CHAPTER-1

INTRODUCTION

1.1 Motivation for research

Over the past several decades, semiconductor technology has played a role in almost every aspect of modern technology. Advances in semiconductor technology have initiated the transistor revolution in electronics. Unfortunately, miniaturization results in electronic devices with increased resistance and higher levels of power dissipation and higher speeds lead to a greater sensitivity to signal synchronization. Moreover, they are simply not suitable for operation at very high frequencies or bandwidths. To further progress of high density integration and system performance and perfectly suited to operation at high frequencies, scientists are now turning to light instead of electrons as the information carrier. Light waves have several advantages over the electron. Light are enabled to carry a large amount of information per second and wide-bandwidth data handling beyond the limitations of the electron as the information carrier. Moreover, photons are not strongly interacting as electrons, which help to reduce energy losses. In spite of the numerous advantages of photons, all possible photonic devices have yet not to be commercially available on a large scale. Because it is difficult to confine or store light in a small volume and control the speed of light. The strength of the light-matter interaction is also generally very weak that make signal manipulation and control in the optical domain difficult. There is a pressing need to find the new physical mechanism that would improve our ability to manipulate and control light. In the search for a solution, researchers have turned a growing interest to a new class of optical materials known as photonic crystals (PCs) or photonic band gap (PBG) materials which may respond to light waves over a desired range of frequencies by perfectly reflecting them, or allowing them to propagate only in certain directions, or confining them within a specified volume [Yablonovitch (1987); John (1987); Joannopoulos (1997)]. These properties, which can be used to confining, manipulating and guiding photons, should allow the creation of all optical-integrated circuits. Ultimately, such photonic circuit will probably play a key role in sophisticated light based signal processing tasks such as sending data across future all-optical networks. The unusual properties to confine, control, manipulate and guide photon of PBG materials may also provide new types of photonic devices in the areas of communications, computing, and signal processing. With the help of PCs, devices could advance to a new level in terms of compactness, performance, and reliability.

Owing to new developments in optical materials science, PCs have great potential in the future world of optical technologies for instance. These materials show some new interesting properties to confining, guiding, and coupling light in sub-wavelength scale that was not observed in conventional materials. Properties of PCs leading to newer applications including efficient radiation sources, sensors, filters and optical computer chips, etc. and thus “photonic crystals devices” are the future products with high-speed and wide-bandwidth data handling beyond the limitations of electronic technology. Some applications are depicted in figure 1.1 [Inoue (2004)].

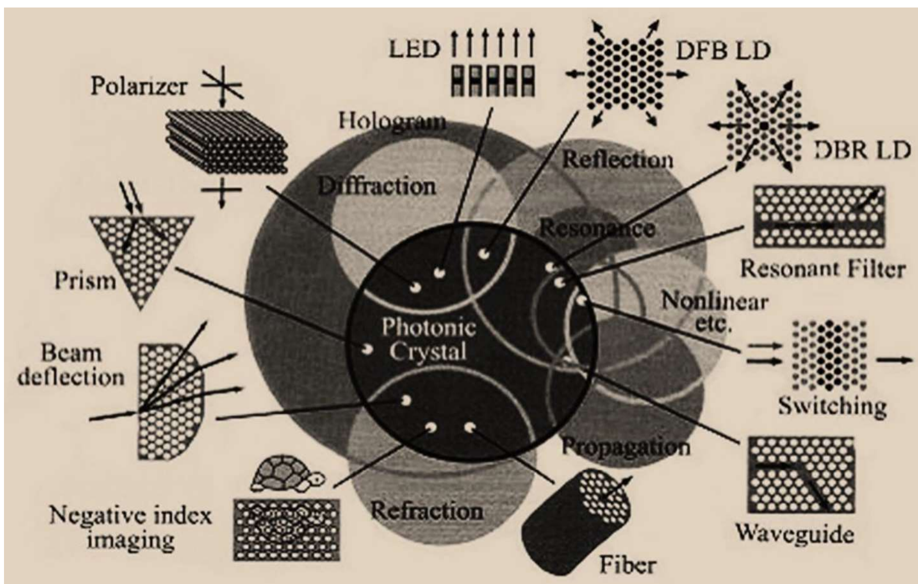


Figure 1.1 Some applications on the basis of different optical properties of the photonic crystals.

Research in this direction is still in its infancy, and this study is motivated by current research trends on to control the radiative properties of material and effect photon localization by introducing a random refractive index variation. In the meantime, the rich physics underlying these functionalities has become a great part of the hot topics in modern physics, such as negative refraction, super-collimation, defect modes, disorder structures, optical localization, ultrafast phenomena, near field effects, and quantum optics, etc. To some extent, the floodgate holding the next generation photon based science and technology have been opened. Several efforts have been made to achieve better confining, guiding, and coupling light in PCs by considering different structures and materials etc. The chapter starts with general motivation, introduction and importance of the PC. Main attentions paid to the types of PCs and their applications, and the existence of the PCs in nature and effect of quasi-periodic systems on PBG, light scattering and wave localization phenomena. General concepts of the optical properties of graded PCs and their applications have also presented. Next, the details of theoretical techniques that were employed for the theoretical study of light scattering, interference, or diffraction caused by photonic structures have introduced. The mathematical expression of the distribution of electromagnetic waves in homogeneous and inhomogeneous (graded index) media have also described. Brief description of the design of PC structures with the help of Transfer matrix technique used is presented and performed the transmission, reflection, dispersion relation and photonic band structure. Moreover, this chapter concludes with an overview of the current research trends on 1-D PCs. The aim of the thesis has been presented in the last of this chapter.

1.2 Photonic crystals

Photonic crystals (PCs) provide the ability to control, bend, trap, switch, slow, reflect and effectively extract light in an analogous fashion to the way in which nanostructures have been harnessed to control electron-based phenomena [Joannopoulos (2008)]. PCs are a novel class of optical composite structures represented by natural or artificial structures with periodic modulation of the refractive index on a length scale comparable to the wavelength of light. PCs consist of at least two different materials having different refractive indices and scatter light due to their refractive-index contrast. The periodic modulation of the refractive index creates a forbidden gap known as photonic band gap (PBG) that excludes the existence of optical modes within a specific range of frequencies. Thus, PCs are also commonly referred to as PBG structures [Yablonovitch (1987); John (1987)]. PCs have great potential for providing new types of photonic devices. The continuing demand for photonic devices in the areas of communications, computing, and signal processing, using photons as information carriers, has made research into PCs an emerging field with considerable resources allocated to their technological development. Proposed applications of PCs for the telecommunication sector include optical cavities, filters, mirrors, sensors, super prisms and compact waveguides for use in so-called planar light wave integrated circuits [Vlasov (2001); Yanik (2003); Prather (2009)]. According to the specific periodic arrangement of materials along the directions to the light wave propagation, PCs can be divided into three broad categories, namely one-dimensional (1-D), Two-dimensional (2-D) and three-dimensional (3-D) structures. Examples are shown in the figure 1.2.

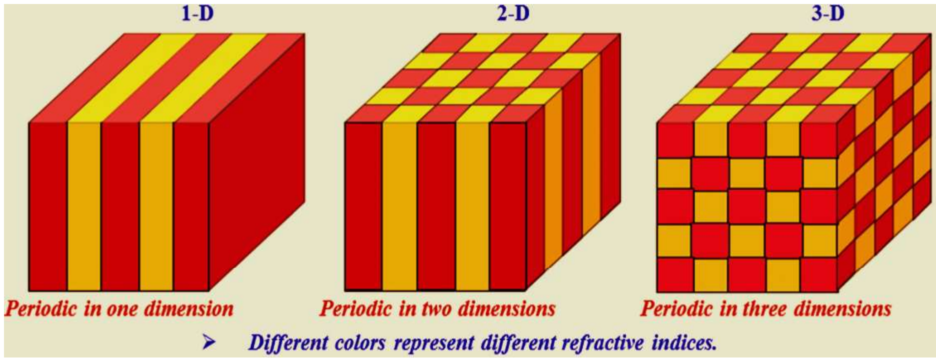


Figure 1.2 Simple examples of one-, two- and three-dimensional PCs.

1.2.1 Natural photonic crystals

Although the term "Photonic crystal" has been used after the appearance of two milestone papers published by Yablonovitch and John in 1987 [Yablonovitch (1987); John (1987)], but relevant studies have been carried out in one form or another since 1887. In 1887, Lord Rayleigh [Rayleigh (1887)] published one of the first analyses of the electromagnetic wave propagation in periodic media. His work was related to the peculiar reflective properties of a crystalline mineral with periodic planes. These structures are comparable with the current one-dimensional (1D) PCs. Lord Rayleigh found out that there is a narrow band gap (forbidden gap) prohibiting light propagation through the planes. Forbidden band gap is angle-dependent and producing iridescent reflected color patterns that vary sharply with the angle. This effect is responsible for many other iridescent colors in nature such as butterfly wings, sea mouse threads, natural opals and peacock feathers as shown in figure 1.3. Their corresponding scanning electron microscope (SEM) images or optical microscope images indicate the periodic arrangement of the structures [Zhao (2012)]. Such color effects in different photonic structures have been found to result from the interaction of light with periodically arranged microstructures of a single biological material and known as structural colors. Precious opal is also a natural photonic crystal example, in which brilliant color result from close-packed domains of colloidal spheres of amorphous silica [Armstrong (2015)]. All the beautiful color examples have microscopic structures known as PCs.

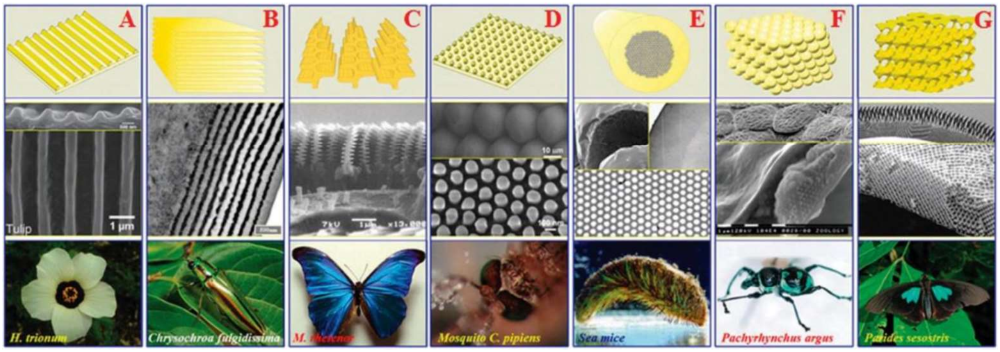


Figure 1.3 Typical photonic nanostructures in natural creatures: (A) 1-D grating; Hibiscus trionum and Tulipa species; (B) 1-D periodicity in the form of multilayers existing in some insects, birds, fish, plant leaves, berries and so on; (C) some discrete 1-D periodicity; Morpho-butterflies and certain plant leaves; (D) natural surfaces with 2-D gratings in some nocturnal insects such as moth and some butterflies; (E) natural 2-D periodicity in the form of cylindrical voids found in the iridescent hairs of certain marine worms-Aphrodite; (F) close-packed spheres of solid materials generate the iridescence of gem opals; (G) inverse opal analogous nanostructures generate the iridescence of several species of exotic butterflies such as Parides sesostris [Zhao (2012)].

A detailed theoretical study of 1-D optical structures with a strong modulation of the dielectric function was performed by Bykov in 1972 [Bykov (1972)]. Bykov was the first to investigate the effect of a PBG and inhibition of the spontaneous emission of atoms and molecules embedded within a periodic structure. The First self-consistent treatment for the calculation of the electromagnetic eigenmodes and photonic band structure in a 3-D periodic medium with large dielectric function modulation was given by Ohtaka in 1979 [Ohtaka 1979]. These pioneering works did not gain the attention they deserved at the time. The idea to control and confine the flow of light wave by the periodic media becomes popular after the appearance of two milestone papers of Yablonovitch and John in 1987. Yablonovitch [Yablonovitch (1987)] proposed a 3-D periodic medium, which he called a "photonic crystal", to inhibit the spontaneous emission of the atom and to realized localized defect modes and consequently to enhance the spontaneous emission. In the same year, John [John (1987)] proposed the use of a disordered 3-D periodic medium to affect localization and control of electromagnetic waves. Many interesting quantum optical phenomena such as the bound state of photons and non-exponential decay of the spontaneous emission were predicted. After publication of these articles, the number of research papers concerning PCs physics and technology began to grow exponentially. In 1989, Yablonovitch and Gmitter [Yablonovitch (1989)] fabricated a face-centered-cubic (FCC) lattice on a large scale (microwave frequencies) and measured the transmission spectra at various angles, in the hope of observing a complete PBG, which would prevent the propagation of electromagnetic wave with each polarization and corresponding wavelengths in all directions within the crystal. Unfortunately, they did not find one. For this reason, theoretical physicists were motivated to investigate the problem systematically. Subsequent solutions incorporating the vector nature of the electromagnetic field were developed, based on the plane-wave expansion method. Application of these tools showed that the FCC structure did not have a complete band gap. Ho et al. [Ho (1990)] proposed the use of a diamond lattice to reduce the degeneracy of the FCC lattice, and a complete band gap was found for spheres with a dielectric constant of 3.6. Yablonovitch et al. [Yablonovitch (1991)] then proceeded to fabricate the first artificial photonic structures known as Yablonovite. Transmission measurements for this photonic structure showed a complete band gap in the microwave regime. After this initial success, the field of PBG devices grew at an exponential rate. Innovations have been made in developing PC lasers, optical fibers, micro cavities, light emission diodes (LEDs), performance enhanced solar cells and many advanced components for optical communication such as polarization splitters, sensors, switches, multiplexers, etc. PCs can also be used as reflecting coating on lenses, color pigments in paints and inks, waveguides for directing and controlling the propagation of light in specific path, highly reflecting mirrors in laser cavities, and many other optical components [Ge (2011)].

1.2.2 One dimensional photonic crystals

The simplest possible photonic crystals are the one-dimensional (1-D) multilayer structure. This type of structure consists of alternating layers of minimum different materials having different dielectric constants with each pair of layers being identical to the previous or next pair and form band gaps in a single direction. Lord Rayleigh [Rayleigh (1887)] published one of the first analyses of the optical properties of the multilayer structures in 1887 and shown that such structures have a 1-D PBG, a spectral range of large reflectivity, known as a stop-band (or forbidden band). A Bragg mirror is an example of this type of PCs which can possess a so-called PBG due to the interference of electromagnetic waves within the PC structure. PBG is a spectral band in which no electromagnetic states exist in the multilayer structure. Thus, light incident on a Bragg mirror at frequencies within the PBG are highly reflected and this region is also known as the stop-band of the Bragg reflector [Joannopoulos (2008)]. The traditional approach to developing the understanding of 1-D PCs is to allow a plane wave to propagate through the multilayer structure and to consider the sum of the multiple reflections and transmissions that take place at each interface, and the phase changes that occur for plane waves propagating from layer to layer. Based on this concept, a matrix method has been introduced by Yeh to treat the phenomenon of electromagnetic waves propagating in layered media, which laid the very foundation for numerical research for 1-D PCs [Yeh (1988)]. Finite-difference time-domain is also one of the popular numerical analysis technique used for calculating the dispersion diagram, electromagnetic mode, and propagation of the light wave in 1-D PC structures [Prather (2009)]. 1-D PCs are found in nature as seen for examples in the iridescent colors of abalone shells, butterfly wings and some crystalline minerals and manmade 1-D PCs. Moreover, PCs are widely used in a variety of optical devices including dielectric mirrors, optical filters, optical fiber and so many others. Some other examples of 1-D PC applications are shown in figure 1.4 [Shen (2016)].

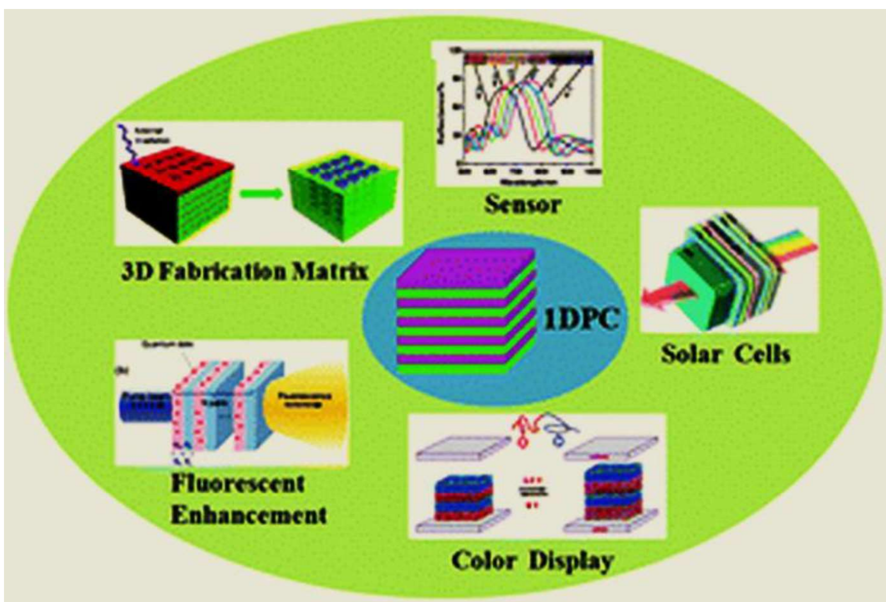


Figure 1.4 One-dimensional photonic crystals and their some applications [Shen (2016)].

The generation and frequency region of the PBGs depends on the refractive index contrast of the component materials in the PC structures. Figure 1.5 is an example of a 1-D PC with a periodic arrangement of low-loss dielectric materials. This multilayer film is periodic in the z-direction and extends to infinity in the x- and y-directions. In this structure, a PBG occurs between every set of bands either at the edge or the center of the Brillouin zone – PBGs will appear whenever n_1/n_2 is not equal to unity [Joannopoulos (2008)]. For such multilayer structures, corresponding

PBG diagrams show that the smaller band gaps for the smaller contrast of the refractive index of media. It is also important to note that at long wavelengths (i. e., at wavelengths much larger than the periodicity of the PC), the electromagnetic wave does not probe the fine structure of the crystal lattice and effectively sees the structure as a homogeneous dielectric medium.

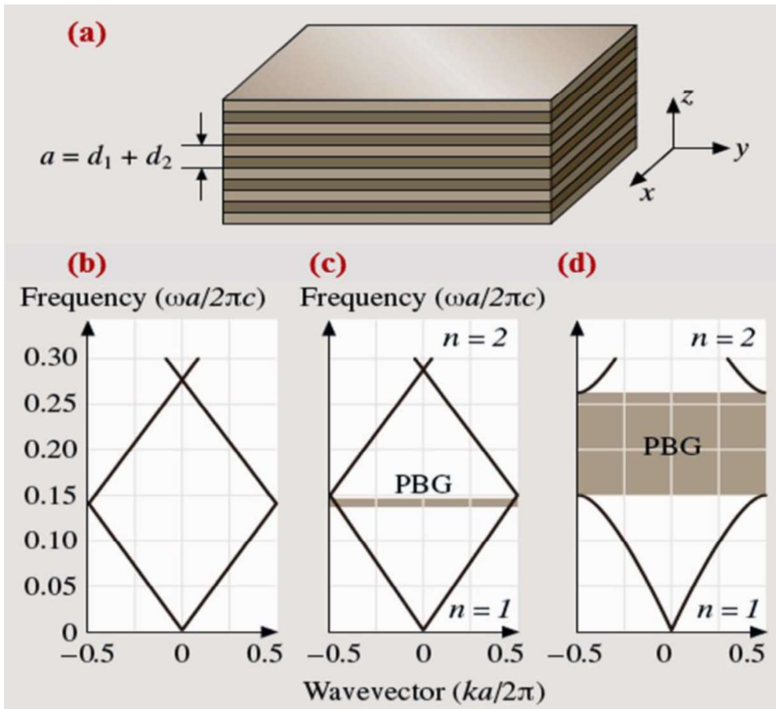


Figure 1.5 1-D photonic crystal structure with d = 0.5a, the corresponding band gap diagrams are shown for: (a) GaAs bulk (ε = 13); (b) GaAs/GaAlAs multilayer (ε_1 = 13, ε_2 = 12); and (c) GaAs/air multilayer (ε_1 = 13, ε_2 = 1) [Joannopoulos (2008)].

In the past two decades, various methods have been developed to fabricate 1-D PCs at various length scales. Up to now, the most widely used method has been spin coating. Spin coating can be applied to many materials, including nano-particles solutions, inorganic precursor sols, and polymer solutions. Self-assembly and layer-by-layer deposition are also a convenient method to fabricate 1-D PCs [Shen (2016)]. Even though the fabrication process can now proceed automatically with layer-by-layer coating robots, a hundred or more cycles of deposition is still a time-consuming process compared to spin coating. Many other methods including chemical vapour deposition (CVD), physical vapour deposition (PVD), top-down etching techniques molecular beam epitaxy have also been utilized to build 1-D PCs [Ge (2011)]. These techniques produce microstructures with desired shape, size and order from the bulk material.

1.2.3 Two-dimensional photonic crystals

Ideal two-dimensional (2-D) photonic crystals are structures with a periodicity of low and high refractive index materials in two-dimensions and homogeneous along the third dimension. These structures exhibit most of the important characteristics of planar PCs and can be used to investigate many of the physical effects present in the structures and optical devices [Joannopoulos (2008); Krauss (1999)]. 2-D PCs can be represented in space by two primitive vectors $\overrightarrow{a_1}$ and $\overrightarrow{a_2}$ as seen in figure 1.6(a) and (c). 2-D PC can be classified into different types corresponding to different sets of these two primitive vectors. The most common are the square and triangular lattice. It can see the real lattice of two common types of PC structures: the square lattice in which $|\overrightarrow{a_1}| = |\overrightarrow{a_2}|$ and $\theta_{lattice} = (\overrightarrow{a_1}, \overrightarrow{a_2}) = 90^o$ and the triangular lattice where $|\overrightarrow{a_1}| = |\overrightarrow{a_2}|$ and $\theta_{lattice} = (\overrightarrow{a_1}, \overrightarrow{a_2}) = 60^o$. Figures 1.6(a) and (d) give an example of the real lattice dielectric maps of two simple PC structures (square and triangular lattices) made of air holes in a high dielectric constant medium [Berger (1999); Saleh (2007)].

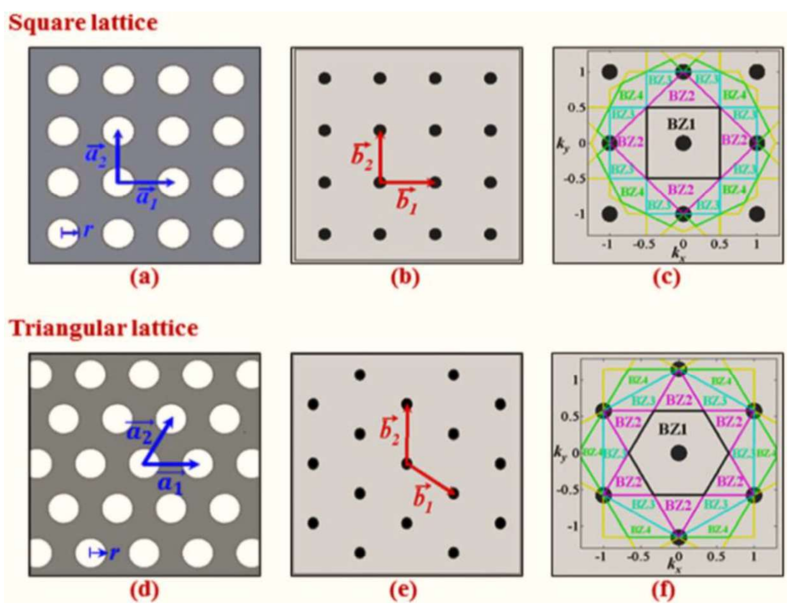


Figure 1.6 Panels (a), (b) and (c) are real lattice, reciprocal lattice and Brillouin zones of square lattice in which $|\overrightarrow{a_1}| = |\overrightarrow{a_2}| = a$, and $\theta_{lattice} = (\overrightarrow{a_1}, \overrightarrow{a_2}) = 90^o$; and panel (d), (e) and (f) are real lattice, reciprocal lattice and Brillouin zones of Triangular lattice in which $|\overrightarrow{a_1}| = |\overrightarrow{a_2}| = a$, and $\theta_{lattice} = (\overrightarrow{a_1}, \overrightarrow{a_2}) = 60^o$ made of air holes $r = 0.3a$, respectively [Saleh (2007)].

Beside the real lattice, reciprocal space, and Brillouin zone are also used for the study of PBG properties in 2-D PC structures. In figure 1.6, the two primitive vectors in reciprocal space and Brillouin zones can see. The first Brillouin zone of a square lattice is a square while it is hexagonal for the case of a triangular lattice. The reciprocal space of a 2-D PC is defined from the relation: $\vec{a_i}.\vec{b_j} = 2\pi\delta_{ij}$, where $\vec{a_i}$ and $\vec{b_j}$ are the primitive vectors in the real lattice and reciprocal lattice, respectively, and δ_{ij} is the Kronecker symbol. The band structure or dispersion diagram of a PC lattice is the graphical representation of the frequency (eigenvalues) against the wave-vector (eigenvectors) relationship. This relationship depends on both the lattice parameters and the polarization of light. In two-dimensional systems, electromagnetic fields can be divided into two independent polarizations: the transverse electric (TE) modes, in which the electric field is in the plane of periodicity and the magnetic field is perpendicular to this plane, and the transverse magnetic (TM) modes where the magnetic field is in the plane of periodicity and the electric field is perpendicular to it. Figures 1.7 (a) and (b) show the band structure diagram of the square and the triangular lattices for both TE (red line) and TM (blue dashed line) polarizations along the main direction $\Gamma - X - M - \Gamma$ for the square lattice, and $\Gamma - M - K - \Gamma$ for the triangular lattice, respectively (the boundaries of the irreducible Brillouin zone presented as the orange regions in two insets of the two figures 1.7(a) and (b)). The frequency range where the band gaps for both TE and TM polarized light are overlap that known as omnidirectional PBG, where reflection occurs independently of the direction of the incident wave.

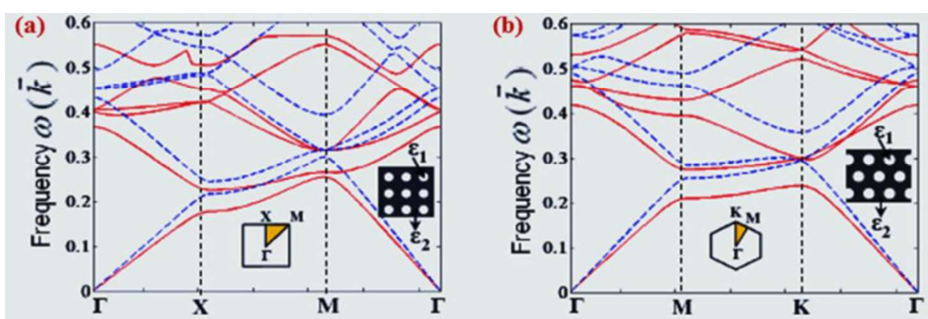


Figure 1.7 Band structure diagram of 2-D photonic crystal structures made of air hole (r = 0.3; $n_1 = \sqrt{\varepsilon_1} = 1$) in silicon (Si) host material ($n_2 = \sqrt{\varepsilon_2} = 3.45$) calculated by the Plane wave expansion method for the polarizations TE (line) and TM (dashed line) of (a) the square lattice, and (b) the triangular lattice [Joannopoulos (2008)].

1.2.4 Three-dimensional photonic crystals

Three-dimensional (3-D) photonic crystals feature a variation of the refractive index in all three spatial directions and allow for control and manipulation of light in all directions in space. Therefore, a complete band gap for all polarizations and all spatial directions can be enforced. For this reason, the first experimental evidence of spontaneous emission suppression was based on these kinds of photonic crystals. The first experimental realization of a 3-D PC was achieved by Yablonovitch et al. [Yablonovitch (1991)] who fabricated a face centered cubic (fcc or opal-like) crystal in a low-loss dielectric medium, with a band gap operating in the microwave region, and shown in figure 1.8. This system is known Yablonovite in recognition of this achievement.

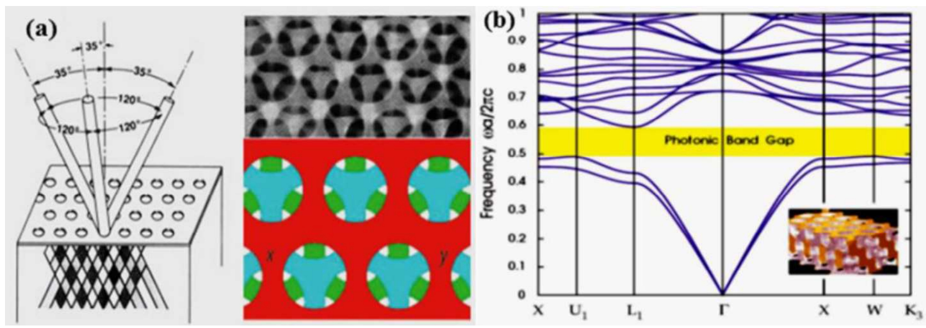


Figure 1.8 (a) Schematic illustrations and SEM image of 3-D Yablonovite structure fabrication, (b) Photonic dispersion curve of Yablonovite. Inset is the schematic illustrations of Yablonovite and photonic band gap is indicated in yellow region [Yablonovitch (1991)].

Today the most popular examples are woodpile PCs and opal structures [Sozuer (1994); Lin (1998); Reynolds (1999); Aguirre (2010)]. Woodpile structure has diamond symmetry and could be made layer-by-layer by stacking pre-patterned dielectric wafers or rods with alternating orthogonal orientations [Lin (1998); Joannopoulos (2008); Rybin (2015)]. Other classes of PCs are the opals or the inverse-opals types. The opal structure is created with dielectric spheres (usually SiO_2) by self-assembly techniques suitable for mass production [Vlasov (2001); Xia (2001)]. The spheres assemble in closed packed fcc geometry, which does not exhibit a band gap, while the inverted structure (inverse-opal) has one. The inverse-opal is achieved by filling the opal structure with dielectric material and removing the opal sphere during a subsequent etching step. All the 3-D PC structures are difficult to fabricate even with the best technology available currently. Jiang et al. [Jiang (1999)] and Ozin et al. [Ozin (2001)] have demonstrated that lateral attractive capillary forces can be used to build 3-D lattices with well-controlled numbers of layers. Xia et al. [Xia (2001)] demonstrated an effective approach that allowed for the fabrication of colloidal crystals with domain sizes as large as several square centimeters by using a specially designed packing cell. This method is relatively fast, and it also provides tight control over the surface morphology and the number of layers of the crystalline assemblies [Cai (2014); Ge (2011)].

1.2.5 Defects in photonic crystals

Main attention in the previous sections was that the periodicity of the PCs induced PBGs where no electromagnetic modes are allowed within the band gaps. When the periodicity is broken by introducing a defect into a PC structure, a localized defect mode will appear within the PBGs due to change of the interference behavior of light, which lead to the selective transmission of electromagnetic waves [Joannopoulos (2008); Prather (2009); Inoue (2004)]. If a new state is obtained within the PBG, the fields remain localized at the defect mode position and decay exponentially into the PCs. The presence of defect modes within the PBG strongly depends on the PC structures, including materials and thickness of the defect layer. The knowledge of the phenomena of the defect modes will be informative to design more interesting applications such as narrow band filters, sensors, and switches and so on. Defects in such PCs are defined as regions having different geometrical parameters and/or refractive-index contrast from that of the periodic structure. Figure 1.9 shows some examples of various types of defect inserted into 1-D, 2-D and 3-D PC structures [Joannopoulos (2008)].

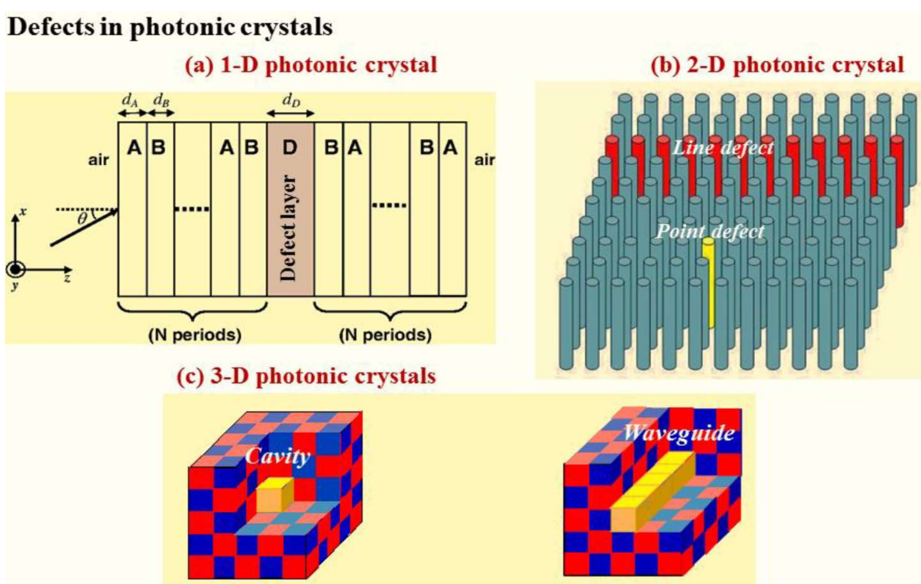


Figure 1.9 Schematic representations of the PCs with defects. (a) 1-D PC structure with defect layer, (b) line and point defects in 2-D PC structure and (c) 3-D PC structures with cavity and waveguide defects.

1.3 Graded Photonic Crystals

Manipulating and controlling light propagation have become a topic of strong interest from the past decades. It is motivated by the purpose of exploiting original electromagnetic phenomena, easing the fabrication, reducing the losses and the possibility of integrating several optical functions onto one single device. In the last five decades, the ability to control the flow of light further improved by introducing the idea of a graded index optics [Moore (1980); Reino (2002)]. A conventional graded index medium is characterized by a gradual variation in refractive index along the directions transverse to light propagation. Within the graded index medium, light bends gradually toward higher refractive index per Snell's law, resulting in superior control over the propagation of light that cannot be achieved by an ordinary medium. In general, we witness graded index media in nature via different means: some examples are the crystalline lens of the eye, the atmosphere of the earth and the mirage effect. As mentioned before, the possibility of employing graded index media in optic and photonic systems has been attracted a great attention of scientists in this area. The widely employed version of a graded index medium can be found in the fiber optic technology that is known as graded index fibers. The unique feature of graded index fibers is the nature of its rich modal dispersion relation. The non-uniform index distribution enables the different order of modes to travel different distances at equal times [Feit (1978); Sharma (1981)]. It is known that light-rays follow curved trajectories in a graded index medium. Consequently, curving the light path gives birth to the optical effects same in conventional optical elements with curved interfaces such as focusing, diverging or collimation. Pioneering works paved the way for future developments in the field of graded index optics and its optical applications. To work in the diffraction regime, PCs are also a possible approach. As presented in the previous section, the dispersion properties of PCs can be used for the manipulation of light. Because of their ability to control and manipulation of the propagation of light and their compatibility with conventional micromachining techniques, PCs are promising candidates to assist the development of integrated photonic circuit and on-chip optical processing. The versatility of PCs in controlling manipulating light propagation can be further enhanced by introducing the gradual modulation of structural and material parameters. Such type structures are called graded photonic crystals (GPCs). GPCs rely on the gradual modifications of the PC lattice parameters (filling factor, refractive index etc.) that gradually change their dispersive properties and thus, result in a smooth reorientation of the light propagation direction as light flows. J. Russel made the first theoretical study of GPCs in 1999 [Russel (1999)]. However, the real growth of GPCs began with the works of E. Centeno and co-authors in 2005 [Centeno, 2005]. The gradual modification of structural parameters in GPCs opens a new way to control electromagnetic wave propagation in PCs, and many applications are inspired by this notion.

1.3.1 Design and applications of graded photonic crystals

It is feasible to design a graded index media if the parameters of the PCs are rearranged appropriately. These structures are known as graded index PCs and can be designed by engineering of PC parameters such as gradual changing of filling factor, lattice period, and/or material index [Zhu (2015)]. By modifying the PC parameters, the index variation is obtained in the structures. GPCs are readily fabricated in 1-D/2-D by using the state-of-the-art e-beam direct write micro-fabrication. Self-assembly of micro-spheres of different sizes and direct laser write could also be used to fabricate 3D GPCs [Park (2005); Han (2012); Rybin (2015)].

1.3.2 One-dimensional graded photonic crystals

In the case of 1-D GPCs, there are two ways of modifying PC Parameters; the first way is to change the PC lattice constant. In literature [Gaufillet (2013)], authors designed and fabricated a graded index PC lens as shown in figure 1.10.

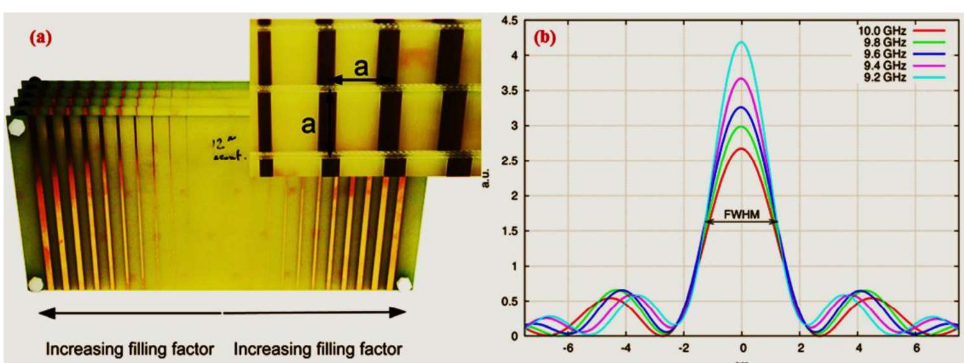


Figure 1.10 (a) Picture of the graded photonic crystal lens, and (b) Profile of the electric field at several frequencies in the focal plane [Gaufillet (2013)].

In this case, the gradient of index forms by the variation of filling factor of the PC in the direction perpendicular the propagation of the electromagnetic waves. The designed graded PC structures are supposed to focus a plane wave at the required focal length. In literature [Rauh 2012], the authors studied the optical transmittance of 1-D graded photonic structures generated by logarithmically similar dielectric constituents. The designed graded PC structures are capable of unfolding desirable and useful optical properties such as transparency at low frequencies but opacity or selectivity at higher frequencies in one single photonic device. The second way of achieving index variation is to change the refractive index of the constituents. Recently, Sang et al. [Sang (2006)] and Rauh et al. [Rauh 2010] demonstrated the optical properties of 1-D GPCs with space dispersive permittivity and permeability which vary along the direction perpendicular to the surface of the layers. Pandey et al. [Pandey (2008)] also studied the PBG properties in 1-D PC composed of exponential graded index material and observed that graded material enhanced the PBGs and affects the reflectance significantly. One way is to tailor refractive index in PC structures as a function of temperature because the permittivity and permeability of materials are very much dependent on temperature. The properties revealed for 1-D GPCs offer unique possibilities regarding optical filters, mirrors, sensors and other optical devices.

1.3.3 Two-dimensional graded photonic crystals

In the case of 2-D GPCs, there are three methods of modifying PC parameters; the first method is to change the PC lattice constant. In literature [Centeno (2005); Centeno (2006)], the author designed GPC structures by changing the lattice constant. The authors claim that these structures through modifying the lattice constant can bend the incident Gaussian beam. The bending of the electromagnetic waves depends on the wavelength of the electromagnetic waves, which leads to the possibility of the application on wavelength division multiplexing. The second method of modifying PC parameter is varying the filling factor, including the hole radius and shapes. Qi Wu et al. [Wu (2008)] designed a graded negative index lens by increasing the air-hole radius from the center towards the edges along the transverse direction and keeping the lattice constant unchanged. They studied the focusing of a graded PC when different modifications to the size of scatters are introduced Lei et al. [Lei (2013)] studied the focusing property of Graded index PC with different air-hole shapes on a dielectric film. Such GPCs designed with elliptical or circular air holes have longer focal length, while the GPCs with square or rectangular air-holes have smaller focal spot size. The final way of realizing index variation is to change the refractive index of the rods. It requires different materials with desired index values to be used. It is difficult to find proper materials to constitute a certain index gradient, so this method is seldom used. Comparing these three methods, the change of lattice spacing seems to be more practical than the others because the changes in the hole radius require precise and small increments, and the range of the index gradient is limited that can be achieved. Moreover, Kun Ren and Xiaobin Ren [Ren (2011)] constructed a Graded index PC with a square lattice of elliptical dielectric rods observed that the direction of propagation could be easily manipulated by the gradually varying the orientation of the elliptical rods. H. W. Wang et al. [Wang (2011)] designed 2-D graded index PC and used it for forming an optical black hole. GPCs play an important role to design spectral filters, beam aperture and deflector, high-efficiency bending waveguides and couplers, self-focusing media, lenses, artificial optical black holes, antireflection coating and other optical devices can also be designed with the help of GPC concept which will be efficiently guiding and manipulating the flow of light [Zhu (2015); Turduev (2015); Oner (2013)].

1.3.4 Three-dimensional graded photonic crystals

The gradient in 3-D PCs poses the gradual variation of the structural and material parameters in all three directions. In literature [Freymann, 2005], the authors presented enhanced coupling to slow photon modes in graded 3-D colloidal PCs. This is achieved by a convenient and precise post-fabrication method to incorporate filling fraction gradients into 3-D polymer colloidal PCs. Park et al. [Park, 2005] also demonstrated a novel PC structure with a graded index distribution in which an infiltrated polymer in a colloidal opal causes a gradual increase in the refractive index. Positional refractive index variation in the GPC was successfully achieved using interfacial gel polymerization and a high-index dopant, which leading to the positional band gap tunability. These GPC structures may be useful for a wide range of photonic applications such as tunable optical filters and various passive optical components. The GPCs show wider and deeper photonic band gaps as compares to the ungraded ones. Han et al. [Han, 2012] fabricated 3-D GPCs in dichromate gelatin holographic plates using a multi-beam optical interference holography technique by imposing a gradient refractive index. It may also be possible to fabricate compositionally graded materials by doping method; wherein the composition is varied in the desired direction resulting in graded profile refractive index. The variety of processes can fabricate these types of structures, included nanolithography and thin film techniques such as chemical vapour deposition, sputtering deposition, spin coating techniques. and self-assembled method, etc. [Park (2005); Chhajed (2011); Aytug (2015)].

1.4 Photonic quasicrystals

The physics of periodic PC structures has fundamental importance and result in various phenomena that govern wave transport and interference. However, deviations from periodicity may result in higher complexity and give rise to a number of surprising effects and make the PC promising to realize integration with the integrated circuits and optical devices. One such deviation can be observed in the field of optics in the realization of quasi-periodic PCs, a class of structures made from building blocks that are arranged according to well-designed patterns but the lack of translational symmetry [Levine (1984)]. Quasi-periodic systems break translational periodicity while maintaining a well-defined and long-range ordered structure [Socolar (1986); Kohmota (1987)]. Quasiperiodic sequences are one of the most interesting arrangements to obtain the suitable PBG because of several structural parameters accessible to tune PBG as compared to the periodic and disordered systems. Quasiperiodic structures provide distinctive opportunities to tailor light matter interaction, electromagnetic transport, light scattering and wave localization phenomena in complex photonic media. The structural complexity of such media profoundly influences their linear and nonlinear optical properties and offers to the novel and interesting functionalities. Recently, some research groups have reported their works on electromagnetic wave propagation in quasi-periodic structures so called photonic quasicrystals. Photonic quasicrystals are artificial dielectric inhomogeneous media and have neither true periodicity nor translational symmetry but have a quasi-periodicity that exhibits long-range order and orientational symmetry [Steurer (2009); Poddubny (2010); Vardeny (2013)]. These structures show sharp diffraction patterns that confirm the existence of wave interference ensuing from their long-range order. Quasi-periodic systems open a new field of research in photonics in perspective of their vast technical applications.

As like conventional PCs, photonic quasicrystals (PQCs) are the structures composed of two or more materials of different refractive index arranged in a quasi-periodic configuration along one, two and three dimensions.

1.4.1 One-dimensional photonic quasicrystals

Structures wherein the deterministic quasiperiodic modulation of dielectric constant is present only in one spatial direction are termed for simplicity as 1-D PQCs. These structures are very important because their formation is relatively easy and they may provide the description of light propagation in one direction. 1-D PQCs are composed of layers of different materials according to different types of quasi-periodic sequences such as the Fibonacci, Thue–Morse and Periodic-doubling, etc. [Steurer (2009); Poddubny (2010)]. Among the various 1-D quasicrystals, the Fibonacci quasiperiodic sequence has been the subject of an extensive theoretical and experimental effort in the last three decades. The first example of an aperiodic system that possesses long range order in the field of optics was described by Kohmoto et al., [Kohmoto (1987)] who proposed a suitable system for studying the photonic localization in a Fibonacci quasiperiodic layered medium. The transmission spectra from dielectric multilayer stacks composed of two transparent dielectrics of different dielectric constant arranged in a Fibonacci sequence are shown in figure 1.11 [Vardeny (2013)].

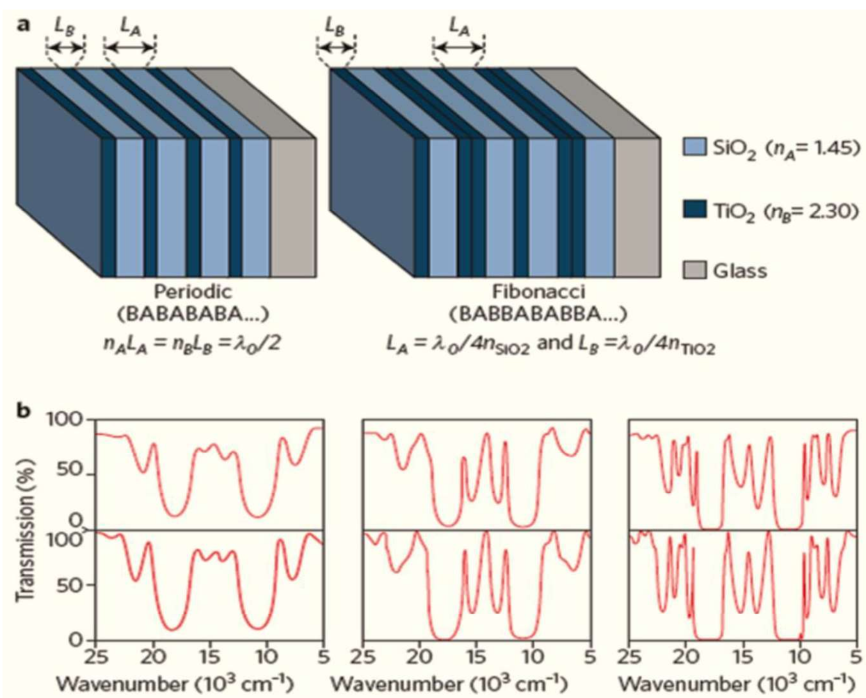


Figure 1.11 (a) Schematic of a non-resonant multilayer Fibonacci structure composed of two dielectric layers (SiO_2 and TiO_2) of thicknesses L_A and L_B deposited using electron-beam evaporation on a glass substrate. (b) Optical transmission spectra for Fibonacci dielectric coating stacks F_6 to F_8, that show the evolution of the transmission spectrum with the number of layers as F_n increases.

More recent theoretical and experimental investigations have focused on application-oriented issues, including filtering properties, broad omnidirectional reflection, symmetry-induced perfect transmission, pulse compression and band-edge resonances [Steurer (2009); Poddubny (2010); Macia (2012); Vardeny (2013)]. A simple example of Fibonacci PQC is a two-component Fibonacci multilayer, where layers of two different materials are arranged according to the Fibonacci substitution rule $\sigma(A) \rightarrow AB$ and $\sigma(B) \rightarrow A$. According to these substitution rules, Fibonacci sequence F_j (j = 0, 1, 2, 3 …) satisfied the recurrence relation; $F_{j+2} = \{F_{j+1}F_j\}$ with initial conditions $F_0 = B$ and $F_1 = A$ and F_j represent the j^{th} generation of the Fibonacci sequence. Using above recurrence relation; $F_2 = AB$, $F_3 = ABA$, $F_4 = ABAAB$ and so on. The ratio of the two successive Fibonacci numbers forms a series with $\lim_{j\to\infty} F_{j+1}/F_j = \tau$, where τ is known as Golden mean and equal to $(1 + \sqrt{5})/2$. A key feature of these man-made materials is the presence of two kinds of order in the same sample at different length scales: the usual crystalline order is determined by the periodic arrangement of atoms in each layer at the atomic level, whereas at longer scales, the aperiodic order is determined by the sequential deposition of the different layers. Negro et al. [Negro (2003)] have reported the first experimental study on light transport through the band edge resonances of a 1-D optical Fibonacci system. Same groups have investigated the propagation of the light pulse through Fibonacci quasicrystals and demonstrated the delays of the transmitted signals and strong pulse stretching close to the band gap and mirror symmetric transmission spectra [Ghulinyan (2005); Peng (2002)]. The mirror symmetry creates dimers of the type A│A, B│B, ABA│ABA, etc., which give rise to narrow resonance modes with the perfect transmission. Recently, Gomez et al. [Gomez (2010)] have investigated the properties of Plasmon polaritons in 1-D Fibonacci PQC made up of positive refraction and metamaterial (negative refraction) layers. Results show that the Plasmon polariton modes are considerably affected by the increasing of the Fibonacci-sequence order. The interest has also been progressively moved on toward other classes of aperiodic structures which also exhibit interesting photonic properties. Thue-Morse structures present another popular 1-D quasi-periodic system [Kohmoto (1987); Liu (1997)]. The optical properties of multilayers based on the Thue–Morse sequence have also received considerable attention during the last two decades [Moretti (2006); Jiang (2005)]. This popular sequence has been extensively studied in the mathematical literature as the prototype of a sequence generated by the substitution rule σ(A) → AB and σ(B) → BA. In this case, the continued process reads A → AB → ABBA → ABBABAAB → ABBABAABBAABABBA → .... Thus, starting from a single layer T_0 = A, which is defined to be the Thue-Morse of the 0^{th} generation, others obtain T_1 = AB, T_2 = ABBA, T_3 = ABBABAAB and so forth. The Frequency of letters (A, B) in this sequence increases geometrically, and these are equal. The length of the sequence is 2^k, where k indicates the iteration order. In the infinite limit, the relative frequency of both kinds of letters in the sequence takes on the same value. One important difference is that in the Fibonacci sequence B letters always appear isolated, whereas in Thue–Morse sequence both dimers AA and BB appear alike [Steurer (2009)]. Agarwal et al. [Agarwal 2005] have presented the light transport in the Thue–Morse multi-layered structures from porous silicon and observed an enhancement in the number of photonic bandgaps with a significant blue shift in reflectance peaks. The linear transmission spectrum of such photonic structures was shown to have some remarkable properties. Recently, Grigoriev et al. [Grigoriev (2010)] have investigated the nonlinear properties of PQCs based on the Thue-Morse sequence and shown that the interplay between the intrinsic spatial asymmetry of these structures for odd generation numbers and Kerr nonlinearity that makes the switching thresholds induced by bistability and multi-stability sensitive to the propagation direction. Periodic-doubling structures are other deterministic 1-D aperiodic systems. For this sequence, the substitution rule is σ(A) → AB and σ(B) → AA, and the continued process gives A → AB → ABAA → ABAAABAB → ... The number of letters in this sequence increases as N = 2^k (like the Thue–Morse sequence) but letters B appear always isolated (like the Fibonacci sequence) and the ratio of the frequencies of the letters A, B in the sequence is 2 to 1 [Steurer (2009); Poddubny (2010)]. There are only very few studies devoted to the spectral properties of the periodic doubling PQCs. Recently, Vasconcelos et al. [Vasconcelos (2007)] have investigated the photonic band gaps in quasiperiodic PC structures. The structures are characterized by the nature of their Fourier spectrum, which can be dense pure point (Fibonacci sequences) or singular continuous (Thue-Morse and double-periodic sequences). Authors pointed out the distribution of the allowed photonic bandwidths and localization modes for high generations. The self-similarity properties of quasicrystal transmission spectra for such structures have also reported by several research groups [Albuquerquea (2003); Aynaou (2005); Coelho (2010)]. Moreover, Ali et al. [Ali (2011)] have presented theoretical models of stop band filters using hybrid periodic/quasiperiodic 1-D photonic crystals in the microwave region.

1.4.2 Two-dimensional photonic quasicrystals

Two-dimensional (2-D) photonic quasicrystals (PQC) are the structures based on the arrays of dielectric or metallic cylindrical rods or air holes in a dialectic or metallic slab located at the tile vertices (or centers) of aperiodic tilings. Quasiperiodic PC structures in 2-D can possess the higher degree of rotational symmetry than traditional 2-D PCs. The PQCs exhibit the remarkable property to have complete bandgaps in the presence of sufficiently high statistical symmetry [Chen (1998); Zoorob (2000)]. In the first studies, the most common 2-D quasicrystals (QCs) was devoted to geometries based on the octagonal [Chen (1998)], Penrose (or decagonal) [Jin (1999)] and dodecagonal [Zoorob (2000)] tiling, which highlighting the possibility of achieving band gap, wave guiding, and localization effects. Notomi et al. [Notomi (2004)] fabricated PQC laser with a Penrose lattice that does not possess translational symmetry but has long-range order. Authors observed coherent lasing action due to the optical feedback from quasiperiodicity. A comparative study of the local density of state of octagonal- and decagonal-PQCs was performed by Wang et al. [Wang (2003)]. 2-D deterministic aperiodic arrays (Fibonacci, Thue–Morse, Rudin–Shapiro) of gold nanoparticles were fabricated by electron beam lithography on quartz substrates in reference [Gopinath (2008)]. Recently, the PBG properties of octagonal-, decagonal- and dodecagonal- rotational symmetric PQCs defined by level set equations with various phase parameters have reported by Jia et al. [Jia (2012)].

1.4.3 Three-dimensional photonic quasicrystals

Higher-dimensional PQCs (2-D and 3-D) offer greater flexibility over 1-D PQC structures in the design of their geometry and potential applications. Most important and well known 3-D PQCs is an icosahedral structure. PQCs with icosahedral geometry was fabricated by Man et al. [Man (2005)] via stereo lithography and experimentally characterized at microwave frequencies. PQCs with the quasiperiodic order arranged in all three spatial directions have been fabricated by Ledermann et al. [Ladermann (2006)] by using the direct laser writing technique for infrared frequencies. Another realization of 3-D icosahedral quasicrystal by optical interference holography technique has been reported by Xu et al. [Xu, 2007]. The lasing effect from dye doped icosahedral quasicrystals has been observed by Kok et al. [Kok, 2009]. In 2010, Ledermann et al. [Ledermann (2010)] rationally construct first-time rhombicuboctahedral 3-D PQCs.

PQCs have higher rotational symmetries than conventional PCs and corroborated interesting optical properties including isotropic photonic band structures, defect-free localized modes, multiple band gaps, and the possibility to open a photonic band gap (PBG) at quite low refractive index contrast. Therefore PQCs are excellent candidates for various photonic applications, including lensing, wave-guiding, negative refraction, nonlinear interaction, optical fiber devices, plasmonics, photonic gels and energy applications. [Steurer (2009); Poddubny (2010); Macia (2012); Vardeny (2013)].

1.5 Research trends on 1-D photonic crystals

PCs have emerged as attractive optical materials for controlling and manipulating the transmission and reflection of light based on the properties of photonic band gaps. After two decades of intensive research, PCs are poised to reap their commercial benefits. Several companies have been developed the technology to market initially as waveguides and high-resolution spectral filters, mirrors in optical communications. Now a day, several different strategies have been explored to efficiently use solar light for photo-catalytic reactions. One of these strategies is to use photonic crystals to enhance light-matter interactions. It is also well known that every rapid development of optical communication depends on the breakthrough of optoelectronic devices, such as semiconductor lasers and optical amplifiers. Photonic integrated circuits (PICs) have been considered as the key technology for breaking the bottleneck of transmission capacity and energy consumption in the future broadband network. The optical properties of PCs can be tuned by various external stimuli through the manipulation of refractive index, lattice constant, crystal symmetry, and orientation. Their usefulness as sensors for detecting the presence of or change in stimuli is itself-evident. A great number of studied have been reported for using PCs as temperature, chemical, biomolecule, humidity, and vapor and pressure sensors.

PCs with bandgaps in the visible range can show brilliant colors and therefore hold great potential for many applications that require presentation of visual information. The structural colors produced by PCs feature many unique characteristics that cannot be mimicked by traditional pigments, dyes, or phosphors. A PC may produce a wide range of colors. Photonic printing and inking are also important technical extensions of PCs. For recording purposes, the structural colors of PC structures are more durable than traditional pigments and dyes. R&D (research and development) now under way will develop the applications of photonic crystals in displays include LEDs, optical fibers, image sensors, laser and super continuum sources, solar and PV cells, integrated and discrete optical components, biosources and PCs thin films to serve as anticounterfeit protection on credit cards. Ultimately, researchers hope to build diodes and transistors from this novel material that will one day enable to the construction of an all-optical computer.

All the PCs application based on the photonic band gap properties that lead to manipulating and control the flow of light. The ability to control and manipulating the flow of light further improved by introducing the idea of graded index optics in PC structures. Such type structures are called GPCs. GPCs play an important role in designing spectral filters, high efficiency bending waveguides, couplers, self-focusing media, artificial optical black holes and antireflection coating, etc. In addition, it is possible to create energy levels in the photonic band gap by introducing defect and aperiodicity in the structures of PCs that can be tuned by of refractive index, lattice constant of slabs and aperiodicity of PC structures. This feature makes PCs especially useful in optical telecommunications and as laser sources, and sensors.

1.6 Theoretical aspects of one-dimensional photonic structures

The fabrication of novel photonic devices is usually preceded by a design phase, involving the theoretical modeling of the device's optical behavior, based on the properties of the applied materials. Various techniques have been developed for the theoretical study of light scattering, interference, or diffraction caused by PC structures. Analytical treatments are only possible for some particular cases, and many approaches have to rely on approximations or simulation of the electromagnetic fields in the structure of interest. Common numerical modeling techniques include:

- **Transfer matrix techniques.**
- **Finite-difference time-domain simulations.**
- **Plane wave expansion techniques.**

These theoretical methods are very powerful tools if one keeps aware of their limitations and interprets results correctly. The PC structures are designed with the help of numerical modeling techniques using any of the above methods. One of the main aspects of this thesis is the study of periodic multilayer structures known as 1-D PCs. Interference effects, occurring in flat multilayer structures can be treated analytically by using transfer matrix techniques or by extending the derivation of the reflection coefficients of a single thin film to the case of any number of layers. These calculations give precise solutions but cannot easily be extended to the treatment of non-planar structures.

Transfer matrix method [Yeh (1988), Born (2005)] essentially converts Maxwell's equations into a set of finite difference equations in real space and then rearranges those equations into the form of a transfer matrix. This transfer matrix relates the electric and magnetic fields in one medium to the fields in an adjacent medium. If the field is known at the beginning of a layer, the field at the end of the layer can be derived from a simple matrix operation. A stack of layers can then be represented as a system matrix, which is the product of the individual layer matrices. The final step of the method involves converting the system matrix back into reflection and transmission coefficients. By comparing the transfer matrix equation to Bloch's law, it can be seen that the band structure is given simply by the eigenvalues of the transfer matrix. This approach has several key advantages over the plane wave method. The transfer matrix is calculated for a specific value of ω and gives us all the possible values of k; however, the plane wave method fixes k and searches for all the possible values of ω. This can be far more convenient, especially if the dielectric function is some complex function of frequency as it is in the case of metals. The one major disadvantage is that it becomes impossible to map the band structure along an arbitrary direction in k-space, something which is trivial to do using a plane wave technique.

The plane wave method [Joannopoulos (2008)] was the first technique used to solve the full vector photonic band structure problem. It is the most widely used due to its ease of implementation and wide applicability. It is a computational technique in electromagnetics to calculate the dispersive relationship by solving an eigenvalue problem in a perfect and infinite large lattice and is useful over an inhomogeneous and periodic geometry. Band diagrams can be acquired by sampling the dispersive relationship within the first Brillion zone. Field components can be obtained in the same process. Thus, field distribution for each mode could be plotted accordingly. The advantage of this method is that it can be used for almost any PC structure and yields directly the dispersion diagram and gives a fair insight into the physics of PCs. However, disadvantage lies in the requirement that the materials have positive and relatively constant dielectric permittivity. Metals and other highly dispersive materials cannot be efficiently solved for divergence problems.

Finite-difference time-domain is a versatile modeling technique used to calculate the electric field distribution by solving Maxwell's equations; it can be used to simulate 2-D and 3-D PC structures for transmission, field distribution verses wavelength or Quality factor of a resonant cavity. This method was introduced by K. Yee. Nowadays, this method use as computational analysis for electromagnetic systems allows for the calculation of the time-evolution of electric fields in a given medium or media. The calculations are performed by dividing the computation cell into discrete points and solving Maxwell’s equations at each point in discrete time steps. This is, of course, an approximation of the real system which is improved as the discrete units of space and time are made smaller until a highly accurate representation of the true electromagnetic response may be calculated. However, it has also some disadvantage, which does not facilitate the physical understanding, it is extremely computer resource consuming and requires a right choice of initial and boundary conditions to excite all the desired Bloch modes and to avoid spurious reflections due to the finite size of the calculation area.

The analysis is mainly accomplished by Transfer matrix method in this thesis. Before described how the Transfer matrix is applied to the electromagnetic waves through a multilayer system, the interaction between the electromagnetic field and a medium is the main question for the understanding of fundamentals of optical wave propagation in optical media. In normal cases, optical medium assumed to be isotropic dielectric and time invariant. Electromagnetic wave propagation in a dielectric medium is the starting point, which is governed by Maxwell’s equations. We shall then see how these discrete equations can be recast into the form of a transfer matrix which connects the electric and magnetic fields in one layer of lattice points to those in another. Once we have the transfer matrix problem is, formally at least, solved because by taking products of transfer matrices we can find the fields at every point in our system and from this extract band structure or transmission and reflection information.

1.6.1 Electromagnetic wave in dialectic media

The propagation of electromagnetic wave is characterized by four Maxwell’s equations. In case of an isotropic dielectric medium:

$$\mathbf{D = \varepsilon\, E,\ B = \mu\, H,\ J = \sigma\, E = 0\ and\ \rho = 0.}$$

Therefore, Maxwell's equation in isotropic dielectric medium can be written as:

$$\left.\begin{aligned} \mathbf{div\,E} &= \nabla.\mathbf{E} = 0 \\ \mathbf{div\,H} &= \nabla.\mathbf{H} = 0 \\ \mathbf{curl\,E} &= \nabla\times\mathbf{E} = -\mu\frac{\partial \mathbf{H}}{\partial t} \\ \mathbf{curl\,H} &= \nabla\times\mathbf{H} = \varepsilon\,\partial\mathbf{E}/\partial t \end{aligned}\right\} \quad \ldots\ldots \quad (1.1)$$

In the above equation the notation have the following meaning:

D = electric displacement vector (coulomb/m^2),

E = electric field intensity (volt/m),

B = magnetic induction (weber/m^2), H = magnetic field intensity (amp/m),

P = electric charge density (coulomb/m^3), J = electric current density (Amp/m^2),

ε = absolute permittivity, μ = absolute permeability, σ = conductivity.

It is apparent that equations (1.1) are identical in the form to the well-known free space Maxwell's equations except that ε replaces ε_0 (free space permittivity) and μ replaces μ_0 (free space permeability). Each component of E and H therefore satisfied the wave equation:

$$\nabla^2 \mathbf{u} - \frac{1}{v^2}\frac{\partial^2 \mathbf{u}}{\partial t^2} = 0 \quad \ldots\ldots \quad (1.2)$$

where u is a scalar and can be stand for any one of the components of E and H, and v is the speed of light in the medium and given by; $v = \frac{1}{\sqrt{\varepsilon\mu}}$. Thus, wave equation for electric field (E) and magnetic field (H) may be expressed as:

$$\nabla^2 \mathbf{E} - \frac{1}{v^2}\frac{\partial^2 \mathbf{E}}{\partial t^2} = 0 \quad \ldots\ldots \quad (1.3)$$

$$\nabla^2 \mathbf{H} - \frac{1}{v^2}\frac{\partial^2 \mathbf{H}}{\partial t^2} = 0 \quad \ldots\ldots \quad (1.4)$$

The plane-wave solutions of equations (1.3) and (1.4) in well-known form may be written as:

$$\left.\begin{aligned} E(r,t) &= E_0\, e^{ik.r - i\omega t} \\ H(r,t) &= H_0\, e^{ik.r - i\omega t} \end{aligned}\right\} \quad \ldots\ldots \quad (1.5)$$

where E_0 and H_0 are complex amplitudes which are constant in space and time: while k is wave propagation vector given by; $k = \frac{2\pi}{\lambda}\hat{n} = \frac{\omega}{c}\hat{n}$. Here, $\hat{n}$ is a unit vector in the direction of wave propagation.

1.6.2 Reflection and refraction for electromagnetic waves

In general, a plane wave incident on the interface will be split into two waves: a transmitted wave proceeding into second medium and a reflected wave propagating back into the first medium. The existence of these two waves is a direct consequence of the boundary conditions on the field vector. Assume a light wave impinging on an interface between two media of optically smooth dielectric materials with distinct refractive indices n_1 and n_2, at an angle θ_1 with respect to the interface normal. Part of the wave is specularly reflected, while the rest is refracted (figure 1.12). If angles θ_1 and θ_r are the incident and reflected angles of the wave vectors with respect to the normal of the plane interface normal. The refracted light propagates into the second medium at an angle θ_2 given by Snell's law;

$$\boldsymbol{n_1.\sin\theta_1 = n_1.\sin\theta_r = n_2.\sin\theta_2} \quad \dots\dots \quad \textbf{(1.6)}$$

This implies that the angle of incident must equal the angle of reflection ($\theta_1 = \theta_r$).

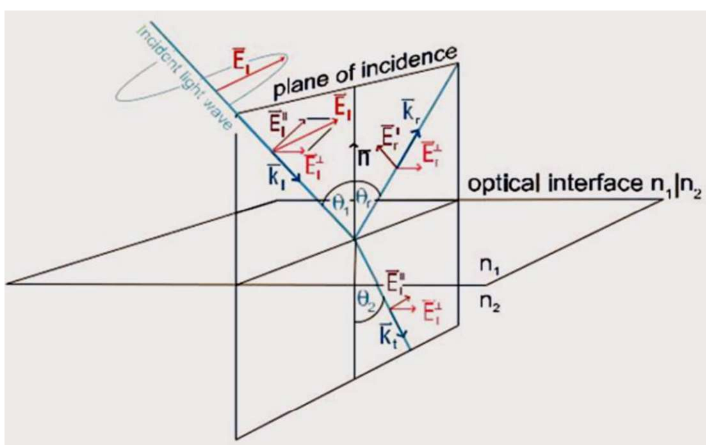


Figure 1.12 Reflection and refraction at an optical interface between two medium (n_1 and n_2). The wave vectors of the incident, transmitted and reflected waves are $\overrightarrow{k_1}$, $\overrightarrow{k_t}$ and $\overrightarrow{k_r}$. The electric field are $\overrightarrow{k_1}$, $\overrightarrow{k_t}$ and $\overrightarrow{k_r}$, decomposed into their components parallel and perpendicular to the plane of incidence, $\vec{E}^{\parallel}$ and $\vec{E}^{\perp}$.

The coordinate system is considered such that the xz plane is the plane of incidence. A general solution (equation 1.5) of each isotropic dielectric optical medium for time considered as invariant can be taken as the superposition of the incident and reflected waves:

$$E = \begin{cases} E_i e^{-ik_1.r} + E_r e^{ik_r.r}, & x < 0 \\ E_t e^{-ik_2.r}, & x > 0 \end{cases} \quad \ldots\ldots \quad (1.7)$$

where E_i, E_r and E_t are the constant complex vectors for the incident, reflected and transmitted waves, $\overrightarrow{k_i}$ $\overrightarrow{k_t}$ and $\overrightarrow{k_r}$ are the wave vector of the incident, transmitted and reflected waves. The magnetic field vector H can be obtained from the equation;

$$H = \frac{i}{\omega\mu} \nabla \times E \quad \ldots\ldots \quad (1.8)$$

where ω is the angular frequency.

The electric field amplitudes E_r and E_t and intensities R and T of the reflected and the transmitted light depend on the polarisation of the incident light. Imposing the continuity of electric and magnetic field at the interface between two media for transverse electric (TE) polarization (the electric field vector E is transverse to the plane of incidence) and transverse magnetic (TM) polarization (the magnetic field vector E is transverse to the plane of incidence), we obtain the Fresnel's reflection and transmission coefficients:

$$\left.\begin{aligned} r_{\parallel} &= \frac{E_r^{\parallel}}{E_i^{\parallel}} = \frac{n_2 cos\theta_1 - n_1 cos\theta_2}{n_2 cos\theta_1 + n_1 cos\theta_2} \\ r_{\perp} &= \frac{E_r^{\perp}}{E_i^{\perp}} = \frac{n_1 cos\theta_1 - n_2 cos\theta_2}{n_1 cos\theta_1 + n_2 cos\theta_2} \\ t_{\parallel} &= \frac{E_t^{\parallel}}{E_i^{\parallel}} = \frac{2 n_1 cos\theta_1}{n_2 cos\theta_1 + n_1 cos\theta_2} \\ t_{\perp} &= \frac{E_t^{\perp}}{E_i^{\perp}} = \frac{2 n_1 cos\theta_1}{n_1 cos\theta_1 + n_2 cos\theta_2} \end{aligned}\right\} \quad \ldots\ldots \quad (1.9)$$

These equations provide a measure for the amplitude of reflected and transmitted light. The intensity of parallel and perpendicular polarised, reflected and transmitted light $R_{\parallel}$, $R_{\perp}$ and $T_{\parallel}$, $T_{\perp}$ are then given by;

$$\left.\begin{aligned} R_{\parallel,\perp} &= r^2_{\parallel,\perp} \\ T_{\parallel,\perp} &= t^2_{\parallel,\perp} \end{aligned}\right\} \quad \ldots\ldots \quad (1.10)$$

Above formulas can be applied to any two media for performing the reflectance and transmittance, respectively.

1.6.3 Matrix Theory of Multilayer Optics

A plane wave normally incident on a layered medium undergoes reflections and transmissions at the layer boundaries, which in turn undergo their own reflections and transmissions in an unending process, as illustrated in figure 1.13(a). The sums of these waves add up to a single forward collected wave A and a single backward collected wave B at any point, as illustrated in figure 1.13(b).

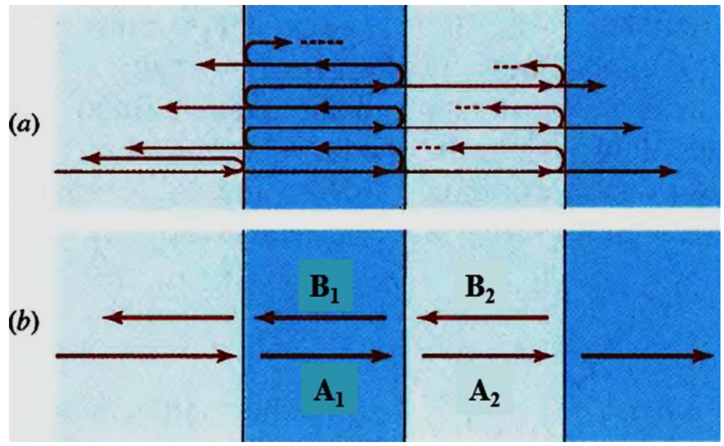
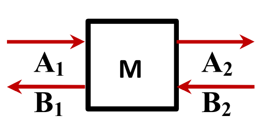


Figure 1.13 (a) Reflection of a single wave from the boundaries of a multi-layered medium. (b) In each layer, the forward waves are lumped into a forward collected wave A, and the backward waves are lamped into a backward collected wave B.

Determining the wave propagation in a layered medium is then equivalent to determining the amplitudes of this pair of waves everywhere. The complex amplitude of the transmitted and reflected waves may be determined by use of the Fresnel equations at each boundary; the overall transmittance and reflectance of the medium can be calculated by superposition of these individual waves, or by imposing the appropriate boundary conditions.

1.6.3.1 Wave-transfer matrix

Tracking the complex amplitudes of the forward and backward waves through the boundaries of a multi-layered medium is facilitated by use of matrix method. Consider two arbitrary planes within a given optical system, denoted plane 1 and 2. The amplitudes of the forward and backward collected waves at plane 1, A_1 and B_1, respectively are represented by a column matrix of dimension 2, and similarly for plane 2 represented by A_2 and B_2. These two column matrices are related by the matrix equation:



$$\begin{bmatrix} A_2 \\ B_2 \end{bmatrix} = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix} \begin{bmatrix} A_1 \\ B_1 \end{bmatrix} \quad \dots\dots \qquad \textbf{(1.11)}$$

The matrix M, whose elements are M_{11}, M_{12}, M_{21} and M_{22}, is called the wave transfer matrix. It depends on the optical properties of the layered medium between the two planes.

A multi-layered medium is conveniently devided into a N of the basic elements described by wave transfer matrices, say M_1, M_2, …, M_N. The amplitudes of the forward and backward collected waves at the two ends of the overall medium are then related by a single matrix that is the matrix product, M = M_N……M_2M_1, where the elements 1, 2, … , N are numbered from initial to end.

1.6.4 Matrix optics of one-dimensional photonic crystals

One-dimensional (1-D) PCs are multi-layered structures whose optical properties vary periodically in one direction, called the axis of periodicity. If the axis of periodicity is taken to be the x direction, then optical parameters such as refractive index are the periodic functions of x satisfying: $n(x + d) = n(x)$, for all values of x, where d is the period. A simple periodic layered medium may be considered as a periodic array of two different dielectric materials. Here, we have also considered a 1-D periodic medium comprises identical segments of dielectric materials with different refractive indices that are repeated periodically along one direction and separated by the period d. The schematic view of 1-D PC structures composed of N periodic unit cell of like $(AB)^N$ is shown in figure 1.14.

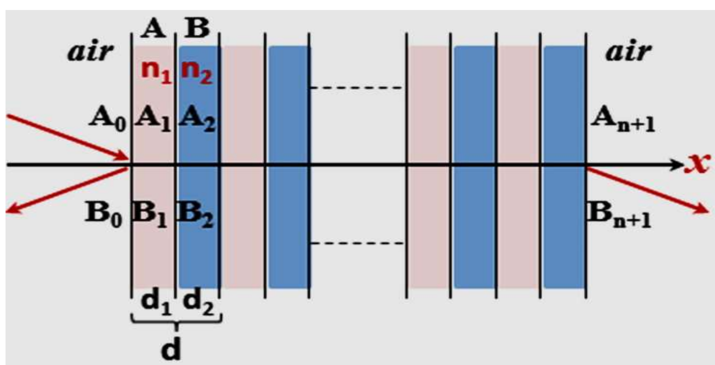


Figure 1.14 The schematic representation of the stacking of two different dielectric materials (A and B) in the form of the periodicity.

The proposed periodic structure consist two kinds of layer A and B with relative refractive index n_1 and n_2, and thickness d_1 and d_2. The propagation of electromagnetic wave in these periodic media can solve using the solution of wave equation of the considered media as equation 1.5. The electric field distribution E(x) within each homogeneous layer can be expresses as the sum of an incident plane wave and a reflected plane wave. The complex amplitudes of these two waves constitute the components of a column vector of forward and backward waves. The expression for the electric field distribution in the structure with N periodic system can express as;

$$E(x) = \begin{cases} A_0 e^{-ik_0x} + B_0 e^{ik_0x}, & x < 0 \\ A_1 e^{-ik_1x} + B_1 e^{ik_1x}, & 0 \le x \le d_1 \\ A_2 e^{-ik_2(x-d_1)} + B_2 e^{ik_2(x-d_1)}, & d_1 \le x \le d \\ \vdots \\ A_{n+1} e^{-ik_0(x-Nd)} + B_{n+1} e^{ik_0(x-Nd)}, & x \ge Nd \end{cases} \quad \ldots\ldots \quad (1.12)$$

where k_0, k_1 and k_2 are the wave vectors in the air, media A and B, A_n, respectively and B_n (n = 0, 1, 2, 3, …) are the constant complex vectors in the different media and d (= d_A+d_B) is the thickness of a period. Wave vector $k_i = (2\pi/\lambda).n_i$ (i = 0, 1, 2) at normal incident angle.

The frequency dependent coefficients A_n and B_n (n = 0, 1, 2,…) are determined the imposing continuity conditions for both the electric field and its first derivative across the interface from one medium to the next. This establishes a set of equations that we solve by making use of the transfer matrix formalism. Under this formalism, the set of equations for the normal angle of incident can be expressed as:

$$\underbrace{\begin{pmatrix} 1 & 1 \\ -i.n_0 & i.n_0 \end{pmatrix}}_{M_0} \begin{pmatrix} A_0 \\ B_0 \end{pmatrix} = \underbrace{\begin{pmatrix} 1 & 1 \\ -i.n_1 & i.n_1 \end{pmatrix}}_{M_{x10}} \begin{pmatrix} A_1 \\ B_1 \end{pmatrix}$$

$$\underbrace{\begin{pmatrix} e^{-i.k_1d_1} & e^{i.k_1d_1} \\ -i.n_1.e^{-i.k_1d_1} & i.n_1.e^{i.k_1d_1} \end{pmatrix}}_{M_{x11}} \begin{pmatrix} A_1 \\ B_1 \end{pmatrix} = \underbrace{\begin{pmatrix} 1 & 1 \\ -i.n_2 & i.n_2 \end{pmatrix}}_{M_{x20}} \begin{pmatrix} A_2 \\ B_2 \end{pmatrix}$$

$$\underbrace{\begin{pmatrix} e^{-i.k_2d_2} & e^{i.k_2d_2} \\ -i.n_2.e^{-i.k_2d_2} & i.n_2.e^{i.k_2d_2} \end{pmatrix}}_{M_{x21}} \begin{pmatrix} A_2 \\ B_2 \end{pmatrix} = \underbrace{\begin{pmatrix} 1 & 1 \\ -i.n_1 & i.n_1 \end{pmatrix}}_{M_{x10}} \begin{pmatrix} A_3 \\ B_3 \end{pmatrix}$$

$$\ldots$$

$$\ldots$$

$$\underbrace{\begin{pmatrix} e^{-i.k_2d_2} & e^{i.k_2d_2} \\ -i.n_2.e^{-i.k_2d_2} & i.n_2.e^{i.k_2d_2} \end{pmatrix}}_{M_{x21}} \begin{pmatrix} A_n \\ B_n \end{pmatrix} = \underbrace{\begin{pmatrix} 1 & 1 \\ -i.n_1 & i.n_1 \end{pmatrix}}_{M_{x10}} \begin{pmatrix} A_{n+1} \\ B_{n+1} \end{pmatrix}$$

$$\ldots\ldots \quad (1.13)$$

If the electric field is known at the beginning of a layer, the field at the end of the same layer can be derived from a simple matrix operation. A stack of layers can then be represented as a system matrix, which is the product of the individual matrices corresponding to each intermediate slab considered within the system. In this way, it can be directly obtained the relation between the coefficients of the fields in the incident and outgoing media:

$$\begin{pmatrix} A_0 \\ B_0 \end{pmatrix} = M_{i,j} \begin{pmatrix} A_{n+1} \\ B_{n+1} \end{pmatrix}$$

$$= M_0^{-1} . \underbrace{M_{x_{10}} . M_{x_{11}}^{-1}}_{M_1} . \underbrace{M_{x_{20}} . M_{x_{21}}^{-1}}_{M_2} \cdots\cdots\cdots . \underbrace{M_{x_{20}} . M_{x_{21}}^{-1}}_{M_2} . M_0 \begin{pmatrix} A_{n+1} \\ B_{n+1} \end{pmatrix}$$

$$= M_0^{-1} . (M_1 . M_2)^N . M_0 \begin{pmatrix} A_{n+1} \\ B_{n+1} \end{pmatrix} = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} \begin{pmatrix} A_{n+1} \\ B_{n+1} \end{pmatrix}$$

$$= M_{i,j} \begin{pmatrix} A_{n+1} \\ B_{n+1} \end{pmatrix} \qquad \ldots\ldots \quad \textbf{(1.14)}$$

where $M_{i,j}$ $(i, j = 1,2)$ is the total characteristic matrix for n layer system, $M_1$and M_2 are the characteristic matrix of medium A and B, respectively. Thus, the transmittance (T) and reflectance (R) coefficients of electromagnetic wave, can be written as; [Yeh (1988)]

$$\boldsymbol{T} = \left| \boldsymbol{A_{n+1}} / \boldsymbol{A_0} \right|^2 = \left| \mathbf{1} / \boldsymbol{M_{11}} \right|^2 \text{ and } \boldsymbol{R} = \left| \boldsymbol{B_0} / \boldsymbol{A_0} \right|^2 = \left| \boldsymbol{M_{21}} / \boldsymbol{M_{11}} \right|^2 \ldots\ldots \textbf{(1.15)}$$

where M_{11} and M_{22} are the elements of 2×2 optical transfer matrix $M_{ij}(i, j = 1, 2)$. If, considered media are lossless dielectric material, the transmittance will be just the reflectance's complement. Similarly, the expressions for the set of equations across the interface from one medium to the other will be similar for other considered periodic structure but their characteristic matrix will has change due to variation of refractive index of the considered materials.

1.6.4.1 Eigenvalue problem and Bloch modes

According to the Floquet's theorem, the electric field vector of a normal mode of propagation in a periodic medium takes the form as;

$$\boldsymbol{E_K(x, z)} = \boldsymbol{E_K(x)} . \boldsymbol{e^{-i.\beta.z}} . \boldsymbol{e^{-i.K.x}} \quad \ldots\ldots \quad \textbf{(1.16)}$$

where $E_K(x)$ is a periodic function with period d, i.e. $E_K(x + d) = E_K(x)$ and β is the z component of the wave vector. The subscript K indicates that function $E_K(x)$ depends on K. The constant K is known as the Bloch wave number. In terms of our column representation and from the expression (1.11) of the electric field distribution in the periodic structure, the periodic condition (1.16) for the Bloch wave is simply

$$\begin{bmatrix} A_{m+1} \\ B_{m+1} \end{bmatrix} = e^{-j\Phi} \begin{bmatrix} A_m \\ B_m \end{bmatrix} \quad \dots\dots \quad (1.17)$$

where A_m and B_m are the complex amplitudes of the forward and backward waves at the initial position $x = m.d$ of the unit cell m, d is the a period. The modes of the period medium are self-reproducing after transmission through a distance d (in this case a unit cell), the magnitudes of the forward and backward waves remain unchanged and the phases are altered by a common shift Φ, called the Bloch phase. The corresponding Bloch wavenumber is K = Φ/d, so that Φ = Kd.

Determination of the complex amplitudes A_m and B_m, and phases Φ = Kd that satisfy the self-reproduction condition (1.17) can be cast as an eigenvalue problem. This is accomplished by using the transfer matrix expression for a unit cell and equation (1.17), the column vector of the Bloch wave satisfies the following eigenvalue problem;

$$M \begin{bmatrix} A_m \\ B_m \end{bmatrix} = e^{j\Phi} \begin{bmatrix} A_m \\ B_m \end{bmatrix} \quad \dots\dots \quad (1.18)$$

This is an eigenvalue problem for the 2x2 unit cell matrix M (= $M_1.M_2$), $M_1$and M_2 are the characteristic matrix of medium A and B, respectively. The phase factor $e^{-j\Phi}$ is thus the eigenvalue of the translation matrix M and is given by

$$e^{j\Phi} = \tfrac{1}{2}(M_{11} + M_{22}) \pm \left\{\left[\tfrac{1}{2}(M_{11} + M_{22})\right]^2 - 1\right\}^{1/2} \quad \dots\dots \quad (1.19)$$

or equivalently, $$\cos\Phi = \tfrac{1}{2}(M_{11} + M_{22}) \quad \dots\dots \quad (1.20)$$

The eigenvectors corresponding to the eigenvalues of equation (1.19) are obtained from equation (1.18) and are given by

$$\begin{bmatrix} A_0 \\ B_0 \end{bmatrix} = \begin{bmatrix} M_{21} \\ e^{j\Phi} - M_{11} \end{bmatrix} = e^{jm\Phi} \begin{bmatrix} A_m \\ B_m \end{bmatrix} \quad \dots\dots \quad (1.21)$$

where M_{11} and M_{22} are the elements of 2×2 optical transfer matrix $M_{ij}(i, j = 1, 2)$.

1.6.4.2 Dispersion relation and photonic band structure

The dispersion relation is an equation relating the Bloch wavenumber K and the angular frequency ω. The Bloch waves that result from equation (1.20) can be considered as the eigenvectors of the translation matrix with eigenvalues exp(±jKd) given by equation (1.19). The two eigenvalues in the equation (1.19) are the inverse of each other since the translation matrix is unimodular. Equation (1.20) gives the dispersion relation between ω, k_y and K for the Bloch wavefunction

$$\boldsymbol{K(\omega, k_y) = \frac{1}{d}\cos^{-1}\left[\frac{1}{2}(M_{11} + M_{22})\right]} \quad \dots\dots \quad \textbf{(1.22)}$$

where d is total thickness of a period of the periodic system, M_{11} and M_{22} are the elements of 2×2 optical transfer matrix M (= $M_1.M_2$), $M_1$and M_2 are the characteristic matrix of medium A and B, respectively.

The dispersion relation exhibits multiple spectral bands classified into two regimes:

- **Propagation regime.** Spectral bands within which K is real correspond to propagating modes. Defined by the condition $|(M_{11} + M_{22})/2| \leq 1$, these bands are numbered, 1, 2 …, starting with the lowest-frequency band.
- **Photonic bandgap regime.** Spectral bands within which K is complex correspond to evanescent waves that are rapidly attenuated. Defined by the condition $|(M_{11} + M_{22})/2| > 1$, these bands correspond to the stop bands. They are also called photonic bandgaps (PBG) or forbidden gaps since propagating modes do not exist. [Yeh (1988); Yariv (2007)]

1.6.5 Electromagnetic Wave in Inhomogeneous Media

Here, we consider a layered medium whose index of refraction varies as a function of the depth of layer. Layers with continuous varying index of refraction play an important role in spectral filters and broad-band antireflection coating. We consider the propagation of light in an inhomogeneous layer described by an index profile *n(x)*. The wave equation for light propagating along the *x* axis is given by

$$\boldsymbol{\frac{d^2}{dx^2}E(x) + \left(\frac{\omega}{c}n\right)^2 E(x) = 0} \quad \dots\dots \quad \textbf{(1.23)}$$

where ω is the angular frequency and c is the velocity of light in a vacuum.

When the index profile *n(x)* is uniform (i.e., n(x) = constant), the solution is the well-known plane wave, as we have discussed in section 2.2. We shall adopt the description of inhomogeneity by using the index profile *n(x).* Here, inhomogeneity describe by index profile n(x) varies linear or exponential fashion as a function of the depth of layer.

1.6.5.1 Linear Graded Index layer

Consider a dielectric layer whose index profile is linear and is given by; [Yeh (1988)]

$$\left[\boldsymbol{n}(\boldsymbol{x}) = \boldsymbol{n_i} + \frac{(\boldsymbol{n_f} - \boldsymbol{n_i})}{\boldsymbol{d}} \times \boldsymbol{x}\right] \quad \dots\dots \quad \textbf{(1.24)}$$

where n_i and n_f are lower and higher index of refraction of the graded layers, respectively and d is the layer thickness. Subscript *i* and *f* represent the lower and higher refractive index positions in graded layers, respectively. By introducing a new variable, $\xi = \frac{\omega}{c} n(x)$, $d\xi = \alpha\, dx$, with $\alpha = \frac{\omega}{c} . \frac{n_f - n_i}{d}$, the wave equation becomes

$$\frac{d^2}{d\xi^2}\boldsymbol{E}(\boldsymbol{x}) + \frac{1}{\alpha^2}\xi^2 \boldsymbol{E}(\boldsymbol{x}) = \boldsymbol{0} \quad \dots\dots \quad \textbf{(1.25)}$$

The solution of equation (1.25) consists of Bessel function of order (1/4) and can be written as;

$$\boldsymbol{E} = \sqrt{\xi} . \left[\boldsymbol{A}\, \boldsymbol{J}_{\frac{1}{4}}\left(\frac{\xi^2}{2\alpha}\right) + \boldsymbol{B}\, \boldsymbol{Y}_{\frac{1}{4}}\left(\frac{\xi^2}{2\alpha}\right)\right] \quad \dots\dots \quad \textbf{(1.26)}$$

where A and B arbitrary constants and $J_{1/4}$ and $Y_{1/4}$ are $(1/4)^{th}$-order of first and second kinds Bessel functions, respectively.

1.6.5.2 Exponential Graded Index layer

Here, consider a dielectric layer whose refractive index profile is exponential and is given by; [Yeh (1988)]

$$\boldsymbol{n}(\boldsymbol{x}) = \boldsymbol{n_i} \exp\left(\frac{\boldsymbol{x}}{\boldsymbol{d}} \ln \frac{\boldsymbol{n_f}}{\boldsymbol{n_i}}\right) \quad \dots\dots \quad \textbf{(1.27)}$$

where n_i and n_f are lower and higher index of refraction of the graded layers, respectively and d is the layer thickness. Subscript *i* and *f* represent the lower and higher refractive index positions in graded layers, respectively. By introducing a new variable, $\xi = \frac{\omega}{c} n(x) = \frac{\omega}{c} n_i e^{\gamma x}$, $d\xi = \gamma \xi\, dx$, with $\gamma = \frac{1}{d} \ln\left(\frac{n_f}{n_i}\right)$, the wave equation becomes;

$$\xi^2 \frac{d^2}{d\xi^2} \boldsymbol{E} + \xi \frac{d}{d\xi} \boldsymbol{E} + \frac{\xi^2}{\gamma^2} \boldsymbol{E} = \boldsymbol{0} \quad \dots\dots \quad \textbf{(1.28)}$$

The solution of equation (1.28) consists of Bessel function of zero-order and can be written as;

$$E(x) = A J_0\left(\frac{\xi}{\gamma}\right) + B Y_0\left(\frac{\xi}{\gamma}\right) \qquad \dots\dots \quad (1.29)$$

where A_G and B_G are arbitrary constants for graded layers, J_0 and Y_0 are first and second kind of the zero-order Bessel function, respectively.

To investigate the propagation properties of the electromagnetic wave in the periodic structures that consist of layers whose index of reflection varies as a function of the depth of layer. We embrace the transfer matrix operation to calculate the reflectance, transmittance and band gap spectra similarly as matrix optics of periodic structures (1-D PCs) with dielectric homogenous materials that refractive index profile is uniform. After applying the transfer matrix approach on the periodic structures that consist of inhomogeneous layers whose index of refraction varies as a function of the depth of the layer, the electromagnetic wave propagates through the whole structures can be expressed by multiplying the characteristic matrices of the constituent layers as transfer matrix equation (1.14). Using the generated matrix equation for periodic structures with inhomogeneous layers, we can calculate the reflectance and transmittance spectra from the steps of algebraic operation equation (1.15) and dispersion relation and photonic band spectra from the equation (1.22).

Using the transfer matrix approach, we have simulated and calculated the reflectance, transmittance and band gap spectra through the self-designed Matlab coding. The Matlab coding of some cases are incorporated in the Appendix.

1.7 Aim of the Thesis

The objective of this thesis is to study the novel aspect of photonic band gap materials. We have selected periodic and quasi-periodic one-dimensional photonic crystal structures consisting different materials such as Linear and exponential graded index materials, negative index material and semiconductor for our study.

The study on the tunability of photonic band gaps has been presented in one-dimensional photonic crystals constituted with linear and exponential graded index materials in first two chapters. The influences of optical and geometrical parameters on the photonic and omnidirectional band gap of the considered structures have also been discussed.

Further, photonic band gap properties of one-dimensional photonic crystals composed of alternate layers of graded index and dispersive (metamaterials and semiconductor) materials have been investigated. The effects of material properties, geometrical parameters, material composition and temperatures on the photonic band gap characteristics have been corroborated.

Moreover, the investigation on the photonic localization modes and photonic band gap properties in the one-dimensional quasi-periodic photonic crystal structures consisting of graded index materials and semiconductor has been presented. The effect of different quasi-periodic systems and their sequences, optical and structural parameters, and temperatures on photonic localization modes and photonic band gap properties has been demonstrated.

The presented scientific understanding will help in the development of the photonic band gap structures for suitable optical applications.

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