an ordered structure (usually the fcc structure).This technique is particularly useful for fabrication of thin polystyrene photonic crystals in water. Their thickness usually does not exceed 20 µm, and lateral dimensions are of the order of 1 cm. The method can be used when one wants to investigate emission from dye-incorporated photonic crystals. A disadvantage of this method is that when a crystal dries, defects are formed inside its structure. This is probably because particles are highly charged, and not all particles that form a crystal are in physical contact with each other. When the water evaporates, the crystals form large domains, with cracks forming between these domains.

1.6.2 Two-Photon Lithography

This method has been used for 3D photonic crystal fabrication. It utilizes the fact that certain materials, such as polymers, are sensitive enough to two-photon excitation to trigger chemical or physical changes in the material structure, with nano-scale resolution in three dimensions. Since the two-photon absorption is confined to a tiny volume, scanning the focus within the material can produce three-dimensional micro-scale patterns. Among the structures that have already been fabricated by two-photon lithography, the log pile-type photonic crystal is the most common one .

1.6.3 E-Beam Lithography

Electron beam lithography is a method that enables one to create various photonic crystals with extremely high resolution. It is a relatively complicated method, because it includes many variables. Its main disadvantage is its high cost. In this method, the sample (wafer) is covered with an electron-sensitive material called resist.

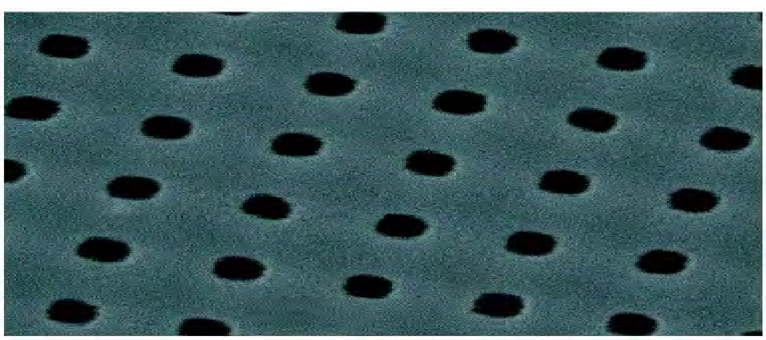


Fig 1.8 SEM image of a photonic crystal fabricated by E-beam lithography [10].

The material, used as resist, undergoes a substantial change in its chemical or physical properties, when it is exposed to an electron beam . The beam position and intensity are computer controlled, and electrons are delivered only to certain areas to get the desired pattern. After exposition, a part of the resist is dissolved away and the sample can be further processed with etching procedures to get the final crystalline structure. Electron beam lithography is mostly used for fabrication of 2D photonic crystals

1.6.4 Etching Methods

These methods are more suitable for the fabrication of 2-dimensional photonic crystals and have been used for semiconductors. These methods utilize marking of a planar pattern of unwanted areas on the surface of a semiconductor, using a lithographic technique such as E-beam lithography. These marked areas are then etched to create holes. The two techniques used in in this methods are:

(i) **Dry Etching:** An example is reactive-ion etching (RIE), which utilizes reactive ions generated by plasma discharge in a chlorine-based (SiCl4 and Cl2) or fluorine-based (CHF3 , CF4 , C2 F6 , and SF6) reactive gas. These ions are accelerated toward the sample surface under an electric field. This dry etching provides a good control over the hole size, but has a limited maximum etching depth. The method has been used for many semiconductors, such as GaAs, AlGaAs, and Si.

(ii) **Wet Etching**: An example is electrochemical etching that has also been used for many semiconductors. Electrochemical etching of Si to produce microporous silicon photonic crystal is an example. In this case, a pre-pattern with etch pits was first created on the front face of a silicon wafer by using lithographic patterning and subsequent alkaline chemical etching using KOH solution. The wafer was then mounted in an electrochemical cell and electrochemically etched using an HF solution.

The pre-etched pits form nucleation centers for electrochemical etching. The advantage provided by an electrochemical etching method is that deep holes can easily be produced.

1.6.5 Holographic Methods

Holographic methods, which utilize interference between two or more coherent light waves to produce a periodic intensity pattern,have been used to produce a periodic photo produced photonic structure in a resin (photo resist). Here, the initial laser beam is split into several beams and allowed to overlap in the resin at angles predetermined by the desired periodicity. The simplest is the fabrication of a one-dimensional periodic structure (a 1D photonic crystal or a Bragg grating) produced by overlap of two beams, where the angle between the two beams determines the periodicity. This method has been in practice for a long time[10].

1.7 Metallic photonic Crystals and Plasmonics

In the preceding sections, photonic crystals have been essentially considered as periodic ensembles of dielectric elements, which allow the control of the propagation of light through the effects of photonic band gaps and transmission bands. It might be pointed out, however, that the first periodic (one, two and three dimensional) ensembles of materials had been historically fabricated from metals rather than from dielectrics. The use of periodic metallic grids for filtering radio frequency waves with different polarizations can thus be traced back to the beginnings of the 20th century (Marconi 1919).

The idea that any dielectric function could be artificially 'realized' through the use of metals led to the concept of 'artificial dielectrics' developed in the 1950s . In either case, these periodic filters and artificial dielectrics were fundamentally photonic crystals, even though realizations at this time were restricted as regards their applications to wavelengths much larger than wavelengths in the optical region. As this brief survey indicates, the concept of photonic crystal can be extended, in quite a natural way, to metallic as well as to metallo-dielectric periodic structures. Standard metals present electromagnetic properties which are fundamentally different from those of dielectrics[2].

In nano-photonics, light is controlled using metallic and dielectric nano-structures with feature sizes much smaller than a wavelength. The first modern application of nano-photonics was probably the near-field scanning optical microscope. But there is also historical evidence that ancient Greek and medieval artisans unwittingly used nano-photonics to impart bright colors on glass objects; the glass had been doped with metallic nano-particles that caused it to absorb and scatter light at certain wavelengths. *Absorption in metallic nano-particles is caused by confined collective oscillations of electrons interacting with an electromagnetic field, known as surface plasmon resonances*. Surface plasmons can also propagate along the interface between a metal and a dielectric as electron density waves coupled to the electromagnetic field. Researchers have known about plasmons for decades, but it wasn't until recently that they began integrating plasmonic structures onto common optical components, such as semiconductor lasers and optical fibers, in order to engineer their near- and far-fields and create new functionalities.

The manipulation of light using surface plasmons, *known as plasmonics*, has a wide range of applications in imaging, sensing, communications and optical manipulation. Unlike conventional optical components, plasmonic structures manipulate light at the sub-wavelength level in real space or over a wide range of k vectors in wave-vector space.

While interesting PC, discussed in the previous sections are still microlevel constructs. Plasmonics, on the other hand, is an emerging"field of optics aimed at the study of light at the nanometer scale. The goal of plasmonics is to develop new optical components and systems that are the same size as to day's smallest integrated circuits and that could ultimately be integrated with electronics on the same chip. The properties of metallic nano-structures and their near-field properties and applications are currently receiving increased research attention. There is interest in the manipulation and focusing of optical “fields by metal structures with sub wavelength features. Plasmons can be thought of as ripples of waves in the ocean of electrons ”owing across the surface of metallic nano-structures. Plasmonic devices are ultra small metal structures of various shapes that capture and manipulate light; they make use of optical properties of metallic nano-structures[9].

When light is incident upon a metal surface, an unusually strong electromagnetic field may form on the surface. It is in the state where surface plasmons are excited on the metal surface. The enhanced electromagnetic field results from the long propagation length of the surface plasmon, and it enhances fluorescence of dye molecules near the metal surface. Moreover, the electric field can be further enhanced by modulating the metal surface profile with a random corrugation or with a 2-D relief grating. Indeed, a 2-D grating surface carries out Bragg reflection of the surface plasmon, and propagation is forbidden in all in-plane directions in certain frequency regions. We call such a structure and such a forbidden frequency range a plasmonic crystal and a plasmonic band gap, respectively. At the edge frequency of the plasmonic band gap, the surface plasmons serve as standing waves, therefore, photons are confined in three dimensions resulting in a strong enhancement

The plasmonic crystal that we deal here can be regarded as a two dimensional photonic crystal in which photon confinement in the normal direction is performed by surface plasmon polariton instead of waveguide modes .Figure 1.9 shows the dispersion relation of surface plasmon at the interface between a metal and a dielectric medium represented by

$$K_{sp} = \frac{\omega}{c}\sqrt{\frac{\varepsilon_m \varepsilon_d}{\varepsilon_m + \varepsilon_d}} \qquad 1.11$$

where ksp is the wave vector of the surface plasmon, ω is the angular frequency,and ε_m , and ε_d are the dielectric constants of the metal and the dielectric,respectively.

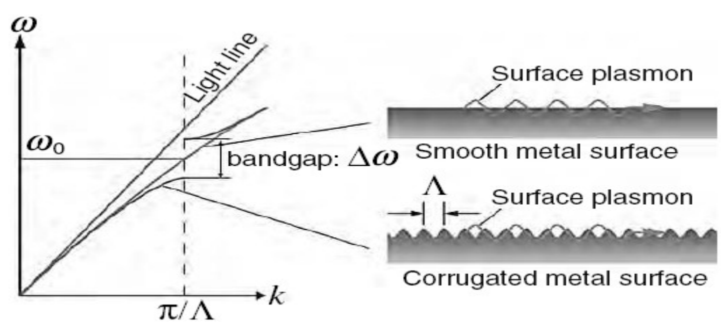


Fig. 1.9 Dispersion relation of surface plasmon traveling on a flat metal surface and a corrugated metal surface [19]

If the interface is smooth, the dispersion relation has no discontinuity. However, if a periodic corrugation is introduced into the interface,the dispersion relation shows band structure and energy gaps. The energy width of the gap depends on the amplitude of the introduced corrugation.

A full energy band gap opens when a two dimensional corrugation is introduced onto metal surfaces. A full band gap means that a gap opens in all in-plane directions, so that in this energy region no surface plasmon can propagate. At the edges of the band gap, called band edges,the group velocity of surface plasmon, which is given by the slope of the dispersion relation, tends to zero and surface plasmons behave as standing waves. Therefore, the density of photons becomes extremely high at the band edges[19].

Therefore, the historical developments of photonic crystals made a transitions to a wise and systematic treatments of various ideas related to the propagation of light by exploiting the band gab principle of semiconductor and Maxwell equations .The next chapter deals the details of maxwell equations and nature of photonic crystals.

Chapter 2

Electronic Maxwell Equations and the Inspiration of Photonic Bandgaps

So as to understand the nature of photon(light modes) we need to get a good insight on the maxwell equations from which the eigenvalue problems of light are to be induced and adopt some ideas of the solid state such us periodicity in a crystal which are governed by Bloch-Floquent theorems. Thus, in this chapter, we review the four macroscopic maxwell equations and their importance in a periodic patterns of materials consistently to Bloch-Floquent theorem. Moreover, we will see the basic idea on the origin and size of photonic crystal.

2.1 Macroscopic Maxwell Equations

All of macroscopic electromagnetism, including the propagation of light in a photonic crystal, is governed by the four macroscopic Maxwell equations[1].

A photonic crystal is characterized by a relative dielectric permitivity ε_r (x, y, z) assumed to be real and periodic along N directions (with N = 1, 2 or 3) and invariant along the other 3 - N orthogonal directions[2]. Our starting points are the four maxwell's equations which are written in CGS form as:

$$\nabla\times\vec{E}=-\frac{1}{c}\left(\partial\vec{B}/\partial t\right) \qquad 2.1$$

$$\nabla\times\vec{B}=\frac{1}{4\pi}\vec{J}+\frac{1}{c}\left[\frac{\partial}{\left(\partial t\right)}\varepsilon\vec{E}\right] \qquad 2.2$$

$$\nabla\cdot\varepsilon\vec{E}=\frac{4\pi}{c}\rho \qquad 2.3$$

and

$$\nabla\cdot\vec{B}=0 \qquad 2.4$$

where $\vec{E}$ and $\vec{B}$ are the electric and magnetic fields, $\vec{J}$ is the free current density, ρ is the free charge density, and ε is the dielectric function; all of these are potentially functions of both the position x and the time t . c , of course, is the speed of light in vacuum.

Recall that a dielectric is a material in which tiny dipoles, the bound charges, line up to oppose any applied electric field—this process is encapsulated entirely by the dielectric function ε. In particular,that will be of interest in photonic crystals. Finally, we assume that we can neglect any absorption of light by the material; in this case, ε is a real number. Furthermore, in optics we are normally interested only in cases where no free charges or currents are included, so $\vec{J}$ and ρ are zero. If we then combine Eq. (2.1) and Eq. (2.2), we can eliminate $\vec{E}$ in favor of B to write:

$$\nabla\times\frac{1}{\varepsilon}\nabla\times B=\frac{\left(\partial^2\right)}{\left(\partial ct^2\right)}\vec{B} \qquad 2.5$$

This equation can be compared to Schrödinger's equation from quantum mechanics, with a Hermitian (self-adjoint) "Hamiltonian" operator $\nabla\times\frac{1}{\varepsilon}\nabla\times$ on the left (instead of Schrödinger's $-\frac{\hbar^2}{2m}\nabla^2+V$ and a time derivative $\partial^2/\partial ct^2$ on the right (instead of $i\partial/\partial t$).Here,1/ε plays a role analogous to that of the potential function V. Next, like in quantum mechanics, we look for time-harmonic states whose time dependence is exp (–iωt) for some (angular) frequency ω - all possible solutions can be expressed via this form, since the equation is linear—and thus Eq. (2.5) becomes:

$$\nabla\times\frac{1}{\varepsilon}\nabla\times B=\left(\frac{\omega}{c}\right)^2\vec{B} \qquad 2.6$$

This is a Hermitian eigen problem over an infinite domain, and generally produces a continuous spectrum of eigen frequencies ω .

We should note one important property of Maxwell's equations in general, and of Eq. (2.6) in particular: they are scale-independent. If you multiply all the dimensions of our system by 10, say, the solutions are exactly the same except that the frequencies are divided by 10. This means that we can solve the equations once and then apply the same results to problems at all length scales and frequencies. Because of this scale invariance, it is convenient to use dimensionless units for distance and time: we pick some natural length scale a in the system (usually the periodicity), and then express all distances as a multiple of a and all angular frequencies ω as a multiple of 2πc⁄a . (This is equivalent to writing the frequencies as a/λ , where λ is the vacuum wavelength.) we consider here the case of linear dielectrics, for which ε is independent of E —this is reasonable, as nonlinear effects in optical materials are typically so weak that you cannot observe them without enormous fields or great distances of propagation. We will also assume that ε is independent of frequency (and therefore independent of time as well), which is reasonable for the relatively narrow frequency ranges[5].

2.2 The Bloch-Floquet Theorem and Electromagnetism

The Bloch-Floquet theorem tells us that, for a Hermitian eigenproblem (or actually, a larger class of differential equations) whose operators are periodic functions of position, the solutions can always be chosen of the form $e^{ik \cdot x}$ (periodic function) . A periodic function f(x) is one such that f (x + R_i) = f (x) for any primitive lattice vector R_i of the crystal—there can be up to three such lattice vectors, if the function is periodic in all three dimensions. A corollary of this theorem is that the wave vector k is a conserved quantity, and hence propagating waves with a fixed k cannot scatter. This theorem is easily proven by noting that the translation operator of the crystal commutes with the Hamiltonian operator, and then recalling that simultaneous eigenfunctions can be chosen for commuting operators. When applied to our situation, the Bloch-Floquet theorem means that the solution of Eq. (2.6) ,for a periodic ε can be chosen of the form:

$$\vec{B} = \exp i\left(\vec{k}\cdot\vec{x} - \omega t\right)\vec{B}_k \qquad 2.7$$

where $\vec{B}_k$ is a periodic function of position. If we substitute Eq. (2.7) into Eq. (2.5), we find that the function $\vec{B}_k$ satisfies the "reduced" Hermitian eigenproblem:

$$(\nabla + i\vec{k}) \times \frac{1}{\epsilon}(\nabla + i\vec{k}) \times \vec{B}_k = \left(\frac{\omega}{c}\right)^2 \vec{B}_k \qquad 2.8$$

Because B_k is periodic, we need only to consider this eigenproblem over a finite domain: the unit cell of the periodicity. There is a general theorem that eigenproblems with a finite domain have a discrete set of eigenvalues. Thus, the eigenfrequencies ω are a countable sequence of continuous functions: $\omega_n(k)$ (for n = 1, 2, 3, ...). When they are plotted as a function of the wave vector k , these frequency "bands" form the band structure of the crystal.

Another important consequence of the Bloch-Floquet theorem is that the solutions are periodic as a function of the wave vector k ; this is easy to see if we examine a one-dimensional example. Suppose that we have a one-dimensional structure with period a (ε (x + a) = ε (x)) and consider the eigenstates for the wave vector k + 2π ⁄ a . The function $e^{i2\pi x/a}$ is periodic (with period a), however, so this part of Eq. (2.7) can be absorbed into the function B_k ! Since the resulting expression then solves the eigenproblem for a wave vector k, and those solutions are unique, we can therefore conclude that the eigensolutions at k +2π /a are the same as those at k. Because k is only unique to within multiples of 2π /a, then, it is sufficient to only solve the eigenproblem for k in a finite range -

$\pi/a, \ldots \pi/a$, called the first Brillouin zone. Moreover, we usually have additional symmetries that further reduce the range of unique wavevectors—for example, time-reversal symmetry tells us that k and – k produce the same results, so in this case we can look at just $k = 0 \ldots \pi/a$ **.** This symmetry-reduced region is called the irreducible Brillouin zone [5].

2.3 The origin of photonic crystal

Complete photonic band gap is a range of ω in which there are no propagating (real k) solutions of Maxwell's equations for any k, surrounded by propagating states above and below the gap. There are also incomplete gaps, which only exist over a subset of all possible wave vectors, polarizations, and/or symmetries. In either case their origins are the same, and can be understood by examining the consequences of periodicity for a simple one-dimensional system. Consider a one-dimensional system with uniform $\varepsilon = 1$, which has plane wave eigen solutions $\omega(k) = ck$, as depicted in Fig.1.1(left). This ε has trivial periodicity a for any $a \geq 0$, with $a = 0$ giving the usual unbounded dispersion relation. We are free, however, to label the states in terms of Bloch envelope functions and wave vectors for some $a \neq 0$ **,** in which case the bands for $|k| > \pi/a$ are translated ("folded") into the first Brillouin zone, as shown by the dashed lines in Fig. 2.1(left). In particular, the $k = -\pi/a$ mode in this description now lies at an equivalent wave vector to the $k = \pi/a$ mode, and at the same frequency; this accidental degeneracy is an artifact of the "artificial" period we have chosen. Instead of writing these wave solutions with electric fields $IE(x) \sim e^{\pm i\pi x/a}$, we can equivalently write linear combinations $e(x) = \cos(\pi x/a)$ and $o(x) = \sin(\pi x/a)$ as shown in Fig. 2.3, both at $\omega = c\pi/a$. Now, however, suppose that we perturb ε so that it is non trivially periodic with period a; for example, a sinusoid $\varepsilon(x) = 1 + \Delta \cdot \cos(2\pi x/a)$, or a square wave as in the inset of Fig 2.1. In the presence of such an oscillating "potential," the accidental degeneracy between e(x) and o(x) is broken: supposing $\Delta > 0$, then the field e(x) is more concentrated in the higher-ε regions than o(x), and so lies at a lower frequency. This opposite shifting of the bands creates a band gap, as depicted in Fig.2.1(right). (In fact, from the perturbation theory described subsequently, one can show that for $\Delta \ll 1$ the band gap, as a fraction of mid-gap frequency, is $\Delta\omega/\omega \simeq \Delta/2$) .

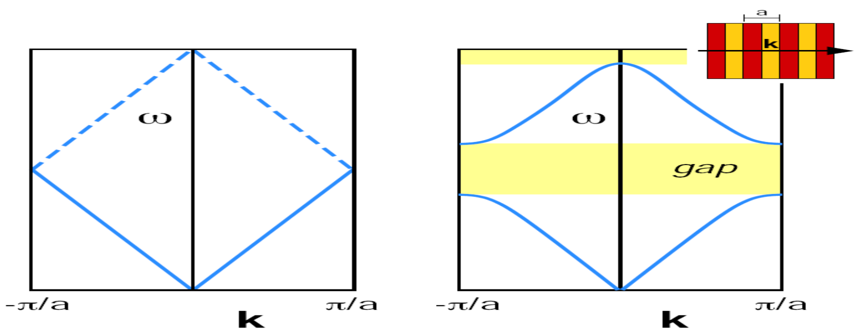


Fig 2.1: Left, Dispersion relation (band diagram), frequency ω versus wavenumber k, of a uniform one dimensional medium, where the dashed lines show the "folding" effect of applying Bloch's theorem with an artificial periodicity a . Right,Schematic effect on the bands of a physical periodic dielectric variation(inset), where a gap has been opened by splitting the degeneracy at the k = ±/a Brillouin-zone boundaries (as well as a higher-order gap at k = 0) [3]

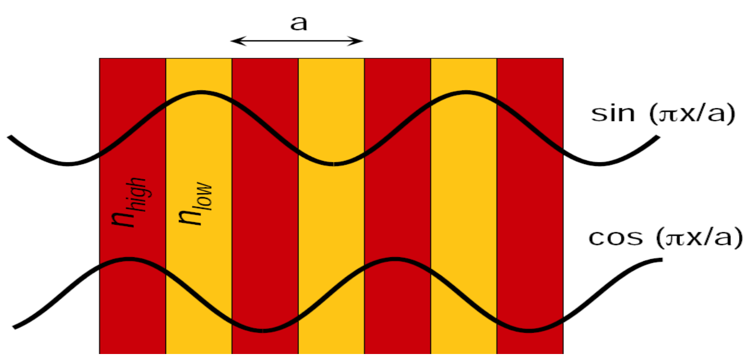


Figure 2.2: Schematic origin of the band gap in one dimension. The degenerate k = ±/a plane waves of a uniform medium are split into cos(x/a) and sin(x/a) standing waves by a dielectric periodicity, forming the lower and upper edges of the band gap, respectively—the former has electric-field peaks in the high dielectric (n_{high}) and so will lie at a lower frequency than the latter(which peaks in the low dielectric) [3].

By the same arguments, it follows that any periodic dielectric variation in one dimension will lead to a band gap, albeit a small gap for a small variation; a similar result was identified by Lord Rayleigh in 1887. More generally, it follows immediately from the properties of Hermitian eigen systems that the eigenvalues minimize a variational problem:

$$\left(\omega_{nk}\right)^2 = \frac{min}{\vec{E}_{nk}} \frac{\left(\int | \ (\nabla + ik) \times \vec{E}_{nk} \ |^2 c^2\right)}{\left(\int \ | \varepsilon En,k |^2\right)} \qquad 2.9$$

in terms of the periodic electric field envelope $E_{n,k}$, where the numerator minimizes the "kinetic energy" and the denominator minimizes the "potential energy." Here, the n > 1 bands are additionally constrained to be orthogonal to the lower bands:

$$\int \vec{H}_{mk} \cdot \vec{H}_{nk} = \int \varepsilon \vec{E}_{mk} \cdot \vec{E}_{nk} = 0 \qquad 2.10$$

for m < n

Thus, at each k, there will be a gap between the lower "dielectric" bands concentrated in the high dielectric (low potential) and the upper "air"bands that are less concentrated in the high dielectric: the air bands are forced out by the orthogonality condition, or otherwise must have fast oscillations that increase their kinetic energy. In order for a complete band gap to arise in two or three dimensions, two additional hurdles must be overcome. First, although in each symmetry direction of the crystal (and each k point) there will be a band gap by the one-dimensional argument, these band gaps will not necessarily overlap in frequency (or even lie between the same bands). In order that they overlap, the gaps must be sufficiently large, which implies a minimum ε contrast (typically at least 4/1 in 3d). Since the 1d mid-gap frequency $\sim c\pi/a\sqrt{\varepsilon}$ varies inversely with the period a, it is also helpful if the periodicity is nearly the same in different directions—thus, the largest gaps typically arise for hexagonal lattices in 2d and fcc lattices in 3d, which have the most nearly circular/spherical Brillouin zones. Second, one must take into account the vectorial boundary conditions on the electric field: moving across a dielectric boundary from ε to some ε' < ε, the inverse "potential" $\varepsilon|E|^2$ will decrease discontinuously if E is parallel to the interface (E is continuous) and will increase discontinuously if E is perpendicular to the interface ($\varepsilon E\perp$ is continuous). This means that, whenever the electric field lines cross a dielectric boundary, it is much harder to strongly contain the field energy within the high dielectric, and the converse is true when the field lines are parallel to a boundary. Thus, in order to obtain a large band gap, a dielectric structure should consist of thin, continuous veins/membranes along which the electric field lines can run—this way, the lowest band(s) can be strongly confined, while the upper bands are forced to a much higher frequency because the thin veins cannot support multiple modes (except for two orthogonal polarizations). The veins must also run in all directions, so that this confinement can occur for all k and polarizations, necessitating a complex topology in the crystal[3].

2.4 The Size of the Band Gap

The extent of a photonic band gap can be characterized by its frequency width Δω, but this is not a really useful measure. Remember from the Scaling Properties of the Maxwell Equations that all of our results are scalable. If the crystal were expanded by a factor s, the corresponding band gap would have a width $\Delta\omega$/s. A more useful characterization, which is independent of the scale of the crystal, is the gap–midgap ratio. Letting ω_m be the frequency at the middle of the gap, we define the gap–midgap ratio as $\Delta\omega/\omega m$, generally expressed as a percentage (e.g., a "10% gap" refers to a gap–midgap ratio of 0.1). If the system is scaled up or down, all of the frequencies scale accordingly, but the gap–midgap ratio remains the same. Thus, when we refer to the "size" of a gap, we are generally referring to the gap midgap ratio. For the same reason, in the band diagrams in figure 2.1, as well as all of the other band diagrams, the frequency and wave vector are plotted in dimensionless units $\omega a/2\pi c$ and $ka/2\pi$. The dimensionless frequency is equivalent to a/λ, where λ is the vacuum wavelength (given by $\lambda = 2\pi c/\omega$).

We are emphasizing general principles of periodic systems that will apply equally well to the more complicated two- and three-dimensional structures . It is worthwhile, however, to point out a few exceedingly useful analytical results that are only possible for the special case of one-dimensional problems. In a multilayer film with weak periodicity, we can derive a simple formula for the size of the band gap from the Effect of Small Perturbations . Suppose that the two materials in a multilayer film have dielectric constants ε and $\varepsilon + \Delta\varepsilon$, and thicknesses $a - d$ and d. If either the dielectric contrast is weak ($\Delta\varepsilon/\varepsilon << 1$) or the thickness d/a is small, then the gap–midgap ratio between the first two bands is approximately

$$\Delta\omega/\omega m \approx \left(\Delta\varepsilon/\varepsilon\right)\frac{\sin\left(\pi d/a\right)}{\pi} \qquad 2.11$$

This quantifies our previous statement that even an arbitrarily weak periodicity gives rise to a band gap in a one-dimensional crystal. For one of the structures considered in the previous section, with $\Delta\varepsilon/\varepsilon = 1/12$ and $d = 0.5a$, the perturbative formula (2.11) predicts a 2.65% gap, which is in good agreement with the results of a more accurate numerical calculation (2.55%). Equation (2.11) would predict that the gap–midgap ratio is maximized for $d = 0.5a$, but this is valid only for small $\Delta\varepsilon/\varepsilon$. More generally, one can obtain a number of analytical results for arbitrary $\Delta\varepsilon/\varepsilon$, which we summarize here . For two materials with refractive indexes($\sqrt{\varepsilon}$) n_1 and n_2 and thicknesses d_1 and $d_2 = a-d1$, respectively, the normal-incidence gap is maximized when $d_1 n_1 = d_2 n_2$, or, equivalently, $d_1 = an_2/(n_1 + n_2)$. In this specific case, it can be shown that the midgap frequency ωm is

$$\omega_m = \frac{n_1+n_2}{4n_1 n_2}\cdot\frac{2\pi c}{a} \qquad 2.12$$

The corresponding vacuum wavelength $\lambda m = 2\pi c/\omega m$ satisfies the relations $\lambda m/n_1 = 4d_1$ and $\lambda m/n_2 = 4d_2$, which means that the individual layers are exactly a quarter-wavelength in thickness. For this reason, this type of multilayer film is called a quarter-wave stack. The reason why the gap is maximized for a quarter-wave stack is related to the property that the reflected waves from each layer are all exactly in phase at the midgap frequency.

2.5 Microcavities in Photonic Crystals

As we have tried to state the localization of light modes above, introducing a point defect in a PC can make a microcavity. As such, the defect can have any shape, size, or dielectric constant. By varying any one of these parameters, the number of modes and the center frequency of the localized mode, or modes, inside the cavity can be changed.

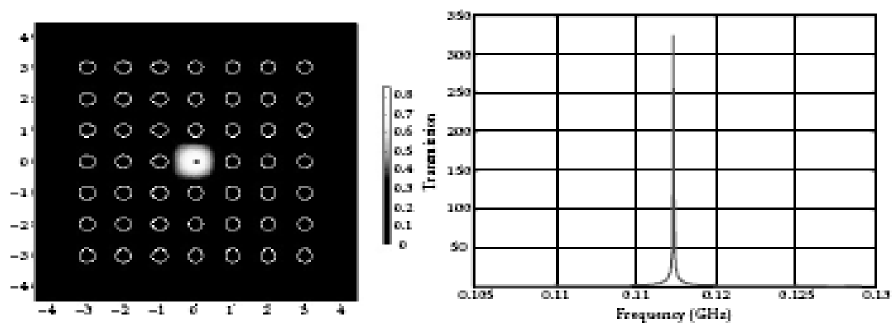


Figure 2.3 *A micro cavity built in a PBG by removing a single rod from the center of a rectangular unit lattice. FDTD simulation is on the left, and the spectral result for the field inside the cavity is on the right [6]*

If we consider the case of a square lattice of cylindrical rods with a difference in dielectric constant much greater than 2**,** between the host material and the lattice material, we can introduce a point defect by simply changing one of the parameters of a given rod within the crystal. For example, a point defect consisting of a rod with a radius smaller than those surrounding it will guarantee a single mode to be localized at the point defect. Alternatively, as we increase the radius of the defect, to be equal to or greater than those surrounding it, we will introduce a multiple of closely separated modes localized within the cavity.

Chapter 3

Propagation of Light in Periodic Media

In order to get deep understanding on the behavior of photonic crystals, we will first study electromagnetic waves in a homogeneous and 1-D periodic medium. We will then extend these insights to more dimensions, and apply them to 2-D&3-D photonic crystals. The optical properties of a one-dimensional layered system may be familiar, but by expressing the results in the language of band structures and band gaps, we can discover new phenomena such as omni-directional reflectivity, as well as prepare for the more complicated two- and three-dimensional systems that lie ahead.

3.1 Light in Homogeneous Media

As we have seen in the previous chapter light is a form of electromagnetic radiation, which is governed by Maxwell's equations and can be rewritten as follow

$$\nabla \times \vec{E} = -\partial \vec{B} / \partial t \qquad 3.1$$

$$\nabla \times \vec{B} = \vec{J} + \partial \vec{D} / \partial t \qquad 3.2$$

$$\nabla \cdot \vec{D} = \rho \qquad 3.3$$

$$\nabla \cdot \vec{B} = 0 \qquad 3.4$$

In a macroscopic world, where we disregard the quantum nature of matter, the electromagnetic fields are linked by constitutive relations:

$$\vec{D} = \varepsilon_r \varepsilon_0 \vec{E} \quad where \varepsilon = \varepsilon_r \varepsilon_0$$

$$\vec{B} = \mu_r \mu_0 \vec{H} \quad where \mu = \mu_r \mu_0 \qquad 3.5$$

In free space, or in a linear, isotropic and homogeneous (LIH) medium, ε_r and μ_r are a scalar function of the frequency. For our convenience, we also assume that there is no material dispersion, hence no frequency dependence, so ε_r and μ_r are constant. When we now insert the constitutive relationships for these materials into the Maxwell equations, and set all currents J to zero, we can rewrite the equations in the following form:

$$\nabla^2 \vec{E}(r,t) - \varepsilon \mu \partial^2 / \partial t^2 \vec{E}(r,t) = 0$$

$$\nabla^2 \vec{B}(r,t) - \varepsilon \mu \partial^2 / \partial t^2 \vec{B}(r,t) = 0 \qquad 3.6$$

The solutions of these wave equations are plane waves, traveling at the speed **v**, which is determined by the dielectric constant and magnetic permittivity μ of the material:

$$v=\frac{1}{\sqrt{\varepsilon\mu}}=\frac{c}{\sqrt{(\varepsilon_r \mu_r)}}=\frac{c}{n} \qquad 3.7$$

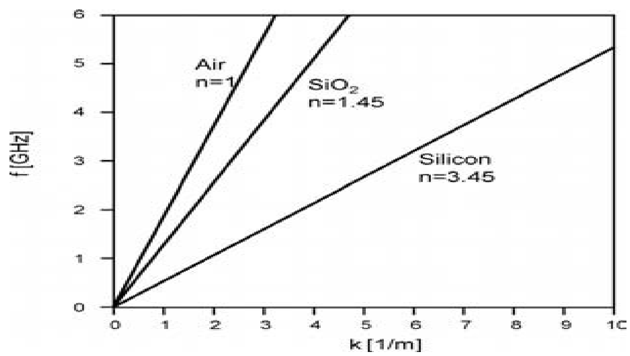


Figure 3.1: The dispersion relation for LIH media with refractive index n of 1 (Air), 1.45 (Silica or glass) and 3.45 (Silicon)[4].

with c the speed of light in vacuum, and n the index of refraction. We can thus rewrite the equations as

$$\left(\frac{c^2}{n^2}\right)\nabla^2 \vec{E}(r,t)-\partial^2/\partial t^2 \vec{E}(r,t)=0$$

3.8

$$\left(\frac{c^2}{n^2}\right)\nabla^2 \vec{B}(r,t)-\partial^2/\partial t^2 \vec{B}(r,t)=0$$

The general solution for the electric field E on time t and in position r is a superposition of plane waves of the form

$$\vec{E}(r,t)=ReE_0\exp(j\vec{k}\cdot r.e-j\omega t) \qquad 3.9$$

where E_0 is complex, describing both the amplitude and the phase of the plane wave. f is the frequency of the plane wave, and is related to ω as ω = 2πf, $\vec{k}$ is the wave vector, indicating the propagation direction of the wave. The magnitude of **k**, k is linearly dependent on f , or ω:

$$\frac{\omega}{\|\vec{k}\|}=\frac{\omega}{k}=\frac{c}{n} \qquad 3.10$$

The relation between k and f or ω is called the dispersion relation and is of course dependent on the medium through the refractive index n. Figure 3.1 shows the dispersion relation for a plane wave propagating in the x direction in vacuum (n = 1), in glass (n = 1.45) and in Silicon (n = 3.45) in a **f‖k** diagram. We see that the slope of the dispersion curve is lower as the refractive index of the material increases

3.2 One-D Periodic Media

Plane waves describe the propagation of light in a uniform medium. However, photonic crystals are far from uniform, and the wave equation for E will change to

$$\frac{c^2}{n^2(r)}\nabla^2 \vec{E}(r,t) - \partial^2/\partial t^2\, \vec{E}(r,t) = 0 \qquad 3.11$$

To simplify the problem, let's consider a one-dimensional medium,with waves propagating along the z-axis. This simplifies the wave equation:

$$\frac{c^2}{n^2(z)}\nabla^2 \vec{E}(r,t) - \partial^2/\partial t^2\, \vec{E}(r,t) = 0$$

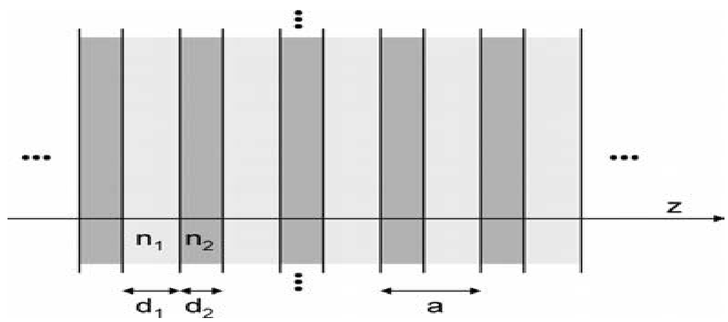


Figure3.2: A 1-D periodic medium consisting of a stack of piecewise constant refractive index materials [4].

In a homogeneous medium, where n (z) is constant, the solution of the wave equation will become a plane wave traveling in the +z or −z direction:

$$\vec{E}(r,t) = Re E_0 \exp\left(j\vec{k}\cdot z.e - j\omega t\right) \qquad 3.12$$

Let us now consider an infinite 1-D periodic medium with period a,like the layer structure in figure 3.4, n(z) becomes a periodic function of z. We consider the problem to be uniform in the other directions and only study waves traveling along the z-axis. According to the Floquet-Bloch theorem the solution of the wave equation is of the form

$$\vec{E}(r,t) = Re\left[u_k(z) \exp jkz(w)\cdot z.e - j\omega t\right] \qquad 3.14$$

where $u_k(z)$ is periodic with the same period a as n(z). For linear materials, the general solution consists of a linear superposition of these Floquet-Bloch waves. Note that we have now introduced a preferential scale, and that the solutions of the wave equation do not scale arbitrarily, but scale with the period a. For this periodic medium, k_z is no longer linearly dependent on ω Or f, and for each frequency there are an infinite number of solutions for k_z that are coupled to one another by the periodic lattice.

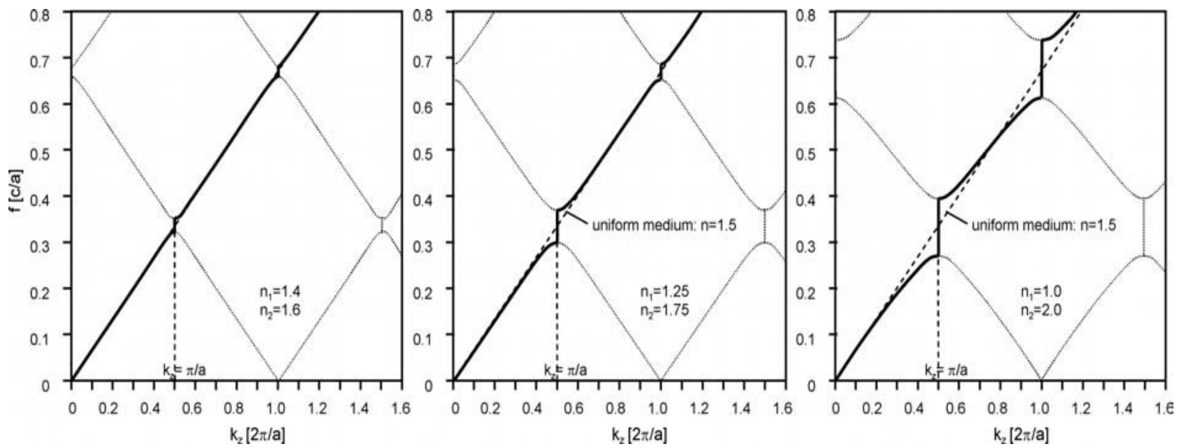


Figure 3.3: The dispersion relation for the 1-D periodic medium of figure 3.2 with (a) n1 = 1.4 and n2 = 1.6, (b) n1 = 1.25 and n2 = 1.75, (c) n1 =1 and n2 = 2. n1d1 = n2d2. The linear dispersion relation of a uniform medium with n = 1.5 is also plotted zone [4]

In figure 3.3 we can see the dispersion relation change as we increase the refractive index contrast in the layer structure. We can see that the dispersion relation is periodic in k_z with a period $2\pi/a$, and symmetric around k = 0. Because of the lattice periodicity all points in the k-space are coupled to a point in the interval $[-\pi/a, \pi/a]$, called the first Brillouin zone. Because of the reciprocity of the Maxwell equations in the absence of an external magnetic field, the dispersion relation in the −z direction is the same as in the +z direction. It therefore suffices to study the dispersion relation for $k \in [0,\pi/a]$, the reduced first Brillouin zone,or just the reduced Brillouin zone. The branches with a positive (upward) slope represent forward propagating waves coupled to the lattice. The branches with a downward slope are the result of the light propagating in the −z direction, but coupled by a lattice vector to the first reduced Brillouin zone. From the group velocity given by

$$v_g = \partial\omega/\partial k = 2\pi\partial f/\partial k \qquad 3.15$$

the slope of the dispersion relation, written as , these branches have a negative group velocity. Therefore, the phase fronts will propagate in the opposite direction as the modulation envelope of the light. For low frequencies, the material behaves more or less like a homogeneous medium, because the period a is much smaller than the wavelength of the light, and index variations are averaged out. However,for higher frequencies, k_z no longer behaves linearly, but splits in 2 branches that flatten out. In the area with low slope, the group velocity v_g of the light waves becomes very small, and the light comes to a halt, resulting in a standing wave at the point where the dispersion is horizontal. In the frequency interval between the two branches, there is no real solution for k_z, but k_z becomes complex. The imaginary part translates into an attenuation in the propagation direction.

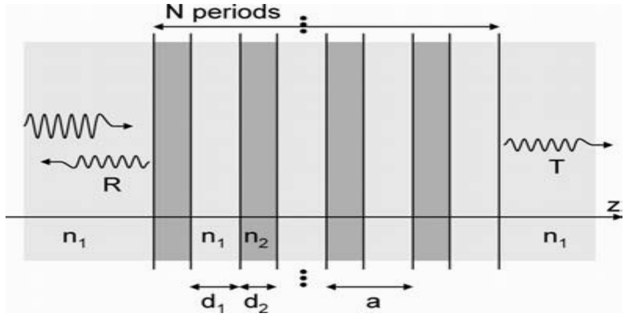


Figure 3.4: A finite 1-D Bragg stack with N periods. The incident plane wave from the homogeneous medium is partly reflected and partly transmitted [4].

In an infinite periodic medium, this means no propagating mode is possible in that frequency range. The frequency or wavelength range in which this happens is called the photonic band gap or PBG, and gets larger for higher index contrast in the periodic structure. The frequency domain is split up by the dispersion relation into photonic bandgaps or stop bands and transmission or pass bands. Because of this, we call the dispersion plot of a periodic structure a band diagram[4].

3.3 Two-D Periodic Structures

After the identification of one-dimensional band gaps, it took a full century to add a second dimension, and three years to add the third. It should therefore come as no surprise that 2d systems exhibit most of the important characteristics of photonic crystals, from nontrivial Brillouin zones to topological sensitivity to a minimum index contrast, and can also be used to demonstrate most proposed photonic-crystal devices. The key to understanding photonic crystals in two dimensions is to realize that the fields in 2d can be divided into two polarizations by symmetry: TM (transverse magnetic), in which the magnetic field is in the (xy) plane and the electric field is perpendicular (z); and TE (transverse electric), in which the electric field is in the plane and the magnetic field is perpendicular[3].

A two-dimensional photonic crystal is periodic along two of its axes and homogeneous along the third axis. A typical specimen, consisting of a square lattice of dielectric columns, is shown in figure 1.2. We imagine the columns to be infinitely tall. For certain values of the column spacing, this crystal can have a photonic band gap in the xy plane. Inside this gap, no extended states are permitted, and incident light is reflected. Unlike the multilayer film, this two-dimensional photonic crystal can prevent light from propagating in any direction within the plane [1].

Corresponding to the polarizations, there are two basic topologies for 2-D photonic crystals, as depicted in Fig.3.5(top): high index rods surrounded by low index (top) and low-index holes in high index (bottom). Here, we use a hexagonal lattice because, it gives the largest gaps. Recalling that a photonic band gap requires that the electric field lines run along thin veins: thus, the rods are best suited to TM light (E parallel to the rods), and the holes are best suited to TE light (E running around the holes). This preference is reflected in the band diagrams, shown in Fig. 3.6 in which the rods/holes (top/bottom) have a strong TM/TE band gap. For these diagrams, the rod/hole radii is chosen to be 0.2a/0.3a, where a is the lattice constant (the nearest neighbor periodicity) and the high/low ε is 12/1. The TM/TE band gaps are then 47%/28% as a fraction of mid-gap frequency, but these band gaps require a minimum ε contrast of 1.7/1 and 1.9/1, respectively. Moreover, it is conventional to give the frequencies ω in units of $2\pi c/a$, which is equivalent to a/λ (λ being the vacuum wavelength)—Maxwell's equations are scale-invariant, and the same solutions can be applied to any wavelength simply by choosing the appropriate a. For example, the TM mid-gap ω in these units is 0.36, so if one wanted this to correspond to $\lambda = 1.55\mu m$ one would use $a = 0.36 \cdot 1.55\mu m = 0.56\mu m$. The Brillouin zone (a hexagon) is shown in the inset, with the irreducible Brillouin zone shaded (following the sixfold symmetry of the crystal); the corners (high symmetry points) of this zone are given canonical names, where Γ always denotes the origin $k = 0$, K is the nearest-neighbor direction, and M is the next-nearest-neighbor direction. The Brillouin zone is a two-dimensional region of wave vectors, so the bands $\omega_n(k)$ are actually surfaces, but in practice the band extrema almost always occur along the boundaries of the irreducible zone (i.e. the high-symmetry directions). So, it is conventional to plot the bands only along these zone boundaries in order to identify the band gap, as is done in Fig. 3.5

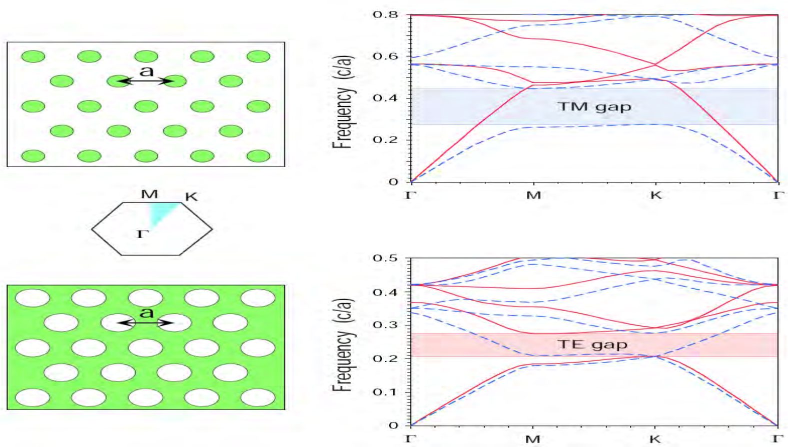


Figure 3.5: Band diagrams and photonic band gaps for hexagonal lattices of high dielectric rods(ε =12, r = 0.2a) in air (top), and air holes (r = 0.3a) in dielectric (bottom), where a is the center- center periodicity. The frequencies are plotted around the boundary of the irreducible Brillouin zone (shaded triangle, left center), with solid-red/dashed-blue lines denoting TE/TM polarization (electric field parallel/perpendicular to plane of periodicity).The rods/holes have a gap the TM/TE bands [3]

Actually, the hole lattice can display not only a TE gap, but a complete photonic band gap (for both polarizations) if the holes are sufficiently large (nearly touching). In this case, the thin veins between nearest-neighbor holes induce a TE gap, while the interstices between triplets of holes form "rod-like" regions that support a TM gap overlapping the TE gap. Thus ,2-D PCs can be realized using either a periodic array of dielectric rods of any shape or geometry, or a perforated dielectric slab of air holes. Such structures can be further optimized to achieve a wider, or a narrower, band gap based on the desired application [5].

3.5 Three-Dimensional Photonic Crystals

The optical analogue of an ordinary crystal is a three-dimensional photonic crystal: a dielectric structure that is periodic along three different axes. Three dimensional photonic crystal shows many properties such as, band gaps, defect modes, and surface states[1].

Just as in two dimensions, we can localize light at a defect or at a surface, but with a three-dimensional crystal we have the additional capability to localize light in all three dimension. The realization of a complete photonic band gap for any direction of propagation and for any polarization of the field can be achieved only with three-dimensional photonic crystals. From the beginnings of research on photonic crystals, numerous attempts were directed toward achieving this objective, and the simplest types of three-dimensional lattices (simple cubic lattice, centered cubic lattice, face centered cubic lattice) were investigated for this purpose. However, most of these attempts failed. The structures investigated at this time were often found to behave like semi-metals, where electronic gaps disappear for certain specific directions within the solid state crystal. very large omni-directional photonic band gaps were then predicted before being reported in the microwave region. Since these pioneering works, a variety of different technological approaches have been explored in order to reproduce the original experiments at shorter wavelengths, and with other types of materials. In the course of these developments, some of the cubic structures, which had been abandoned after the discovery of the Yablonovite, came to reconsidered.

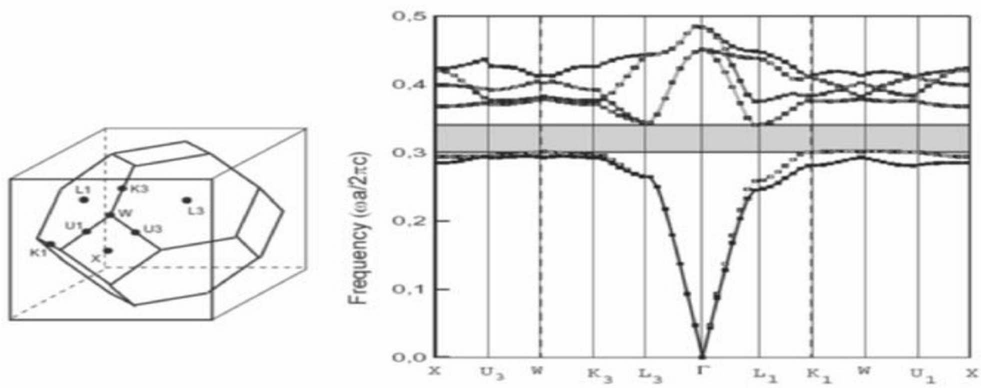


Fig. 3.6 Brillouin zone of the fcc lattice and band diagram of the Yablonovite structure calculated for the first six bands. The permittivity of the dielectric is ε_r = 13, while the ratio between the radius of the holes   and the period of the crystal is such that the air-filling factor is equal to 57% after drilling the holes [2].

In Fig. 3.6, the dielectric substrate is assumed to have a permittivity ε_r = 13, and the ratio between the radius of the holes and the period of the lattice is such that the air-filling factor is equal to 57% after drilling the holes. The Brillouin zone of a Yablonovite is simply that of the fcc lattice, i.e. a truncated octahedron with a nearly spherical shape. The high degree of isotropy presented by such a structure obviously increases the probability for omni-directional band gaps to appear. As can be seen, a complete photonic band gap with a relative width $\nabla\omega/\omega$ equal to 15 percent appears for any direction of propagation and any polarization of the field between the second and the third transmission bands. Of all the parameters of the structure, the air-filling factor and the permittivity (or refractive index) contrast have the main influence on the width of the gap. Accordingly, high values for the air-filling factor and the index contrast tend to result in larger bad gaps. The systematic study on this influence has shown that, for an air filling factor equal to ~60%, a complete band gap appears if and only if the dielectric permittivity is higher than ~ 6, or equivalently if the refractive index is higher than ~ 2.5 [2].

3.6 Defect in Photonic crystals

Introducing a defect in a photonic crystal breaks the translation symmetry of the periodic structure. Therefore, a new state can be created in the photonic bandgap, allowing light to exist in the neighborhood of the defect. However,because the defect is surrounded by photonic crystal,the light cannot propagate away from the defect. In this way,we can create a cavity from which light cannot escape,or a line defect where light can only propagate up and down the direction of the defect. For a finite photonic crystal,the transition surface between the periodic structure and the uniform medium is also a defect,where under some conditions bound states can exist [4].

In the strict sense of the term, the translational symmetry of the crystal disappears as soon as the periodicity is disrupted due to the insertion of defects, with the consequence that Bloch modes are no longer solutions of Maxwell's equations. In the same way as for solid state crystals, two main types of defects exist:point defects and extended defects. Point defects are associated to very local disruptions in the periodicity of the crystal, and their presence is revealed by the appearance of electromagnetic modes at discrete frequencies, which can be viewed as the analogues of isolated electronic states. In the same manner, extended defects can be seen as analogous to the dislocations of a solid state crystal, and they may result in the appearance of transmission bands in spectral regions where a photonic band gap previously existed in the case of a perfectly periodic crystal [2].

Just like the photonic crystal can be periodic in 1, 2 or 3 dimensions, so can the defects be either point-like, or localized along a line or a plane. Figure 3.7 illustrates some defects in a 2-D triangular lattice. Since introducing a defect in a photonic crystal breaks the translation symmetry of the periodic structure, a new state can be created in the photonic band gap, allowing light to exist in the neighborhood of the defect. However, because the defect is surrounded by photonic crystal, the light cannot propagate away from the defect. In this way, we can create a cavity from which light cannot escape, or a line defect where light can only propagate up and down the direction of the defect. For a finite photonic crystal, the transition surface between the periodic structure and the uniform medium is also a defect, where under some conditions bound states can exist.

In a cavity in a 3-D periodic photonic crystal, light can be perfectly confined. A light emitter in that cavity can therefore only generate light in the bound state of the cavity. If we now provide a single escape route from that cavity, e.g. by limiting the number of periods on one side of the cavity, the light in the cavity will couple to that single radiating mode. Because this is the only way light can exit the cavity, the light source in the cavity can be 100% efficient .For integrated photonics, the use of photonic crystals is very attractive. Because in a photonic crystal line defect the light is bound to the line defect, it can only travel back and forth along this defect for wavelengths in the photonic bandgap .

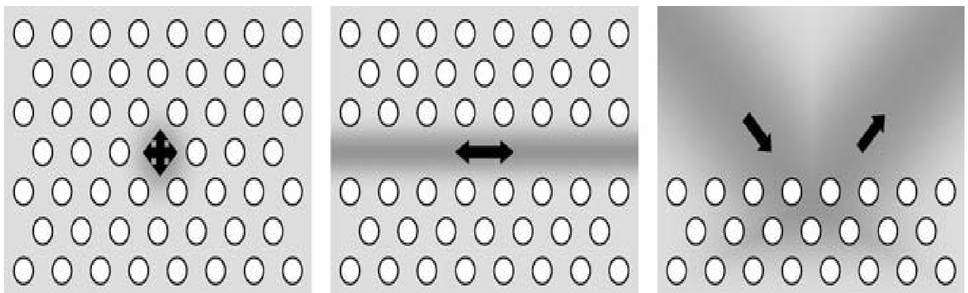


Figure 3.7: Defects in a 2-D photonic crystal. Left to right: a cavity point-defect, a line defect of smaller holes, a surface defect (which, for a 2-D periodic structure, is also a 1-D defect.) [4]

This creates a very effective waveguide. If we now bend this waveguide, as illustrated in figure 3.8,light propagating through it cannot leave the defect, but only continue to propagate through the bend or return along the waveguide .

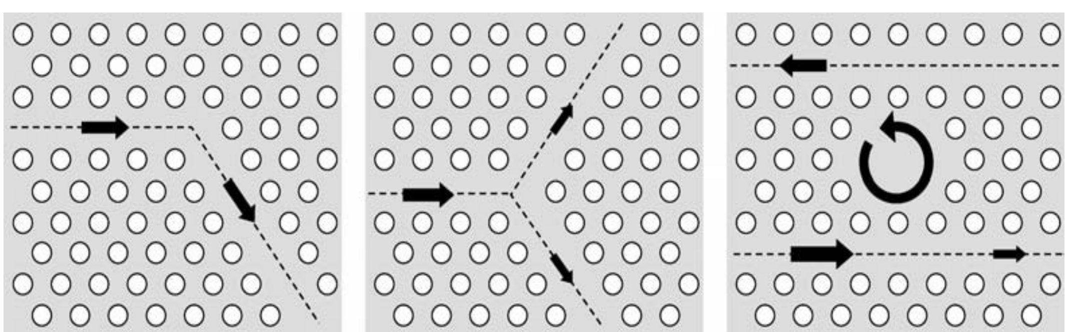


Figure 3.8 : 2-D photonic crystal components. Left to right: a 60° bend, a splitter, a cavity drop filter [4]

A good design of the bend geometry can maximize the bend transmission and eliminate the back reflection[4].

3.7 Photonic Crystal Slabs

While 3-D photonic crystals show the most promise with respect to confinement, 2-D photonic crystals are much easier to fabricate. However,in a 2-D structure which is uniform in the third direction, light will diffract and radiate away. Therefore, light has to be bound in the plane of the photonic crystal. This can be done by combining the 2-D photonic crystal with a slab waveguide in the third direction, as illustrated in figure 3.9. Parallel to the layer structure of the slab waveguide, light is controlled by the 2-D photonic crystal, either propagating through a lattice or along a defect. In the vertical direction, light is bound to the slab waveguide by the layer with the higher refractive index, the slab waveguide core. We call these structures photonic crystal slabs or planar photonic crystals.

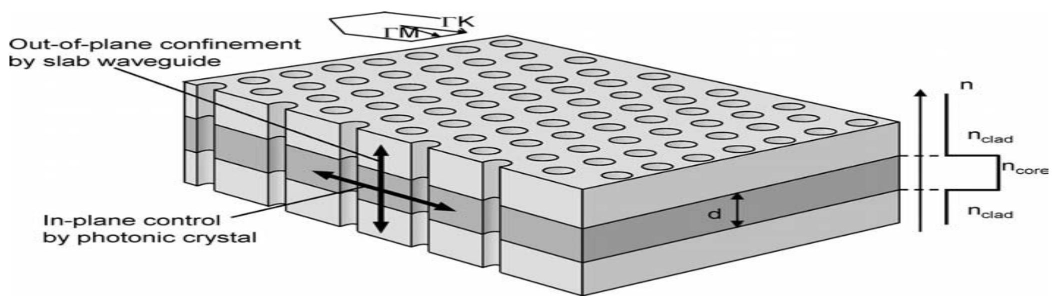


Fig3..9 : 2-D photonic crystal slab. In-plane, light is controlled by the photonic crystal, while in the vertical direction, it is confined by the layer with the higher refractive index [4].

These 2-D photonic crystal slab waveguides are far more easy to make than the 3-D periodic structures. The layered slab waveguide can be made by growing or depositing a layer structure, and the photonic crvstal can be made by defining the structure with lithography and etching them into the slab waveguide.

Chapter 4

Applications of Photonic Crystal

As has been seen in the preceding chapters, photonic crystals in the near infrared and visible regions were primarily conceived for the purpose of achieving a complete control of electromagnetic waves in semiconductor materials. At the same time, however, various hitherto unforeseen applications involving other types of materials have progressively appeared along the 'tree' of photonic crystals.[2] Some among the many applications of phtonic crystals and plasmonic crystals are going to be dealt one by one in this chapter in relation to the previous discussions .

4.1 Low-Loss Optical Waveguides

When line defects are introduced into a PC lattice, an electromagnetic wave having a frequency within the bandgap of the structure can be guided through the crystal. In this case, the line defect resembles a waveguide, as shown in Figure 4.1. In this way, line defects can be formed by either adding or removing dielectric material to a certain row or column along one of the directions of the PC. To this end, PC waveguides can be used as an optical wire to guide an optical signal between different points, or devices, within an optical integrated circuit or an optical network.

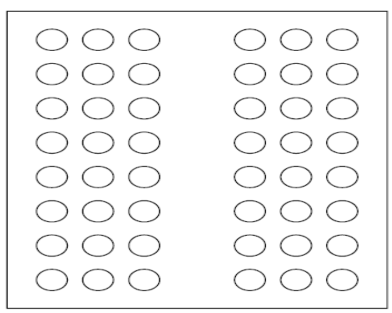


Fig 4.1 *A wave guide created in a photonic crystal by introducing line defect by either removing or adding dielectric to a certain row or column [6].*

To create such a channel, one can decrease the radius of a certain row to the point that it no longer exists. By doing so, it has been created a waveguide that has a width of

$$W_{grect} = (\Omega + 1) a - 2\mathrm{r} \qquad 4.1$$

where Ω is the number of rows or columns, where the line defect will be created, and r the radius of the rods from which the PC was created. The width of the line defect/waveguide is proportional to the number of guided modes for a certain wave vector. Field patterns for every eigenmode, as well as energy flow, can also be calculated using the FDTD method on the 2-D structure presented above. Waveguides can also be created on a 2-D triangular lattice PC of air holes in silicon (Si) background, for which TE modes can be guided through a line defect. In such a structure, the line defect is created in the crystal by increasing the dielectric constant of the line defect, as opposed to decreasing the dielectric constant of the line defect for the 2-D rectangular lattice case, which was used to guide TM waves. For the triangular lattice, the waveguide width can be calculated using

$$W_{gtri} = (\Omega + 1)\left(\frac{\sqrt{3}}{2}\right)a - 2\mathrm{r} \qquad 4.2$$

Note that for the case of a perforated dielectric slab, elimination of a single row or column will not be sufficient to have a single mode of propagation through the line defect, and further design considerations must be taken to achieve that goal. By removing a column, or a row, we can confine the optical beam to the waveguide in a fashion very similar to the TIR concept, which is used to confine the optical signal in optical fibers. However, in PCs, the mechanism of in-plane optical confinement for a wave propagating through the defect is through multiple Bragg reflections, or distributed Bragg reflections. For finite height PC structures (slabs),vertical confinement is achieved through TIR at the interface between the PC slab and lower dielectric constant material, e.g., air.

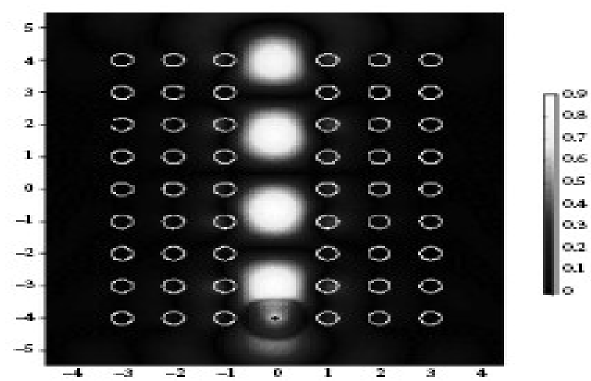


Fig 4.2 Steady state field solution of a TM pulse propagating through a PBG waveguide, simulations were performed using FDTD with PML-absorbing boundary conditions [6].

The main idea of operation for this kind of waveguide is that an incident beam with a frequency within the band gap of the structure will not propagate through the structure, but will propagate through the waveguide with minimal field leakage. Using this approach, a throughput efficiency as high as 100% can be achieved through the waveguide.

4.2 Waveguide Bends

A low-loss waveguide that includes a sharp 90° bend in the 2-D PCs has been reported. Theoretically, it was shown by a simple scattering theory that 100% transmission is possible. Experimentally,over 80% transmission was demonstrated at a frequency of 100 GHz by using a square array of circular alumina rods having a dielectric constant of 8.9 and a radius of 0.2a, where a is the lattice constant of the array.

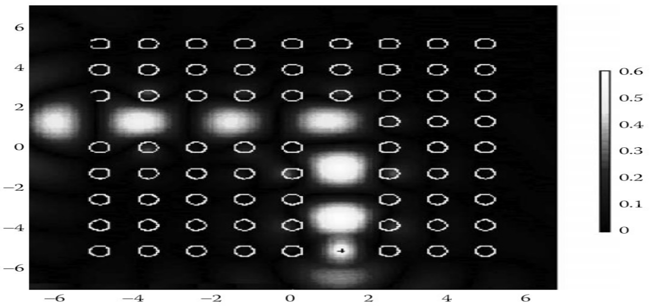


Fig 4.3 A sharp waveguide bend built on a PBG [6].

For a = 1.27 mm, the crystal had a large band gap extending from 76 to 105 GHz. A line defect was created inside the crystal by removing a row of rods. The optical-guided mode produced by the defect had a large bandwidth, extending over the entire band gap.

4.3 Photonic Crystal Fibers

Photonic crystals in the near infrared and visible regions were primarily conceived for the purpose of achieving a complete control of electromagnetic waves in semiconductor materials. The most striking illustration of the unexpected fruitfulness of such generic concepts as that of a photonic crystal is most probably the photonic crystal fiber (PCF) and more generally the micro structured optical fiber (MOF), also known as holey fiber (HF). In conventional optical fibers, which have been the basis of the terrestrial telecommunication industry since the first demonstration of fibers with a high transmission capacity in the spectral window extending around 1550 nm, light is guided owing to the phenomenon of total internal reflection (TIR). The guiding itself occurs inside a silica core with an optical index higher than the optical index of the medium forming the cladding, which is made from silica as well. The index step is created by using a different doping for the core and the cladding respectively. Most of the time, only the core is doped, and the cladding itself is made of pure silica. In this respect, microstructured optical fibers present a completely different structure[2].

Photonic crystal fiber can be constructed by forming patterns of holes along the length of a fiber; the photonic crystal fiber keeps light confined to a hollow core (typically 15µm in diameter) surrounded by a structure of glass and air. In contrast, traditional fiber strand is constructed from solid glass or plastic surrounded by a reflective coating. Photonic crystal is better than traditional reflective coating at keeping light from scattering or being absorbed , which keeps signals stronger over longer distances[9].

Photonic-crystal fibers, also called microstructured optical fibers, can be divided into a few broad classes, according to whether they use index guiding or bandgaps for optical confinement, and whether the periodicity of the structure is one-dimensional or two-dimensional.

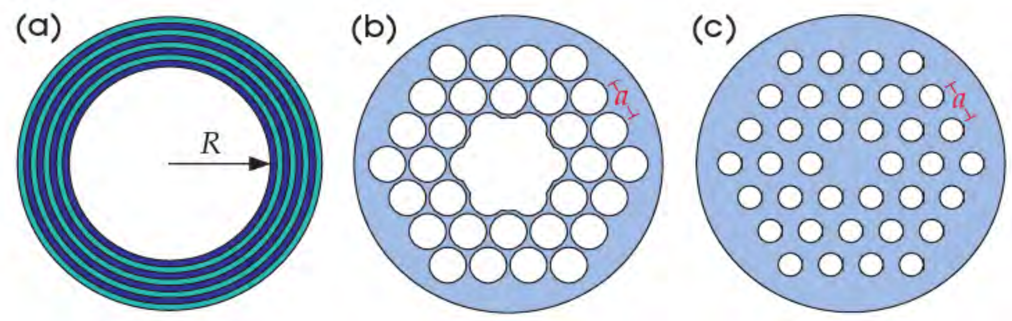


Fig 4.4 Three examples of photonic-crystal fibers. (a) Bragg fiber, with a one-dimensionally periodic cladding of concentric layers. (b) Two- dimensionally periodic structure (a triangular lattice of air holes, or "holey fiber"), confining light in a hollow core by a band gap. (c) Holey fiber that confines light in a solid core by index guiding [1].

Photonic-bandgap fibers confine light using a band gap rather than index guiding. Band-gap confinement is attractive because it allows light to be guided within a hollow core (much as in the section Linear Defects and Waveguides). This minimizes the effects of losses, undesired nonlinearities, and any other unwanted properties of the bulk materials that are available. Band-gap fibers with a one dimensional periodicity—a cladding with a series of concentric layers as in figure 4.4(a)(we called them Bragg fibers). Band-gap fibers with two-dimensionally periodic claddings, as in figure 4.4(b). The most commonly used design is a holey fiber, such as the one shown here, in which the cross section is a periodic array of air holes running the whole length of the fiber.

Another possibility is an index-guiding photonic-crystal fiber, in which the periodic structure is not employed for its band gap, but rather to form an effective low-index cladding around the core. One way to accomplish this is with a solid-core holey-fiber structure, as in figure 4.4(c). In this way, one can obtain a much higher dielectric contrast than is generally possible with solid fiber materials, leading to a greater strength of optical confinement. This is often useful as a means of enhancing nonlinear effects, or of creating unusual dispersion phenomena[1].

Most photonic crystal fiber has been fabricated in silica glass, but other glasses have also been used to obtain particular optical properties (such has high optical non-linearity). There is also a growing interest in making them from polymer, where a wide variety of structures have been explored, including graded index structures, ring structured fibers and hollow core fibers. These polymer fibers have been termed "MPOF", short for microstructured polymer optical fibers [13].

4.4 Enhancing Patch Antenna Performance

4.4.1 Using Photonic Crystal

PCs were used to enhance the performance of a patch antenna. Traditionally, patch antennas have some limitations such as restricted bandwidth of operation, low gain, and potential decrease in radiation efficiency due to surface-wave losses. Using a PBG substrate for a patch antenna minimized the surface wave effects compared to conventional patch antennas, thus improving the gain and far-field radiation pattern[6].

4.4.2 Using Plasmonic Laser

A variety of strategies have emerged that take advantage of localized near-fields that are generated by suitably shaped metallic nano-particles known as optical antennas. Optical antennas can produce very high near-field intensities when their size is properly matched to the wavelength of the incident light. This resonance condition is achieved when the length of the antenna segments is chosen to be approximately half the wavelength of surface plasmons excited in the metal by the incident radiation and the latter is polarized along the antenna length. A variety of strategies have emerged that take advantage of localized near-fields that are generated by suitably shaped metallic nano-particles known as optical antennas. Optical antennas can produce very high near-field intensities when their size is properly matched to the wavelength of the incident light. Length.

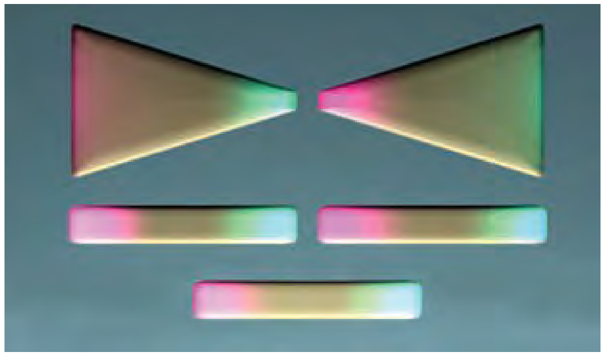


Fig 4.5 Resonant Optical Antenna Designs [18].

The antenna resonance condition leads to a strong near-field enhancement at the antenna ends with respect to the incident field (bottom). The coupled-rods design (middle) is used to create highly localized, well-defined light spots at the central antenna gap. The bow-tie design (top)maximizes field concentration in the nano-gap compared to the outer ends of the antenna segments. Pink and bright cyan stand for positive and negative charge distributions in the antennas, respectively. Resonant optical antennas can capture a light beam with a cross-section much larger than their geometrical size.

Researchers have demonstrated very-small-aperture lasers that consist of a laser diode with its facet coated by a metal film on which a sub-wavelength hole is etched by focused ion beam milling. However, these and related devices suffer from limited throughput, since the transmitted power scales strongly with the hole diameter (with the fourth power through a sub-wavelength hole in a perfect metal). Plasmonic laser antennas, which consist of a resonant optical antenna integrated on the facet of a semiconductor laser, don't suffer from this problem. Resonant antennas indeed can capture a substantial part of the power of the incident laser beam and concentrate it into a spot the size of the nano-metric antenna gap, leading to a light intensity hundreds or even thousands of times stronger than that of the incident beam.

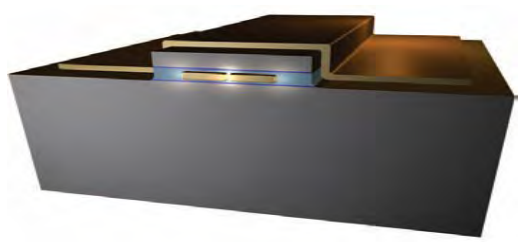


Fig 4.6 A semiconductor laser with a resonant optical antenna integrated on the facet [18].

Such a compact laser source with sub-wavelength spatial resolution could provide distinct advantages in a number of applications, including microscopy, spectroscopy, tera byte-level optical data storage, lithography and laser processing.

4.5 Hybrid Photonic Crystal Structures

When a PC of single-crystalline structure is formed, there is a natural matching of the crystal lattice,and a high-quality single crystal layer results. On the other hand, if a PC is formed from multiple crystalline structures (e.g., rectangular, triangular), the newly created structure is no longer a single crystalline structure but a hybrid structure, which in turn contains the optical characteristics of both structures. Such a structure was called a heterostructure PC. *Heterostructure PCs were used to further optimize the bandgap size obtained from a single PBG structure, such that a bandgap size of 94% was obtained from a heterostructure of a rectangular PC lattice (bandgap size of 55%) and a triangular PhC lattice (bandgap size of 39 and 19%), as shown in Figure 4.7*. Wide bandgap PCs are advantageous for applications such as wide band optical mirrors,wide band optical matching elements, and wide band optical couplers. When PCs of different lattice structures are brought together, discontinuities in their respective energy bands is expected, as both structures will have different bandgaps, as shown in Figure 4.7. The discontinuities in the dielectric bands ΔE_{diel} and the air band ΔE_{air} accommodate the difference in band gap between the two PCs, ΔEg, and the barrier

$$\Delta Eg = Eg_1 - Eg_2 \qquad 4.3$$

on either side of the wide band gap lattice form what is in principle similar to an electronic quantum well in semiconductors, which in this case can be called a photonic quantum well. In PCs, though, the bands above and below the band gap are generally unoccupied and a transition from one Bloch state to another state is only possible if the phase-matching condition is satisfied.

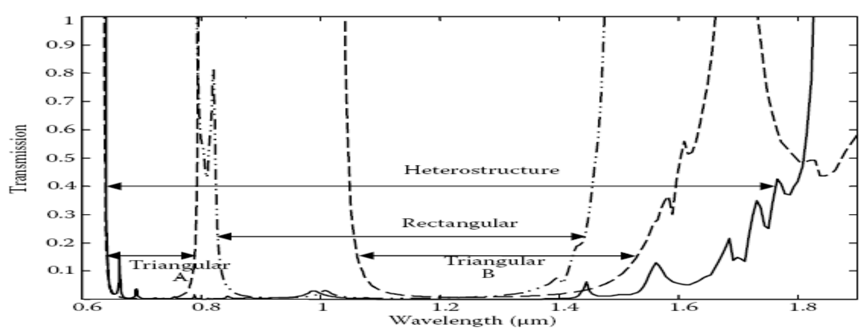


Fig 4.7 Band diagram of a rectangular PC lattice (–) with a bandgap size 54.87%, Band diagram of a triangular lattice (-..-.) with a short wavelength ban dgap size 19.44% and a long wavelength ban dgap size 39.39%,and band diagram of a heterostructure PC lattice (solid line) with a band gap size 94.02% [6].

By careful design of both rectangular and triangular lattices, respectively, the discontinuities in the dielectric band as well as the air band shown in Figure 4.8 can be minimized if not completely eliminated. This basically means that band gap matching between two different lattices can be achieved,and heterostructure PCs can be used as a matching element.

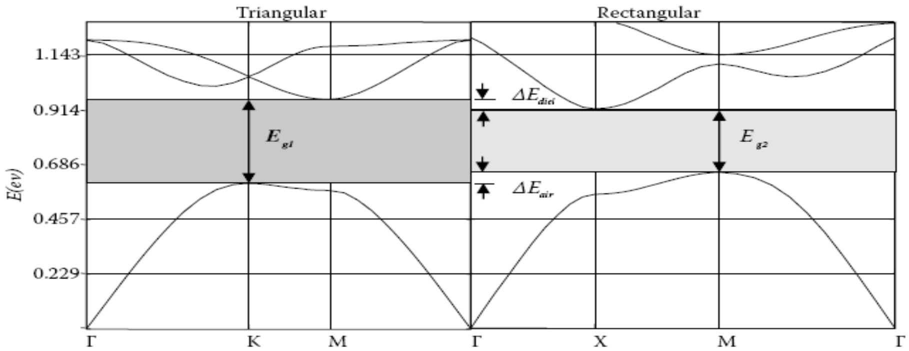


Fig 4.8 Band diagram of a triangular PC lattice with Eg1 and a rectangular PC lattice with Eg2.As both lattices are brought together to form heterostructure, PC band edge discontinuities ΔE_{diel} and ΔE_{air} start to appear at the dielectric and air bands, respectively [6].

An attenuation diagram for a triangular lattice matched with an attenuation diagram for a rectangular lattice is shown in Fig4.9.

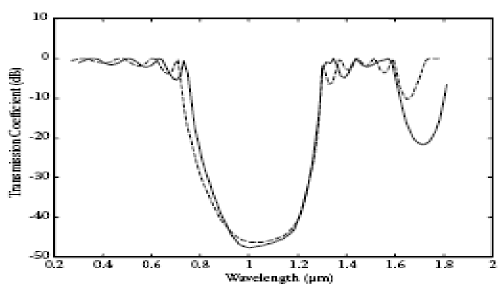


Fig 4.9 Transmission spectra for a rectangular lattice (solid line) with a ratio of r/a = 0.4 versus transmission spectra for a triangular lattice (dashed line) with a ratio of r/a = 0.4 [6].

Another application where heterostructure PCs were used to improve the performance of a device was in an optical beam splitter. An optical beam splitter implemented in a single PC structure (rectangular) is shown in Figure4.10. Such a device achieved an overall throughput efficiency of 50% with most of the loss in transmission contributed by the back reflections at the splitting section.

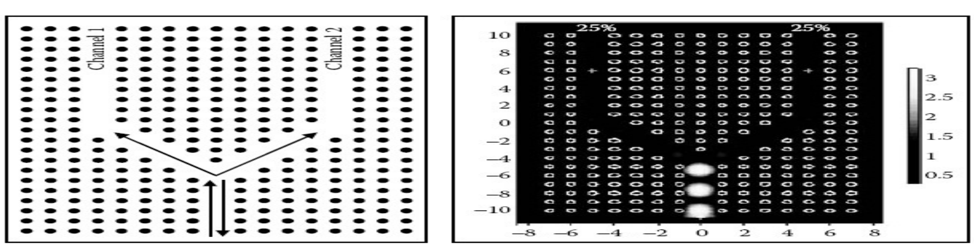


Figure 4.10 An optical beam splitter to demonstrate the idea of an optical matching element [6].

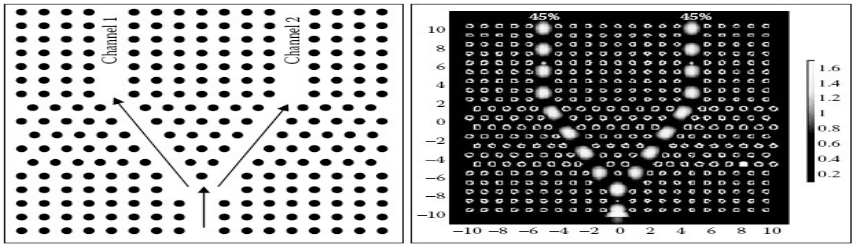


Fig A schematic diagram of an optical beam splitter using heterostructure lattice [6].

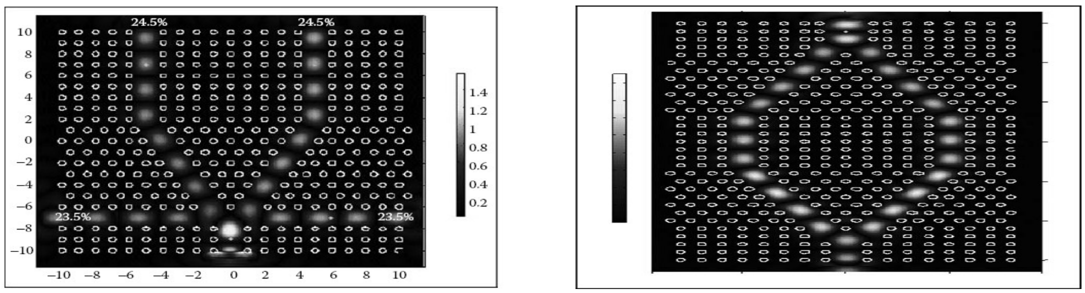


Fig 4.12 Left a 1-to-4 optical splitter using heterostructure PBG lattice and right An optical beam splitter and combiner using heterostructure PBG lattice [6].

Using a heterostructure PC, the device performance increased from 50 to 90% as shown in Figure4.10. Other examples utilizing heterostructure PCs are a 1-to-4-beam splitter shown in Figure 4.11 (left) and a beam splitter/combiner shown in Figure 4.11 (right) [6].

4.6 Optical Switch Using PC

Optical switching is an essential operation for high speed communication networks. For such applications,efficiency, low power consumption, and robustness are important requirements. In recent years, a number of photonic crystal(PC)-based devices have been proposed as compact, low power switches , but many of these rely on a membrane geometry that is susceptible to damage and difficult to integrate with other components. Designs based on silica-on-insulator (SOI) PCs are more robust, but the asymmetric cladding geometry allows coupling between modes that are orthogonal in the membrane structures, and hence increased losses. The lower index contrast between the silica and the silicon also reduces the available bandwidth below the silica light line, above which losses to radiation modes in the cladding can also be an issue.

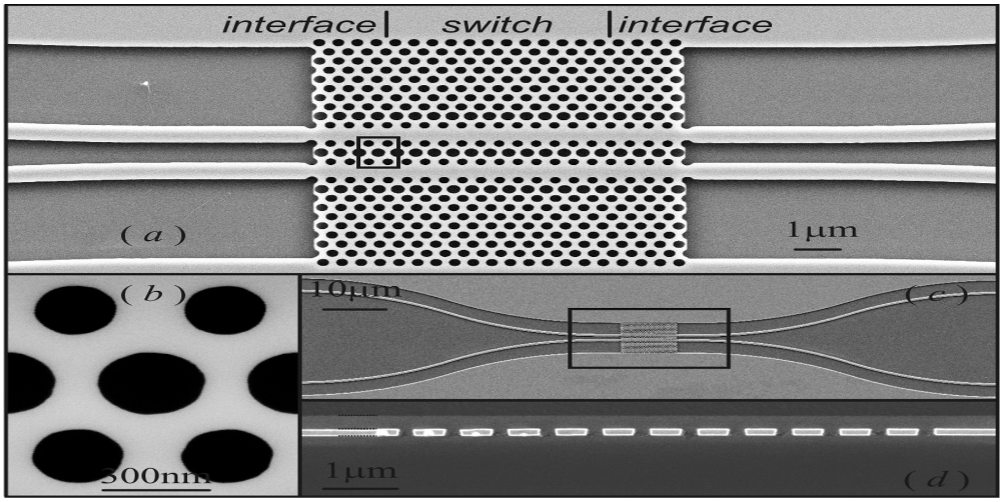


Fig4.13 Scanning electron micro graphs of the PC directional coupler etched into the silicon, before silica infilling. Which Shows (a)the design of the switch (b) hole sizes used for engineering the band structure (c)the on-chip layout: s-bends are used to prevent interaction between the slab waveguides. (d) A cross-section of the PC after etching and silica infilling [25].

However a compact optical switch based on a Si PC directional coupler fully embedded in a symmetric silica cladding. This geometry provides protection from the environment and also enables easy integration with additional components such as micro heaters or electrical contacts. While the ultimate aim for high-speed operation will be actuation of the switch by free carrier modulation , here thermo-optic tuning is used to demonstrate switching. The design of the switch is compatible with either switching method, and the faster operation using free carriers will require the essential components that are demonstrated in this letter, namely integrated electrical components and a silica-embedded design. The directional coupler design is based on the Si membrane PC switch reported in , where the dispersion of the super modes of the coupled system were engineered through a control of the hole sizes in the PC waveguides. In the present work, we demonstrate similar performance in the silica-clad geometry , and illustrate the switching behavior by incorporating an integrated micro heater [25].

Chapter 5
Summery, Conclusion And Future Outlook

5.1 Summery and Conclusion

Here in this project we conclude that the propagation of light in homogeneous medium has different properties than in periodic heterogeneous mediums of one, two and three dimensions. Moreover, if the dielectric constants in periodic materials are sufficiently different and if the absorption of light by the material is minimum, then the refraction and reflection of light from all of the various interfaces can produces many of the same phenomena for photon(light modes) that the atomic potential produce for electrons. We therefore analyzed that the dispersion relation in periodic medium is changed by the interaction between light and the periodic lattice, creating bands where transmission is allowed, and frequency bands where no light can travel through the structure, the photonic band gap. Further more, in order to get a full photonic band gap in all directions for all polarisation, we need a lattice structure with high symmetry and sufficiently high refractive index contrast for which 3-D photonic crystals are best of all the other.

3-D photonic crystals are the best materials to control light because of their omni-directional photonic band gap, but these materials are difficult to design and fabricate. However, 2-D photonic crystals, with help of slab wave guide alleviates the difficulty in 3-D photonic crystals because of their less complexity in fabrication.

Finally, we have shown that photonic crystals are very attractive materials in today's communication era . They are widely applicable in telecommunication industries which they can serve wave guiding devices with less or no loss for long distance communication at high intensity. Photonic crystals fibers are getting more weight than the traditional fiber optics which was working by the principle of total internal reflection that had more losses at large distance propagations and sharp bends.

Generally, we conclude that the whole array of photonic crystal illustrates one aspect or another of basic science, full fill various practical aims or occasionally provide physically based in living things.

5.2 Future Outlook of Photonic Crystals

Photonic crystals are at the very origin of now being increasingly drawn between nanoelectronics and nanophotonics. In addition to the miniaturization of optical devices and systems that they allow, one of the guiding ideas in the practical development of photonic crystals is the possibility of fabricating, in a limited number of technological steps, the main constitutive elements of future large-scale integration photonic circuits. In simple terms, this would provide a practical toolkit for the design of circuits in optics and optoelectronics, combining the most advanced lithography and etching processes. Different methods are now being proposed for the computer-assisted design of the first elementary photonic circuits. Hybrid circuits where photonic circuits would be associated on the same chip to electronic circuits are also being proposed. One of the decisive advantages of using optical rather than electrical signals is the perspective of a much weaker interaction between the signals themselves.

It is expected that systems based on photonic crystals will soon be mature enough to compete with the most performing demultiplexer systems in optical telecommunications, such as waveguide arrays or the so-called ‘phasars’. The encouraging results obtained on light bends, on mode matching systems and on ‘add-drop’ filters, where photonic crystal waveguides are combined to microcavities, demonstrate that photonic crystals hold even greater promises for a great variety of miniature active devices.

There is a common belief that in the near future photonic crystals will give us the same control over photons as ordinary crystals give us over electrons. At the same time, photonic structures are of great promise to become a laboratory for testing fundamental processes involving interactions of radiation with matter in novel conditions. This promise originates from the fact that, in analogy to the case of an electron moving in a periodic potential, certain photon frequency modes within a photonic crystal can become forbidden, independent of the photon polarization and direction of propagation, a complete photonic band gap .

Therefore Photonic crystals are becoming the most popular devices among the many industrial products of big industries. They attracted the eye of computations in many technological and scientific aspect of the present manufacturing industries and give human a good insight in the future of optics and electronics related problems as to be solved easily and accurately.

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