Paper

Recent advances in PBG structures

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Abstract — We propose a review of word science achievements in the extremely extended for the recent few years field of photonic band gap structures. The review concerns both theoretical and experimental investigations on PBG structures toward fabrication of the most optimal ones for different applications. The attention is given to the obtained results as well as to the used and developed methods.

Keywords — photonic band gap, photonic crystals, optical communications.

Introduction

Modelling, development and application of photonic band gap structures is now one of the most actual direction in photonics and optical communication, involving into the research a great number of scientists. A dozen years ago the paper [1] by Yablonovich was published with suggestion that structures with periodical spatial variation of refractive index could for some conditions exhibit a band of frequencies within which electromagnetic wave propagation is forbidden. The band was called a photonic band gap (PBG) by analogy with an electronic gap in semiconductor crystals [2]. We have not the aim to make a historical review but want to stress on the recent investigation to classify its main directions, applications and methods of modelling and development.

By periodically structuring a material in one, two or three dimensions one can fabricate new optical materials with unusual properties. Such PBG crystals materials are of great interest through the word because of their potential applicability to development of new optoelectronic devices. There are obvious such applications of PBG structures as reflectors and narrow-band filters fabrication, for example in a form of photonic crystal waveguide [3, 4].

Photonic band gaps have been both predicted and observed in one, two and three-dimensional photonic crystals. The challenge now is to design functional devices that exploit the new freedom offered by photonic crystal engineering.

Optical fibre band-pass filters based on PBG crystals fulfil a very important role in optical fibre communication systems. Together with the rapidly developing employment of wavelength division multiplexed optical communication systems, a renewed interest in the development of advanced optical fibres for new applications has been seen. The previous years research primarily included the further development of the mature silica fibre technology to handle amplification, dispersion compensation, nonlinearities etc. Completely new fibre concepts have been introduced over the past few years, among which is the photonic crystal fibre (PCF) [5] to be one of the most interesting.

Although it has been possible to fabricate a variety of band-pass filter components, ideal performance is difficult to achieve. For practical applications of PBG structures one needs not only to know the structure parameters and operating characteristics for the chosen model but also to identify quickly the influence of some key parameters because a model could not be perfect for real conditions of its fabrication. All these induce an explosion of different approaches to solving the problems. Theoretical modelling as well as experimental research goes in two directions. The first one is analytical, numerical or experimental investigation of reflection and transmission characteristics for special kinds of the structures and by this way an optimisation of the structures parameters [6]. The second one is an inverse problem approach using different theoretical and measuring techniques to reconstruct the required geometric and material characteristics, which provide the required optical field transformation [7,15].

One of the main principles of the PBG crystals development consists in introduction of microcavities into dielectric. It is now well known [8] that microstructuring of dielectric on the scale of the optical wavelength can strongly alter the photonic density of states, producing what is effectively a new material with optical properties that differ radically from those of the original dielectric [9–12]. It is of particular interest to explore whether this can lead to improved characteristics in devices made from commonly used and well understood optoelectronic materials, where performance limits have already been reached with conventional techniques. For example, work is already underway to improve III-V light emitting devices by incorporating metal-free photonic-crystal-based microcavities that block emission into unwanted modes [13]; and the microstructuring of thin threads of silica glass has been shown to lead to a revolutionary new type of optical fibre which is „endlessly single-mode” irrespective of the wavelength of excitation [5].

An important goal in the microlaser area is high-Q microcavities of volume $(8/2n)^3$ which support only one mode within the gain bandwidth of the lasing medium [11]. A photonic crystal with a true three-dimensional photonic band gap and a single point defect can provide this. The resulting efficient low-threshold lasers could be packed in large numbers onto a single substrate.

We start the review from one-dimensional PBG structures, which are access to consideration of three-dimensional photonic crystals as well as are themselves of a great interest meaning different coating and other planar applications. Then the consideration will be given to multidimensional. The obtained results and used methods will be reviewed.

One-dimensional photonic crystals

The simplest photonic crystal is one-dimensional one, which possesses the fundamental features of photonic crystals in general [4]. This case corresponds to a periodic multi-layered structure.

This type of PBG structures as well as quasi-periodical ones is attractive for theoretical investigations. Classical periodic layered structures were properly investigated theoretically and experimentally for different wavebands [14]. The conditions of wave propagation in them were defined as well as their reflection characteristics. Detailed description of wave behaviour in them is a fundamental base for all consequent investigations.

However, these structures are not ideal for practical applications and the development there is by increasing complexity of the structures (as, for example, dual periodicity) toward the improved model. The criteria for such an optimization are the gap width and shape (preferably a rectangular-like one) as well as the structure dispersion and simplicity for fabrication.

Some other *special requirement to the structure* can be trying to follow when the investigation is directed to their special application. For example, the antireflection coating with ultra-low reflectivity and broad bandwidth for semiconductor lasers and optoelectronic devices is one of the most desired technologies in the field of modern optoelectronics [15]. For semiconductor laser amplifiers a reflectivity of less than 10^{-4} is required to suppress the Fabry-Perot mode oscillation [16]. For wavelength-tunable external cavity mode-locked semiconductor laser, less than 10^{-5} of ultra-low reflectivity is needed both to eliminate the secondary pulse generation and pulse broadening caused by the residual internal reflectivity [17] and to avoid the axial-mode instability [18]. Specifically, the WDM fiber-optic communication systems can have a bandwidth nearing to 100 nm. The tunable laser sources suitable for testing such systems must have comparable bandwidth and the correspondent coating.

Paper [15] proposes a design procedure of broadband multilayer *antireflection coatings for optical and optoelectronic devices* by numerical mappings on the optimization of the four-layer antireflective coating using TiO_2 and SiO_2. The numerical modelling for the considered inverse problem showed that there are four candidate regions realizing broad bandwidths. Preliminary experiments on the four-layer antireflecting coating on glass and InP substrates showed the broadband performance of the proposed design.

Planar structures could be combined forming so a 2D crystal patterns which offer practical advantages in comparison with classical 2D ones [8]. These advantages are that defects, dislocations and so on are easily incorporated either during or post-fabrication, and it is straightforward to access points on the two-dimensional plane, for example, allowing near-field probing of the modal microstructure. Planar photonic crystals can in fact be used in the design of simpler microcavities, which support only one high-Q resonant mode [30]. While these structures also support many modes that are coupled to the outside world, these unwanted modes have very low Q-factors, reducing the amount of spontaneous emission lost to them. Thus, the vacuum field strength is enhanced in the desired high-Q mode, leading in the case of lasers to a lowering of the threshold for stimulated emission. Of course, unlike in a 3D photonic band gap microcavity, diffractive losses increase as the cavities get smaller, so that a compromise must be struck between small volume and high efficiency.

A microcavity, based on a simple 1D photonic crystal waveguide design, was recently reported with a volume of $0.055\mu m^3$ and a Q-factor of 265 [31,32]. It is important to be clear about what is required of a two-dimensional planar photonic crystal in each particular application. For example, coexistence of waveguiding and strong 2D photonic band gap effects may be desired, as in slow-wave structures (optical delay lines), two-dimensional DFB ring cavity lasers or channel dropping filters [33]. In contrast, large area vertical cavity surface-emitting lasers may be required in which photonic crystal patterning is used to eliminate the in-plane guiding just mentioned, or to stabilize the transverse beam profiles. In the first case, in-plane waveguiding is highly desirable; for the vertical cavity surface-emitting lasers, however, one wants no in-plane guided modes and a one high-Q stationary mode radiating vertically with a designable extraction efficiency [13].

By periodically modulating the refractive index in one and two dimensions it is possible to create a dielectric material that behaves as a quasi-metal, i.e., a material that, within a certain wavelength range, rejects all wavelengths and polarisation states for incidence from a medium of lower index (e.g., air or water) [34]. This can be used to create a full photonic band gap in a low index layer sandwiched between two *1D quasi-metallic dielectric* stacks [35].

So, for successful fabrication of different special devices one should know not only spectral characteristics of the considered structure but also other physical features of the transformed by them field behaviour. Note, that what was mentioned above on the optimization criteria for 1D PBG crystals is also actual for multi-dimensional ones.

Quasi-periodic structures

Many researchers turned now to investigation of photonic quasi-periodic structures [24]. It was noticed that small deviations from periodicity could change sufficiently the structure interaction with incident field. They can perform properties of more sharp frequency filters as well as have wider band gap with a shape more similar to rectangular one in comparison with periodical structures.

In [24] the authors deal with the problem of diffraction of an electromagnetic wave by quasi-periodic multilayered structures. They assume three alternating values of the layers permittivity. When studying the reflectance of 1D photonic quasi-crystals numerically they noticed that such structures could exhibit band gap at very large wavelengths. It is necessary still for the global thickness of the structure to be no larger than the wavelength, but the mean thickness of the layers is arbitrary small with respect to the mean wavelength. As a consequence, semi-infinite photonic quasi-crystals cannot be homogenized and can behave as a perfect mirror for arbitrary wavelengths. The stressed result is like to one in diffraction experiments in the domain of x-ray crystals (so called Bragg spectrum consisting of peaks, which reveal the existence of long-range order of solids).

In [25] the gap phenomenon in a common case of aperiodic one-dimensional photonic crystals is investigated analytically. Using a classical characterization of forbidden bands, the authors show that it is possible to define a semi-infinite crystal. They also precise the behaviour of the field in the semi-infinite structure for wavelengths belonging to a forbidden band. The goal of the taking research was to characterize in a simple way the forbidden bands of wavelengths. The used approach is based on detailed explanation of the field behaviour inside the crystal within the gaps. A diffractional approach with introducing the transmission matrix for a period is used.

A general way of specifying the forbidden bands consists in considering periodic medium and in solving for eigensolutions of the introduced wave operator. When the global thickness of the medium is very large with respect to the wavelength, it seems natural to consider that the structure is semi-infinite. The semi-infinite medium has the advantage over the infinite one that it allows at least the formulation of the diffraction problem. In [25] the authors study the limit of the reflection coefficient when the number of periods tends to infinity, but keeping a half-space free. The preceding results is then applied to a structure whose period consists of two layers. The numerical calculations for this case enable one to suppose that the crystal behaves homogeneously within the gap, because of the exponential decrease of the field.

Pulse propagation through one-dimensional photonic band gap structures

Rather a new interesting aspect in considering the 1D PBG crystals is turned to pulse reflection and transmission [35]. An interest in the study of pulse propagation through one-dimensional photonic band gap materials both theoretically and experimentally grows rapidly. In particular, if an optical or microwave pulse is tuned with its carrier frequency well inside the photonic band gap (stop-band), then pulse tunneling takes place with a pseudo-super-luminal group velocity, $v > c$. This curios result has been verified at the single photonic level and reported in [36–38]. On the other hand, if carrier frequency is tuned to one of the photonic band-edge transmission resonances, then the group delay is anomalously large,with a corresponding group velocity $v << c$. This effect has been used in the development of a new type of optical delay device [39-41].

In [35] the author considers the symmetries associated with the group-velocity delay of pulse transmission and reflection in a one-dimensionally inhomogeneous, planar dielectric structure. From the principles of energy and parity conservation the author derives the generalized Stokes reciprocity relation for such a slab. From these relations, he obtains very general equations relating the group delay and phases of the transmitted and reflected pulses.

Multi-dimensional PBG crystals

Modelling of multi-dimensional PBG structures meets much more difficulties in comparison with 1D case. Actually, the high complexity of three-dimensional nanoprocessing has not allowed the fabrication of three-dimensional photonic band gap structures working in the optical range [43]. Within the microwave and sub-millimetre regime, where fabrication is much simpler than in optical regime, several three-dimensional structures have been suggested [44,45]. An usual way in optics is to use 3D combinations of 2D PBG structures [43,46].

2D PBG crystals (and 3D ones, consequently) are usually made as a set of objects like rods [12] or a lattice with holes [47]. Basically, photonic crystals are derived from periodic structures, which exhibit photonic band gap due to their periodicity. It is well known that the introduction of defects in the periodic lattice generates localized electromagnetic modes. Potential applications in many technological areas, such as the development of efficient semiconductor light emitters, filters, substrates for antennas in microwaves, and lossless mirrors, have generated a growing interest in the study of the properties of multi-dimensional photonic band gap materials.

As there are many difficulties in such structures fabrication in optical waverange to pick up an appropriate solution for them experimentally by creation and testing the different kind of ones. Therefore, many researchers have developed theoretical and numerical techniques to study these periodic or quasi-periodic structures.

Some of the *developed techniques* are converted from those of electromagnetic diffraction theory as ones based on transfer matrix approach [54,55]. They have nevertheless a specific way of application in optical waverange. In the papers mentioned above, problems involving finite-size crystals with defects are solved under the supercell approximation, replacing the nonperiodic structure by a periodic one. These methods are applied in the frequency domain, as well as the methods of the problem solution with variational principle [4,56]. In the latest papers the fields are expanded in a set of harmonic waves and the resulting eigenvalue problem is solved for assumed small variations. In [60] the problem is solved by different approach in time domain.

The paper [12] presents a numerical study of two-dimensional photonic structures of finite extension.

Particularly, the authors consider the photonic crystal as a finite set of parallel rods. A rigorous theory in which each rod is characterized by its scattering matrix, which links the diffracted field to the incoming one, is used. These fields are represented by Fourier-Bessel expansion, which is convenient for the considered cylindrical components of the crystals. From translation properties of Bessel functions the scattering problem is reduced to the resolution of a linear system. The method is able to provide a complete description of all electromagnetic quantities for crystals of finite size, with short computation time and good precession. The authors demonstrate the developed numerical tool on periodic structures with one and two defects. The defects are obtained by removing some cylinders inside the crystal in order to get microcavities. The calculation results from [12] were verified experimentally by other authors [61] showing that the progress of technology makes it possible to design such structures in optical domain.

The concept of band theory to describe the behaviour of electromagnetic waves in 3D PBG structures was presented in [57] proposing to apply the concept of reciprocal space, Brillouin zones, dispersion relations etc. to electromagnetic waves. The nearly free photon model is considered there to solve the problem in the crystallography domain.

A theory on the resolution of the wave propagation equation in the reciprocal lattice domain after decomposing the periodic distribution of the structure permittivity into its Fourier series is presented in [58]. Numerical tools as, for example, FDTD and FDFD are sometimes used [3, 59, 62, 65] when the considered structures are of small size being used with other devices as waveguides or antennas, but they works properly mainly in microwave domain.

Among theoretical techniques used to find resonant frequencies of defect states, the real-space Green function approach turns out to be efficient [63, 64].

For microstructures (periodic ones as well as ones with defects of the periodicity) an effective index model approach is also available. It was used in [68] to investigate two-dimensional honeycomb-rod PBG structure. The carried out analysis showed that a relative in-plane band gap of 10% may be obtained for a structure characterized by a rod dielectric constant of 13, air background, and a filling fraction of 0.13. For this structure, it is found through the application of an effective refractive-index model that propagation for a single frequency may be inhibited over a solid angle covering more than a half of the spontaneous emission from a narrow-linewidth point source. It was found that it is necessary for the considered approach to take into account the effective index dependence on frequency, as the field concentrates in the high-index material for increasing frequency.

Unfortunately, still there are no simple ways to predict the stop-band frequency range. When a 3D structure consists of two-dimensional sublattices it turns out that significant properties of the 3D crystals are determined principally by the characteristics of the 2D sublattices [55], and computation of the latter properties is much less costly than computing those of the 3D crystal directly. The paper [55] considers a class of 3D photonic band gap materials formed by interleaving of a pair of 2D lattices. The lattices uniform directions are assumed mutually orthogonal, that is so called „woodpile" geometry is considered. It was concluded there after numerical calculations that 2D square lattices interleaving can provide the properties of full 3D photonic band gap material.

A possibility of 3D confinement of light in low-dimensional photonic crystals was reported in [67]. The authors show theoretically that strong 3D confinement can be produced in part by a photonic crystal, and in part by index confinement. 2D photonic crystals in 3D optical environment were studied experimentally and theoretically in [43]. Reflection spectra of the crystal as a triangular lattice of cylindrical holes in bulk silicon were measured over a wide range of mid-infrared wavelengths by using a Fourier-transform spectrometer with a convergent incident beam. Very high reflection coefficients are demonstrated for the first-order forbidden bands (reaching 98%). Comparing the results of experimental and numerical investigation, the contributions of different effects that degrade the reflector performances are separated. The authors conclude that fabrication inhomogeneities such as the small roughness of the interface or the hole-radius dispersion are shown to be the prime cause of degradation as long as diffraction effects are weak.

Conclusion

The proposed brief review shows a great interest to PBG materials and the research now is extended widely from microwaves domain into an optical one. The engineering of photonic stop-bands and band gaps is opening up new opportunities in many areas of photonics and optoelectronics. Improved operating characteristics, greater packing density of devices (shrinkage of device dimensions from cm to :m), and multi-functionality are among the benefits. New methods for fabricating photonic crystals are continually emerging.

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