Chapter

Introductory Chapter: Photonic Crystals–Revisited

Pankaj Kumar Choudhury

1. Introduction

Mirrors are important optical devices as these are greatly useful in applications, such as imaging, solar energy collection, and filtering. Also, these are indispensable in lasers in which the cavities constitute one of the components of prominence. Metallic and dielectric are the two common types of mirrors highly used in optics. Metallic mirrors reflect electromagnetic waves over a broad range of frequencies. But, these are not suitable for operations in the infrared (IR) and optical frequency regimes due to high absorption of optical power, thereby causing loss. As such, the bandwidth of operation of metallic mirrors (or guides) remains limited. However, dielectric medium-coated metallic guides can be used in the IR regime. Nevertheless, these have been proved to be inefficient for operations in the optical regime owing to the absorption loss in metals. As such, the use of conventional dielectric waveguides remains a preferred option for the transmission of optical frequencies.

Within the context of confinement of light waves in a cavity, the invention of photonic crystals (PhCs) opens up many possibilities of controlling the propagation of light. This made PhCs as the objects of intensive theoretical and experimental research. Properties of optical fibers having high-index core region surrounded by silica or air fall into the class of PhC; various forms of these have been vastly discussed in the literature [1]. It is interesting to note that PhCs having high-index cores possess many features of conventional optical fibers. However, PhCs exhibit photonic band-gap (PBG) effect, which relates to the forbidden regions in dispersion characteristics and transmission spectra—the feature that is distinct from the properties of high-index core optical fibers.

As PhCs have been a research topic in the frontline for quite some time, emphasizing the avenues of such specialized microstructures, the present chapter aims at throwing a glimpse of a few different forms of guides falling in the class of PhCs. Some of the novel applications of PhC-based structures and the current research trends in this specialized area are also touched upon.

2. Periodic band-gap structures

PhCs can be classified to be one-, two-, or three-dimensional (1D, 2D, and 3D) periodic structures (depending on the kinds of periodic variation), comprised of materials with different refractive indices and having the periods comparable with the wavelengths of operation [2, 3]. Based on the configurations, there would be varieties of structures that can be regarded to be in the class of PhCs. For example, materials having periodic structures can exhibit the effect of PBG, provided the periodicity

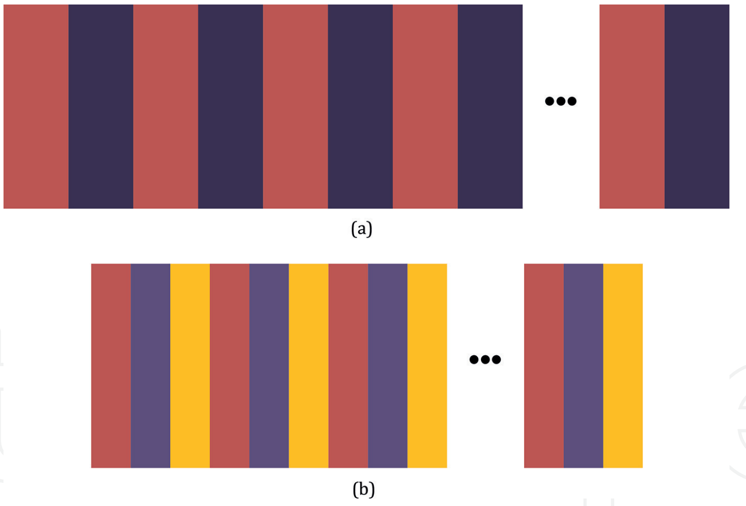

Figure 1.
Periodic stratified mediums with (a) two-layer and (b) three-layer periodicity.

remains on the scale of operating wavelength. Though the concept of periodic layered media had been put forward nearly over 40 years back [4, 5], varieties of new investigations in this front add many promising applications of such mediums. Mathematical formulations of symmetric periodic planar stratified mediums (**Figure 1a** and **b**) have been reported by the investigators [4]. The study deals with the evolution of explicit dispersion relations to determine the guided modes. In **Figure 1**, the periodicities in structure are of the forms of two (**Figure 1a**) and three layers (**Figure 1b**), respectively, which represent the variations in refractive index profiles. Apart from symmetric structures, the asymmetric dielectric film on a substrate is also quite a useful model among the more general types of optical waveguides.

The effects of PBG may be realized by the appropriate choice of periodic configurations, which involves dimensional features as well as the properties of constituent materials. This would result in forbidding the propagation of electromagnetic waves (through the structure) in certain frequency bands. It must be mentioned at this point that, recalling the Kronig-Penney model, the propagation of light waves in stratified periodic mediums can be compared with the situation of the movement of electrons in a periodic potential well [6, 7]. As such, if electrons can be diffracted by a periodic potential well, as evidenced by the theories of solid state physics, photons could equally be well-diffracted by a periodic modulation of the refractive index of medium. That is, such PBG mediums can be analyzed by exploiting the quantum theory of electrons in solids. This is because the basis for the guidance of light waves in dielectric mediums has a close analogy with the propagation of electrons in solid crystals—the fact that caused tremendous interests in PhCs and related research leading to the development of wide range of photonic structures for many novel applications [8]. In fact, multi-layered structures can reflect electromagnetic waves, if the frequency of operation lies within the gap. As such, stratified periodic structures have been proved to be prudent in exhibiting the property of spectral filtering.

3. Band-gap fibers

A PhC fiber (PCF) is a class of 2D periodic structure, wherein the periodic variation occurs in the plane perpendicular to the fiber axis and an invariant structure along it. In PCFs, the core section has the refractive index above the effective index of the surrounding medium. The guidance of light waves happens due to the total internal reflection (TIR). PCFs exhibit band-gap characteristics and present promising optical properties, such as lower and flat dispersion over a very large range of wavelength and reduced optical nonlinearities. Apart from these, PCFs demonstrate transparency in the far IR regime of electromagnetic spectrum [9–11].

In certain PhC configurations, the clad region may be a matrix of different materials with high and low refractive index values, thereby forming a new hybrid material that greatly enhances the core-clad index difference [12]. Within the context, index-guiding and hollow-core are the two different kinds of PCF; the former one consists of a doped-solid dielectric or pure silica core placed inside an air-clad guide, whereas the latter kind confines light waves through the PBG effect. The use of PBG kind of PCF greatly helps in reducing optical nonlinearity and propagation loss.

Among the others, PCFs are highly advantageous in fiber-based device applications. The invention of fiber-based lasers remains of special mention in this context. For example, continuous-wave fiber Brillouin lasers have been reported before utilizing highly nonlinear PCFs [13], wherein simple Fabry-Perot resonator plays the role of cavity. Apart from this, multi-wavelength Brillouin-erbium fiber lasers based on exploiting PCF with a linear cavity Fabry-Perot design have also been reported in the literature [14]. Many different schemes have been implemented to achieve fiber lasers having varieties of features [15].

Tunability of lasing systems using PCFs may be achieved in different ways. For example, one may use stimulated Brillouin scattering in the configurations [16, 17]. Within the context, the use of liquid crystals would also be greatly advantageous as these mediums exhibit the property of birefringence. Being liquid crystals as functional materials, one may recall the physical and/or chemical properties of liquid crystal, which can be altered by externally applied fields [18]. Apart from this, liquid crystals get affected due to the variations in temperature as well. As such, the thermal and electrical tuning of liquid crystals would alter the spectral characteristics—the feature that may be exploited in fabricating tunable PCFs. In fact, PCFs may be infiltrated with liquid crystals, in order to achieve tunable band-gap features.

4. Omniguiding fibers

Omniguiding fibers generally assume structures having the core surrounded by dielectric cylindrical Bragg mirrors comprised of alternating layers of high and low refractive index values, thereby forming a 1D PBG configuration, as shown in **Figure 2**. These are also called as Bragg fibers. However, several forms of omniguiding fibers have been reported in the literature. In certain kinds, the core section may be solid dielectric (e.g., silica or Ge-doped silica). In the case of hollow-core Bragg fibers, the core may be filled up with air or any other gaseous medium, as shown in **Figure 3**. In these guides, light waves remain confined to the core region due to Bragg reflections from the dielectric mirrors. This is because the mirrors reflect a narrow range of wavelength within the angular range. As such, complete photonic band-gap regime exists in phase space above the light cone of the surrounding mediums [19].

The design of omniguiding Bragg fibers requires adjustments of parametric values, such as the core thickness and refractive index of the alternating high- and low-index surrounding layered mediums. The number of layers also plays important roles in determining the allowed and forbidden wavelengths, i.e., the band-gap conditions. Omniguiding fibers may be designed as single-mode structure with no polarization degeneracy and without azimuthal dependence. The core size and number of concentric layers in these fibers govern the guided wavelengths, optical loss, and the effective single-mode operation [20]. As such,

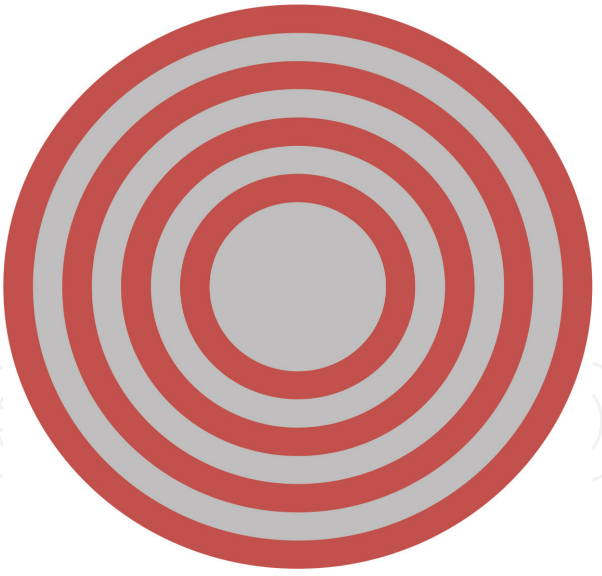

Figure 2.
Cross-sectional view of a typical omniguiding Bragg fiber comprised of periodic multi-layered dielectric mirrors.

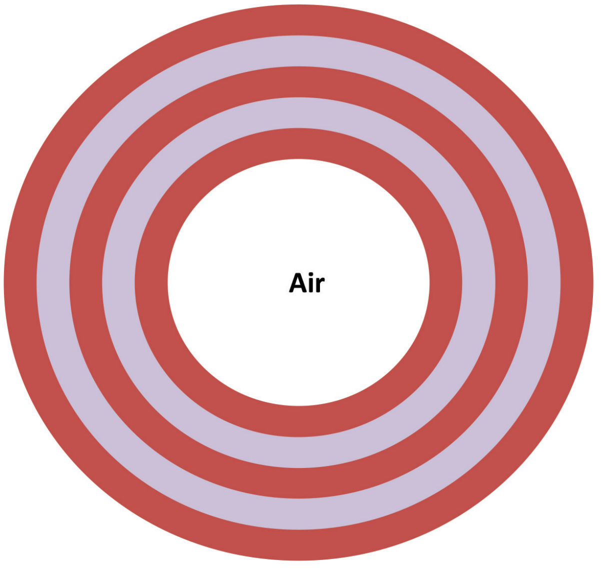

Figure 3.
Cross-sectional view of a hollow-core omniguiding fiber.

these may replace polarization maintaining fibers (PMFs)—the components that are used to eliminate the undesirable polarization dependent effects, such as polarization mode dispersion [21].

5. PhCs with defect

In the periodic configuration of PhC, certain defect units may be deliberately introduced that destroy the periodicity of medium. For example, if in the 1D PhC structure of **Figure 1a**, a defect layer (or unit, in general) is introduced, the configuration would assume the form, as shown in **Figure 4**. In such a case, the transmission characteristics of spectra will be drastically altered. In such situations, defect modes emerge inside the PBG, resulting into the presence of very narrow peaks with large transmissivity. As such, the transmission spectra of PhCs with defect can be controlled, provided the *introduced* defect is comprised of functional materials so that the electromagnetic behavior of these may be externally controlled.

Figure 4.
Periodic medium with a defect unit.

In general, the defect layer may be comprised of dielectric mediums or the mixture of dielectric and other kinds of mediums to yield a complex defect unit. In such situations, the transmission characteristics may be tailored in highly sophisticated ways, as described in ref. [22]. Apart from the planar structures, PCFs in certain forms may also have PhC cladding, wherein a central low-index structural defect would also be able to sustain the propagation of light waves.

6. Analytical approach for omniguiding fibers

Various attempts have been made to analyze the modes in omniguiding Bragg fibers. The most common approach remains as the use of transfer matrix theory that can be applied to any cylindrically symmetric fiber structure surrounded with periodically stacked Bragg cladding [23]. In this kind of formalism, the exact treatment of arbitrary number of inner dielectric layers is taken into account, and the structure of the outermost clad is approximated in the asymptotic limit. The exploitation of transfer matrix theory can yield the confined modes in Bragg fibers by minimizing the radiation loss in the radial direction. Apart from this technique, the asymptotic analysis and finite difference time domain (FDTD) method may also be used [3].

The method of asymptotic analysis of omniguiding fibers involves dividing the bulk of periodic multi-layered cylindrical dielectric mirrors into two groups, namely the inner and outer ones. The former one is in close proximity of the core section, whereas the latter group is assumed to be at relatively larger distance from the center of fiber. In the analyses, however, both the kinds of groups involve several dielectric mirrors. Further, the field in the inner group is represented by Bessel functions, whereas that in the outer group is treated asymptotically using the plane wave approximation. It has been found that the results obtained in this formalism match very well with those achieved by implementing the FDTD technique and/or the transfer matrix method [5].

In the analyses of omniguiding Bragg fibers, the propagation of Bloch waves is of extreme importance to determine the nature of propagation. Within the context, Bloch wave constant remains vital to evaluate as a complex value of it shows the forbidden bands of the periodic structure, whereas a real-valued Bloch constant indicates the propagation of waves. In the former case, however, the fields are evanescent.

Bragg fibers support modes that lie above the light line. These modes have the wave vector that corresponds to a frequency situated at the band-gap of multilayered dielectric mirror. The imaginary part of wave vector indicates the radiative loss of modes that decreases exponentially with the increasing number of layers.

As stated before, the light wave propagation in Bragg fibers can be investigated in the analogy of electron flow in periodic lattice structures. This can be utilized in order to determine the working principle of omniguiding optical fibers. As such, the allowed and forbidden regions of these guides may be obtained by exploiting the quantum theory of electrons in solids. This has been justified that the use of simple Bloch formulation in omniguiding fibers exhibits continuous electric fields and power in dielectric boundaries [24, 25]. Furthermore, it has been found that, in the case of omniguiding fibers, the number of allowed and forbidden bands increases with the increase in the difference between the values of refractive index of different dielectric layers. Furthermore, the widths of the allowed band remain larger in the case of fibers having stacked layers of larger thickness values [26]. In the dispersion characteristics of omniguiding fibers as well, it has been found that the width of allowed range decrease with the increase in k/k_0, k and k_0 being the wave vector in the medium and that in the free-space, respectively. This has been demonstrated through obtaining thick curves [26] that represent the existence of allowed and forbidden bands of wavelengths, instead of simple lined curves shown by conventional optical fibers.

7. Recent research trends

With time, the research on PhC gained enough maturity, thereby yielding exciting results. R&D investigations report the possibilities of exploiting PhCs in many different applications. However, the aim of these remains pivoted to the tailoring of band-gap characteristics in the desired range of frequencies.

As stated in the preceding section, defects introduced in 1D PhC structures modify the propagation of waves, because such modes are governed by the PBG of medium [27, 28]. In this stream, the role of functional materials remains highly demanding as the form of PhC allows the possibility of tuning the spectral characteristics. The external effects, such as electromagnetic fields, temperature generating elastic, and/or shear waves, would be varied to achieve the desirable optical (or electromagnetic, in general) features of PhC. Therefore, hybrid PhCs would be useful in designing tunable optical filters, modulators, pulse compressors, and many others.

Apart from functional materials, metals may also be embedded in 1D PhCs to modify the confinement of modes, thereby altering the band-gap characteristics [29]. Interestingly, PhC structures embedded with metal-matrix arrangements could be used to reduce the low-frequency vibration and noise related issues.

Since PhCs can be exploited to control the light-matter interactions within micro/nano scales, these are advantageous for gas analyzing purpose [30–32]. In particular, the mid-infrared region of electromagnetic spectrum can be utilized for gas sensing applications, which would yield the development of such devices with high sensitivity [33, 34]. Indeed, the variations of optical spectrum and/or measuring the material properties are the techniques to determine the features of sensing.

PhC cavities can also be grown in nano-scaled photonic wire waveguides based on silicon-on-insulator (SOI). Such structures are capable to exhibit high reflectivity, which make them sophisticated candidates for mirroring in PhC structures [35–37]. These have been proved to be useful to realize active tuning—the feature that makes these suitable as basic building blocks for high-density photonic integrated circuits. Apart from this, the efficacy in designing filters and high-speed optical switches for networking applications have also been conceptualized.

The aforementioned features of PhCs describe only a few of the research ventures where these complex structures have been investigated. In reality, however, there are many other novel areas of research pivoted to exploiting varieties of new forms of PhCs to demonstrate fantastic electromagnetic features; all of those scopes remain beyond the coverage of this volume.

8. Summary

In analogy to the propagation of electron waves in periodic lattice structures, waves propagating in a structure that is periodically modulated with refractive index also exhibit photonic bands. Such *periodic* structures, comprised of high refractive index difference materials, yield photonic bands separated by gaps, thereby disallowing the propagation of waves. This triggers many novel approaches to manipulate the electromagnetic fields, thereby opening up varieties of possible technological applications.

Author details

Pankaj Kumar Choudhury
Institute of Microengineering and Nanoelectronics, Universiti Kebangsaan Malaysia, UKM, Bangi, Selangor, Malaysia

*Address all correspondence to: pankaj@ukm.edu.my

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