1

Introduction to Photonic Crystals

Summary. Chapter 1 gives a brief introduction into the basics of photonic crystals which are a special class of optical media with periodic modulation of permittivity. We give a general idea of what photonic crystals are and then describe different kinds of photonic crystal lattices and introduce and discuss the basic terminology. Main attention is paid to the band structure, eigen states and photonic band gaps. Finally, some historical notes are given, where the first computed band structures of three dimensional photonic crystal with face-centered cubic and diamond lattices are presented as well as the band structure of inverted opal. At the end of the chapter different areas of photonic crystal applications in optical communications and lasers are given, such as waveguides, optical insulators, splitters, microresonators for spontaneous emission management, etc.

1.1 Introduction: What are Photonic Crystals?

Photonic crystals (PhCs) are novel class of optical media represented by natural or artificial structures with periodic modulation of the refractive index. Such optical media have some peculiar properties which gives an oportunity for a number of applications to be implemented on their basis. Depending on geometry of the structure, PhCs can be divided into three broad categories, namely one-dimensional (1D), two-dimensional (2D) and three-dimensional (3D) structures. Examples are shown in Fig. 1.1.

In 1D PhCs, the periodic modulation of the permittivity occurs in one direction only, while in two other directions structure is uniform. As an example of such a PhC it can be given the Bragg grating which is widely used as a distributed reflector in vertical cavity surface emitting lasers. Besides, such structures are widely used as antireflecting coatings which allow to decrease dramatically the reflectance from the surface and are used to improve the quality of lenses, prisms and other optical components.

2D PhC can have comparatively large variety of configurations, because it possesses periodicity of the permittivity along two directions, while in the third direction the medium is uniform. A good example of the 2D PhC is

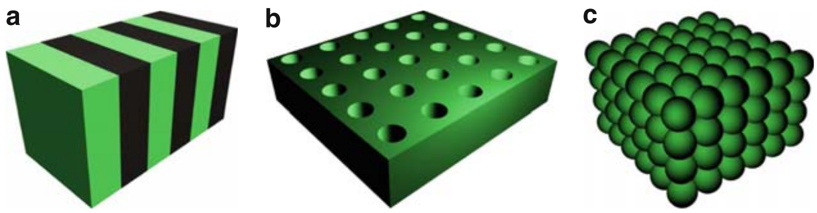

Fig. 1.1. Examples of 1D, 2D and 3D photonic crystals (**a**) 1D PhC, (**b**) 2D PhC, (**c**) 3D PhC

porous silicon with periodically arranged pores, which is represented by the silicon substrate with etched holes. Another example of 2D PhC is a periodically arranged system of dielectric rods in air. 2D PhC can also be found in nature. For instance, the pattern on the butterfly's wing and its rainbow play is caused by the light reflection from the microstructure on the wing.

3D PhC has permittivity modulation along all three directions. At that, the number of possible PhC configurations is much larger than in case of 1D or 2D PhC. Many works are dedicated to the design of new geometric configuration of 3D PhC, which discover new possibilities of their application. The most known naturally formed 3D PhC is valuable stone opal. This stone is known by its unique optical properties. When turned around, it plays different colors. Because of such a behavior, ancient people believed that opal possesses some magic powers. However, now we know that all these peculiarities are caused by the microstructure of opal. It consists of a number of microspheres placed at nodes of face-centered cubic (FCC) lattice. Reflectance of such a structure strongly depends on the radiation incident angle. So when one turns it around, it starts to reflect the radiation with different wavelengths. Thus, optical properties of PhCs are determined by the existence of the periodic modulation of the permittivity or the refractive index of the medium. At that, observed effects have strong analogy to the solid state, i.e., the periodically arranged structure of atoms in crystal lattice. Such a similarity between the physics of PhCs and solid-state physics gives the possibility to draw the analogy between some properties and computation methods applied to solid-state and PhCs physics.

The most important similarities between PhC and solid-state physics are as follows: Periodic modulation of the refractive index in a PhC forms a lattice similar to atomic lattice of solid-state; behavior of photons in a PhC is similar to electron and hole behavior in an atomic lattice; due to the lattice periodicity both PhC and solid-state provide band gap, the range of energies which particle cannot have inside the structure. From theoretical viewpoint, determination of the eigenfunctions in a PhC is very similar to calculation of the particle wave functions in the solid-state. This similarity is used to obtain photonic band structure.

However, along with strong similarity, there exist some essential differences. One of the main differences is the particle energy distribution. Electrons obey the Fermi–Dirac distribution while photons obey Boze–Einstein distribution. Besides, electrons are affected by intracrystalline field which leads to the necessity of taking it into account (it is necessary to note that the shape of intracrystalline field is unknown, and investigators have to use approximate methods such as k–p method). Photons are not affected by intracrystalline field. Therefore, computation of the optical field distribution or the photonic band structure is essentially simplified.

The most important property which determines practical significance of the PhC is the presence of the photonic band gap. The photonic band gap (PBG) refers to the energy or frequency range where the light propagation is prohibited inside the PhC. When the radiation with frequency inside the PBG incidents the structure, it appears to be completely reflected. However, if one introduces the defect to the strictly periodic structure, the effect of such a defect is the same as the defect introduction to the crystalline structure of a semiconductor. This means that new eigen-state appears inside the PBG with energy corresponding to the eigen-frequency of the defect. Thus, the radiation within the defect frequency will propagate inside the structure or, in case of multiple defects radiation will be guided like in waveguide.

Thus, there exist quite strong analogy between PhC physics and solid-state physics both from the physical and mathematical points of view.

1.2 Photonic Crystal Lattice

Previously it was shown that PhCs possess different geometric conformations. These conformations correspond to types of crystal lattice of solid-state crystals. This fact gives the possibility to use the term "lattice" to indicate the geometric conformation of the PhC.

1D PhC have very low number of possible periodic structure variations because it is represented by the layered structure, so only the refractive index, layer's thickness and the number of layers within the period can be varied. Thus, we start consideration of kinds of PhC lattices from 2D case. It is obvious to assume that variation of the elements shape and their placement gives an infinite number of lattice types. However, for technological reasons, there are two commonly used types of the 2D PhC lattice, namely, square and hexagonal. The unit cell of the PhC with square lattice has the shape of square. Elements of such a PhC type must be similar to each other, i.e., they all can have round, square, hexagonal or some other shape. The unit cell of hexagonal lattice have the form of regular hexagon and the elements, like for the square lattice, must be similar. Examples of such PhC types are shown in Fig. 1.2.

3D PhCs geometry can be varied in very different manners so they can have a great number of lattice types. Because 3D PhCs are the most similar to solid-state crystals, many lattice types of such PhCs have similar conformation and

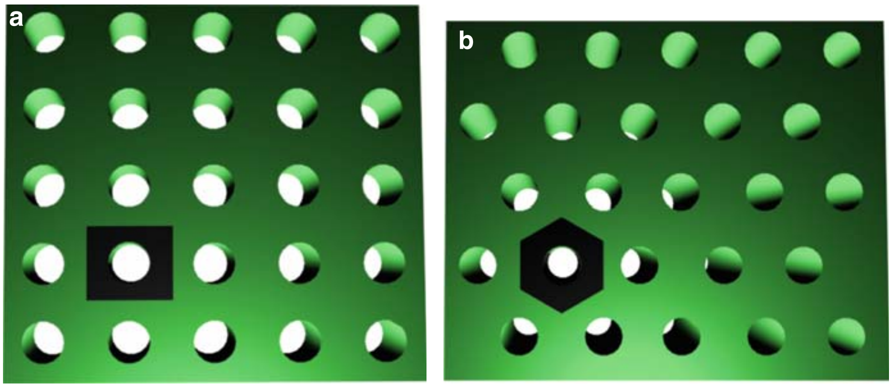

Fig. 1.2. Examples of 2D PhC lattice types. (**a**) 2D PhC with square lattice and round elements shape, (**b**) 2D PhC with hexagonal lattice and round elements shape

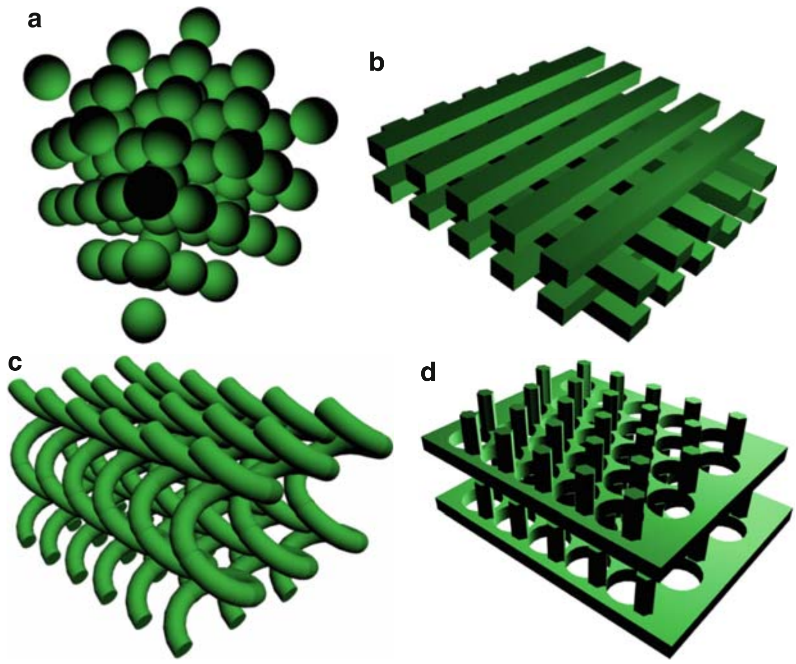

Fig. 1.3. Examples of 3D PhC lattices types. (**a**) FCC (face-centered cubic), (**b**) woodpile, (**c**) spiral lattice (GLAD GLancing Angle Deposition), (**d**) quasi-diamond lattice

similar names. Moreover, depending on the method of the PhC production, it can possess conformation which cannot be obtained in solid-state crystals. Some examples of the 3D PhC crystal lattices are shown in Fig. 1.3. Between them the FCC and diamond lattices have the solid-state analogs while the woodpile and spiral (or GLAD) lattices are unique and can be obtained in PhCs only.

Thus, PhCs have a number of possible lattice types which determines a wide range of their fundamental properties such as the band structure, transmittance and reflectance spectra.

1.3 Basic Terminology

Before we start to discuss the characteristics and computation methods, it is necessary to introduce some basic terms. The first term and the most important one is the band structure of the PhC.

The band structure of the PhC is the characteristic which gives the most general information about the PhC properties. It is represented by a number of eigen-states or eigen-frequencies of an infinite periodic structure.

Eigen-frequency is another important term, it is also called resonant frequency of the structure. Since PhC is an infinite periodic strucutre, a number of Fresnel reflections appear at the media interfaces. Constructive and destructive interference between forward and backward waves causes either transmission or reflection of the radiation.

Each of the eigen-state sets correspond to the specific value of the radiation wave vector. Independent of the dimensionality of the PhC, the band structure is represented by a 2D plot. The example of such a band structure for 1D PhC is given in Fig. 1.4.

The physical meaning of the band structure is to connect the properties of the radiation with properties of optical medium the radiation propagates in.

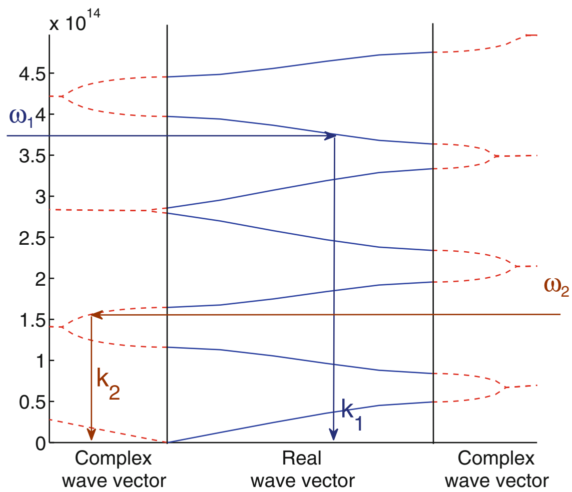

Fig. 1.4. Band structure of 1D PhC

In Fig. 1.4 the horizontal axis corresponds to the wave vector of the radiation and the vertical axis stays for the resonant frequencies of the medium. Let us consider the case when the radiation with frequency ω_1 incidents the PhC. Once it penetrates into the structure, it possesses the exact wave vector which is allowed by the structure. The value of such a wave vector can easily be found from the band structure. We can see from Fig. 1.4 that wave vector value k_1 corresponds to the radiation frequency ω_1. Possessing this wave vector, the radiation propagates through the structure.

Let us now consider another case. If the radiation has frequency ω_2, we can see that it falls at the frequency range where there are no allowed real wave vectors. However, it still can possess the complex wave vector k_2. Later, in Chap. 2, we will see that the imaginary part of the wave vector corresponds to either radiation attenuation or gain. In our case, it corresponds to attenuation. This actually means that the radiation with frequency of this specific range will be reflected from the structure. However, since the attenuation is finite value, it will penetrate to the structure for some distance.

These two cases considered actually contain basic principles of the photonic band structure analysis. Namely, the periodic medium possesses allowed and forbidden frequency ranges. The radiation propagates inside the structure within allowed frequencies only. Otherwise, it will be reflected.

The forbidden frequency ranges are usually referred to as photonic band gaps.

If the radiation possesses allowed frequency, it takes the value of the wave vector which can be found from the band structure. The last statement is more important for 2D and 3D PhCs since the wave vectors for this structures are connected with radiation propagation direction. This allows the PhC to set the radiation propagation direction leading to a number of interesting effects such as strong angular dispersion.

Of course, the list of terms considered here is not complete. Some new terms will be introduced in subsequent chapters.

1.4 Historical Notes

Now, we can briefly consider the PhCs' evolution as well as methods for their design and investigation.

In spite of the fact that PhCs have attracted high attention only during the last several decades, first assumptions of posibility to control the light propagation using the periodic structures relate to 1887 [1]. Those were the investigations of 1D periodic structures.

Almost after 100 years in 1972, Soviet Union scientist V.P. Bykov published a paper where he described the possibility to use periodic structures for the spontaneous emission control [2].

However, the first works assumed to start the intensive progress of PhC are the works of E.Yablonovitch and S. John which was issued in 1987 in *Physical*

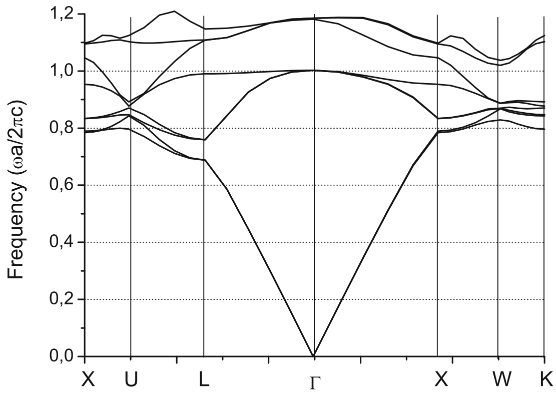

Fig. 1.5. The band structure of 3D PhC with FCC lattice

Review Letters [3], [4]. Papers are dedicated to the possibility of spontaneous emission management as well as the possibility of the radiation propagation control using periodic structures. After publication of these articles, a number of publications dedicated to PhC physics and technology doubles every year.

In 1990, K.M. Ho, C.T. Chan and C.M. Soukoulis [5] obtained the band structure of the PhC with FCC lattices (opal structure) which consisted of dielectric spheres with high refractive index placed in air. Example of such a band structure computed by the PWE method is shown in Fig. 1.5.

As it can be seen from the figure, the first band lies within the relative frequency range of 0–0.8. The second one coincides with the first band at the wave vector section $\Gamma - L$ (within the frequency range of 0–0.7) and $\Gamma - X$ (within the frequency range of 0–0.79). Moreover, within all the investigated frequency ranges at least one eigen-state exists, so no complete PBG appears. For instance, in Γ-point the eigen-frequency is equal to zero. At wave vector range $\Gamma - L$ the eigen-frequency smoothly grows from 0 to 0.8.

The existence of eigen-states at each point of the investigated frequency range tells about the absence of complete PBG. Moreover, it appears that the PhC with such type of lattice does not have the complete PBG at any values of refractive indices. However, considering the band structure, one can conclude that the PhC has wide partial band gaps at some propagation directions (for instance, at the point L within the range from 0.7 to 0.77 there are no eigen-frequencies). This means that the light with frequency in this range propagating in corresponding direction will be reflected. This causes the optical effects typical for all natural and artificial opals.

In the same work, there were also given results of band structure computation for the PhC with diamond lattice made of dielectric spheres placed in air where they found the complete PBG between the second and third bands (see Fig. 1.6).

In 1992, H.S. Sozuer and J.W. Haus [6] computed the band structure of the PhC with inverted FCC lattice (also known as inverted opal) which is

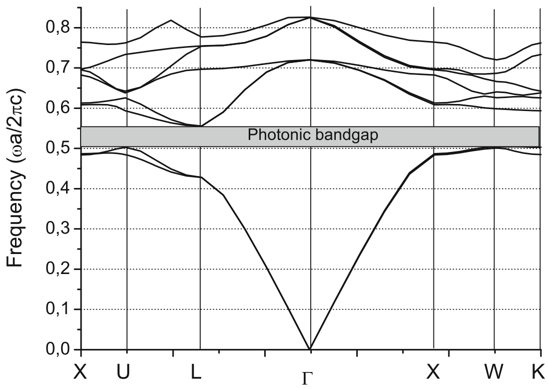

Fig. 1.6. The band structure of 3D PhC with diamond lattice

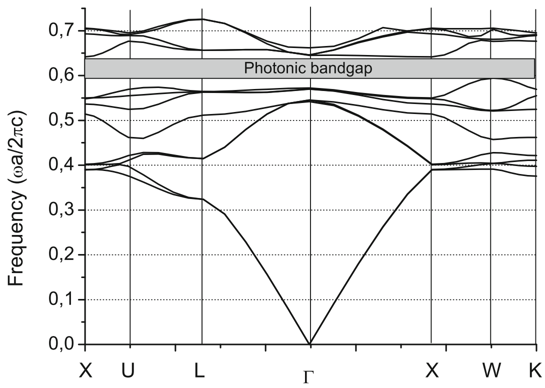

Fig. 1.7. The band structure of the PhC with inverted FCC lattice

presented in Fig. 1.7. The term inverted opal means that instead of dielectric spheres placed in air, the inverted FCC lattice consists of a number of spherical cavities separated by baffles with higher refractive index (see Fig. 1.8). It appeared that such a PhC has complete PBG at relatively high refractive index of material. Investigated inverted opal had complete PBG between the eighth and ninth bands.

The appearance of the complete PBG inside the PhC with inverted FCC lattice attracts a special interest, because today inverted artificial opals provide possibility of mass PhC production.

In 1998, the inverted artificial opal was obtained experimentally [7]. The sphere's diameter in the structure was approximately 1 μm, and the distance between the spheres is very low so the spheres are almost touching. From the technological point of view, it is much easier to grow the structure with such parameters than with high distance between spheres because the base FCC lattice consists of dielectric spheres in air so when the spheres touch each other, their position can be easily locked in. The refractive index of the PhC

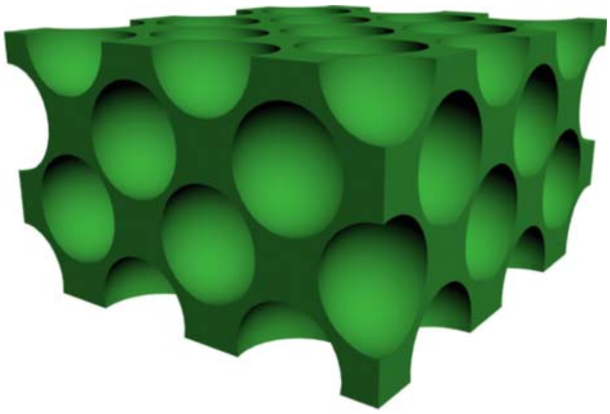

Fig. 1.8. 3D PhC with inverted FCC lattice

material between spheres (TiO_2) is 2.8 and it is too small to form the complete PBG. However, when silica is used as the bulk material, the appearance of the complete PBG is possible at some geometric parameters.

In 2000, the first 3D PhC which had the complete PBG within near infrared range was obtained [8]. Such a PhC consisted of silicon spheres arranged in a diamond lattice.

Starting from 1987 and till 2005 more than 10,000 printed works dedicated to PhCs and PhC-based devices were published. However, the serial production now is available only for microstructured fibers which possess unique properties and the possibility to manage the parameters and characteristics within wide range and 1D PhCs which are produced in the form of distributed Bragg reflectors of vertical cavity surface emitting lasers or in form in the form of fiber Bragg gratings.

In spite of quite undeveloped technology for production of 2D and 3D PhCs, there exist a number of optoelectronics directions such structures can be applied to. The most important are the spontaneous radiation management, optical insulators, nonlinear elements and microstructured fibers. Let us consider each of these directions in detail.

- Spontaneous radiation management [3–9]. This property of PhCs was predicted on dawn of PhCs and it plays important role for the design of light sources on the basis of PhCs. For instance, PhCs can be used to increase the efficiency and to lower the threshold current of semiconductor lasers. 1D, 2D or 3D PhCs can also take a function of distributed reflector [10–15]. The second way to use the PhC as the element for the spontaneous radiation management is the design of principally new radiation sources [16–19]. In such sources, both pure PhCs and PhCs with defects which form high-quality resonators and provide strong radiation localization inside the defect can be used for spontaneous radiation management and improvement of laser characteristics [9, 20–25]. Depending on what type of PhC is used (with or without the defect), the source can be monochromatic or polychromatic, i.e., lasers or light-emitting diodes [26–35].

- Optical insulators. Utilization of the PhC as an optical insulator, as a rule, is reduced to the utilization of the PhC possibility to localize the radiation inside the defect of the periodic structure. At that, the radiation wavelength must lie inside the PBG of the PhC. Main devices which can be developed on the basis of such a PhC property are microcavities [36–43], waveguides [44–55] and sharp waveguide bends [56–65], splitters [66–73], couplers [74–82] and combiners [83–89]. Main function of microresonators is based on the possibility of the PhC to localize the radiation inside the defect area of the periodic structure. In fact, the defect can be represented by the shift, variation of the parameters or missing of some elements or group of elements.
- PhC waveguides [36,44–55] are represented by so-called linear defects of periodic structure. Such linear defects possess waveguiding properties within quite a wide range of wavelengths. One of the unique PhC waveguide properties is the possibility to form very sharp bends under the angle up to 90° [90–98] and even more [99–106]. In contrast to planar waveguides, the principle of which is based on the total internal reflection, the PhC waveguides localize the light due to the presence of the complete PBG. Thus, waveguide bend made on the basis of linear defect has higher efficiency and is much more compact than that on the basis of planar waveguide.
- Splitters represent a class of optical devices which allow dividing an optical power in given proportion or splitting it into polarized beams [66–73], [107–110]. The PhC-based splitter can be represented by a number of optical waveguides connected at a single point. In this case, the power passing from the input waveguide is divided at the connection point. Another type of splitter is based on coupling of parallel waveguides with low distance between them [111–113]. The radiation from one waveguide smoothly flows from the input waveguide to the output one. Varying waveguide parameters, one can easily vary a portion of power to be transmitted to the output waveguide.
- Dispersion management [114, 115]. A unique dispersion property of the PhC allows to use them as super-prisms [116–120], super-lenses [121–125], multiplexers and demultiplexers [126–130].
- When investigating the super-prism-effect, the PhC is considered as a bulk media. At that it possesses some effective refractive index which strongly depends on the PhC geometry and the radiation wavelength. In some cases, the refractive index can be negative [75, 131–135].
- Super-lens effect [121–125] allows to use the PhC in order to focus an optical radiation. Moreover, dispersion properties of PhCs allow to create compact and highly-efficient wavelength division demultiplexers [126–130]. The wavelength division demultiplexer allows to separate information channels which are transmitted at different wavelengths over a single waveguide

channel. The PhC-based demultiplexer will be a compact one because the PhC waveguides and waveguide bends size is of order of the wavelength. Moreover, the channel's density can be dramatically increased if necessary in comparison to commonly used demultiplexers on the basis of dispersion elements.

- Nonlinear elements [136–141]. The introduction of nonlinear materials into the periodic structure can cause the appearance of very interesting and unexpected effects. Nonlinear materials change their refractive index under high intensity radiation passing over them. Such variations of the refractive index can cause essential variation of device fundamental characteristics. These possibilities give rise to a new class of optical devices such as optical information storage elements [142–146], logical elements [147–150] and optical power limiters [138–153]. Discrete optical solitons [154–156] inside the nonlinear PhC may be used for information storage. Such solitons managed by the radiation allow to implement the information writing and reading. A principle of the optical logical elements is based on the fact that the power of a single optical signal is not enough to essentially change the structure properties. However, when two signals incident the nonlinear structure, the refractive index variation appears such that the optical properties of the whole PhC are changed as well, particularly, transmittance and reflectance. At that, some situations may happen. The first one, when the optical gate was closed at low radiation intensity and it opens at high intensity, thus implementing AND gate. The second case is vice versa. At low radiation intensity, the gate is opened and the growth of the intensity leads to the gate closure. This situation is for AND-NOT gate.
- Optical power limiters [151–153] can be used to avoid the optical sensors damage due to the high intensity radiation and for the normalization of the optical source intensity at the input of the optical circuit. Their principle consists of the growth of the reflectance of the nonlinear PhC structure with the radiation intensity. At that, the output optical intensity stays constant.
- Microstructured fibers [157–173]. Such optical fibers consist of finite-size PhC with one or several defects introduced to the center. The radiation is concentrated inside the defect. There are two different types of microstructured fibers. The first one is based on the effect of total internal reflection. In this case, the PhC represents the reflecting cladding with lower refractive index. Such fibers are usually singlemode within wide wavelength range in contrast to ordinary step-index fibers. The principle of the second type of microstructured fibers is based on the radiation localization inside the defect due to the complete PBG. Such fibers are usually multimode, however, they allow to localize high radiation power inside the defect area. Thus, they can be used for transmittance of high radiation power and for achievement of some nonlinear effects. Currently, a variety of applications devices is proposed and implemented, which utilize unique properties of microstructured fibers [174–200].

- Slow light is another important application which is being extensively developed [16–18]. It employs PhC's ability to possess ultra-low group velocity at specific wavelength. The devices based on slow-light effect can be used as photonic routers in transparent optical networks, low modal volume microlaser, optical delay lines, etc.

1.5 Problems and Questions

Problem 1.1. Describe similarities and differences between solids and photonic crystals.

Problem 1.2. Give the definition of the photonic band gap.

Problem 1.3. Describe the lattice structure of square and hexagonal crystals.

Problem 1.4. Describe the different kinds of 3D PhC lattices.

Problem 1.5. Characterize the main terms used for band structure description.

Problem 1.6. What happens to radiation which possesses complex wave vector?

Problem 1.7. Describe the opal structure and its band structure.

Problem 1.8. Describe the inverted opal structure and its band structure.

Problem 1.9. Give examples of PhCs application in passive components of optical systems.

Problem 1.10. Specify examples of the elements controlling optical radiation which are based on PhCs.

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