Foreword

The Analogy between Electronic Waves and Electromagnetic Waves

Since the advent of quantum mechanics and the clear demonstration of the existence of 'matter waves', physicists have never failed to take advantage of concepts and theoretical methods developed in the fields of optics and electromagnetism. Thus, a number of phenomena in solid state physics are commonly interpreted by analysing electronic excitations in terms of electronic waves. By contrast, the opposite situation has rarely occurred, and only on a few occasions have optics and electromagnetism borrowed concepts and theoretical methods from solid state physics. From this point of view, the emergence of photonic bandgap materials and photonic crystals at the end of the 1980s can be seen as a revenge to the benefit this time of optics and electromagnetism. In the same way as the periodicity of solid state crystals determines the energy bands and the conduction properties of electrons, the periodical structuring of optical materials at wavelength scales has turned out to be one the most viable approaches towards the control of the energies and of the fluxes of photons occurring in these materials.

The analogy between electronic waves and electromagnetic waves is a mere consequence of the formal relation between the Schrödinger's equation for electronic wavefunctions and Maxwell's equations for electromagnetic waves. Indeed, leaving aside the spins of the particles, a harmonic electromagnetic wave in a dielectric lossless medium satisfies Eq. 1a, which formally is analogous to the equation ruling the wave function for an electron with mass m in a potential V (Eq. 1b):

$$\nabla \times \left[\nabla \times \boldsymbol{E}(\boldsymbol{r})\right] = \frac{\omega^2}{c^2}\,\varepsilon_r(\boldsymbol{r})\;\;\boldsymbol{E}(\boldsymbol{r}) \tag{1a}$$

$$\nabla^2 \Psi(\boldsymbol{r}) = -\frac{2m}{\hbar^2}\left(\mathrm{E} - V(\boldsymbol{r})\right)\;\;\Psi(\boldsymbol{r}) \tag{1b}$$

The spin difference between the photons, which are bosons, and the electrons, which are fermions, results in different statistics for the energy state populations, and also explains that these two equations are of a different nature: the equation for photons is vectorial whereas the equation for electrons is scalar. We shall return later to the resolution of Eq. 1a, which applies here to the electric field $\boldsymbol{E}$. A brief comparison between this equation and Eq. 1b shows that the relative dielectric permittivity $\varepsilon_r(\boldsymbol{r})$ (the square of the refractive index n) is for photons the analogue of the potential V for electrons. In analogy with the electronic band gaps of semiconductors, it then becomes intuitive that a periodic variation of $\varepsilon_r(\boldsymbol{r})$ may result in the formation of photonic band gaps. In other terms, for a certain range of frequencies, or equivalently of wavelengths, light cannot propagate in the dielectric, whatever its polarization and direction of propagation are. Remaining within the assumption of a lossless dielectric, a light beam incident on this material will be totally reflected.

Of course, the analogy between electronic waves and electromagnetic waves is not restricted to the concept of energy gap. This can be shown by considering the simple system formed by a planar waveguide consisting of a high-permittivity (ε_1) layer, sandwiched between two semi-infinite cladding layers with lower permittivity ($\varepsilon_2 < \varepsilon_1$). Such a system is but the analogue of a potential well V_1 sandwiched between two potential barriers ($V_2 > V_1$). Assuming the propagation constant of light to be larger than ε_2 ω/c in the plane of the waveguide, guided propagation modes occur at discrete frequencies, in much in the same way as electronic levels may exist at discrete energies in the potential well. A transverse distribution of the light intensity ($\alpha|\boldsymbol{E}|^2$) is associated with each guided mode, owing to the fact that the presence of an electron along the transverse axis is characterised by a probability ($\alpha|\,\psi|^2$).

Photonic Bandgap Materials or Photonic Crystals?

In view of the preceding considerations, the reader might have gathered the impression that 'photonic bandgap material' and 'photonic crystal' are two terms that can be used indifferently for the same structures. This is not the case however, since the term 'photonic crystal' actually applies to any periodic dielectric or metallic structure irrespective of the presence of a photonic band gap in this structure. Further, the very concept of a photonic band gap originally emerged with the desire of achieving a complete control of the spontaneous emission and, ultimately, of designing single-mode microcavities. However, since the pioneering works carried out during the 1990s, the interest in photonic band gaps is no longer restricted to omnidirectional photonic bandgap structures, and the very concept of a photonic crystal has somehow 'exploded".

The search for a complete three-dimensional confinement of light is currently a challenging issue. The problem consists in finding the most appropriate cavity structure for solid state microsources with a number of individual emitters as small as possible, possibly a single emitter. Photonic crystal microcavities are promising candidates for addressing this challenge. However, technological difficulties cannot be overlooked, and it is now recognized within the scientific community that there is a long way before the original three-dimensional microwave experiments conducted by E. Yablonovitch *et al* can be reproduced at near-infrared and visible wavelengths[1]. For this reason, efforts have shifted for the most part from the consideration of three-dimensional photonic crystals to that of two-dimensional photonic crystals, with the underlying idea that two-dimensional photonic band gaps and photonic crystals could develop into a direct continuation of planar integrated optics, with the distinctive advantage however of allowing the realization of optical devices much more compact (wavelength-scaled) than currently existing devices. Fortunately enough, this idea has coincided with the tremendous growth of 1.3-1.5 μm telecommunication systems, which requires the development of an 'optical circuitry' capable of simultaneously analysing an ever increasing number of optical signals, both in fibre and in planar substrate configurations. Indeed, the development of photonic band gaps and photonic crystals in the years extending between the end of the 20th century and the beginning of the 21st century has benefited from the strong demand for innovative devices and systems in optical communications.

In the last decade, considerable advances have been achieved concerning the theoretical understanding, the technical fabrication and the experimental characterisation of photonic crystals. Not only has the concept of a photonic crystal been extended from three-dimensional structures to one and two-dimensional structures, but the guiding, dispersion and refraction properties of periodic structures have also been considered anew in the light of these developments, with the same attention as the properties of photonic band gaps themselves. Giant dispersion effects, including superprism as well as negative refraction and slow-light effects have thus been demonstrated. Periodic metallic structures have also been revisited in the continuity of the pioneering works on artificial dielectrics conducted during the 1950s, revealing new potentialities for microwave antennas, for terahertz circuits and for the control of plasmon waves at optical wavelengths. One of the most striking illustrations of the fruitfulness of research on metallo-dielectric photonic crystals is probably the development of the so-called metamaterials, which are expected to provide a new approach towards negative refraction, through the simultaneous control of the effective permittivity and the effective permeability. Photonic crystals have also made their way into the rich world of nonlinear optics, where they are likely to open new perspectives for frequency conversion, for the generation of harmonic waves and for optical bistability. In this context, we shall see that periodic ensembles of materials for nonlinear optics do not necessarily involve photonic band gap effects.

The study of the physical and optical properties of photonic crystals has generated a burst of new ideas for optical devices and systems. Special mention needs to be made here of photonic crystal silica fibres, which appear as the first application of photonic crystals to the real world of optical communications.

In the field of semiconductors and metals, the fabrication of photonic crystals has represented an important challenge for micro- and nanotechnology. In turn, these technologies have benefited from the validation of processes which has thus

[1] Yablonovitch E., Gmitter T.J., Leung K.M. *Photonic band structures: the face-centered-cubic case employing non-spherical atoms*, *Phys. Rev. Lett.* 67, p. 2295, 1991

been completed. In this respect, the evolution of photonics has paralleled the revolution which has been taking place in the field of electronics with the development of nanotransistors and quantum dot memories. Nanophotonics are now being recognized as a special branch of optics, in much the same way as nanoelectronics form a special branch of electronics. As will be seen in this book, some of the technological problems that had appeared at the time of the first studies on photonic crystals, are currently in the process of being solved. However, it should be stressed that future development and applications of photonic crystals are definitively dependent on the degree of accuracy which can be achieved in the fabrication of micro- and nanostructures, and thus on the overall dimensions of the corresponding devices.

Basic One, Two and Three-Dimensional Structures

In the following chapters, the reader will explore the large variety of photonic structures which have been either imagined or fabricated in the world of photonic crystals. However, some among these structures are quite emblematic, and as such they will be systematically used as references throughout this book. It seems therefore useful to acquire a familiarity with these structures. They are represented here in Fig. 1, where they are ordered from the simplest to the most complex.

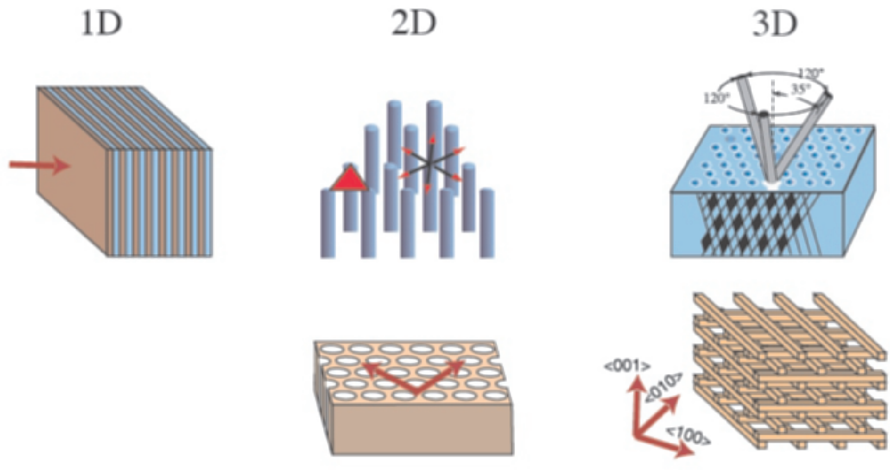

Fig. 1. Emblematic photonic crystals. *From left to right:* One-dimensional structure: Bragg mirror. Two-dimensional structures: hexagonal lattices formed by rods or pores. Three-dimensional structures: 'Yablonovite' and 'woodpile' structures

As is the case in reference textbooks on solid state physics[2], one-dimensional structures are commonly used as reference models, more particularly for understanding the formation of energy band diagrams. In the field of optics, one-dimensional photonic crystals consisting of periodic stacks of thin dielectric layers with a $\lambda/4$ optical thickness are actually nothing else than Bragg mirrors (Fig. 1, *left*). Contrary to one-dimensional solid state crystals, these structures are not artificial, and they are actually used in a variety of optical devices. The fabrication of monolithic Bragg mirrors from III-V semiconductors has reached maturity at the end of the 1980s. The first experiments on optoelectronic devices based on the use of planar microcavities were reported at near-infrared wavelengths during the same period. However, the efficiency of Bragg mirrors is strongly dependent on the angle of incidence with respect to the normal to the dielectric layers. When the incidence angle is progressively increased, the reflectivity decreases and the mirror tends to become transparent in the end. Under these conditions, it turns out impossible to achieve an omnidirectional photonic band gap.

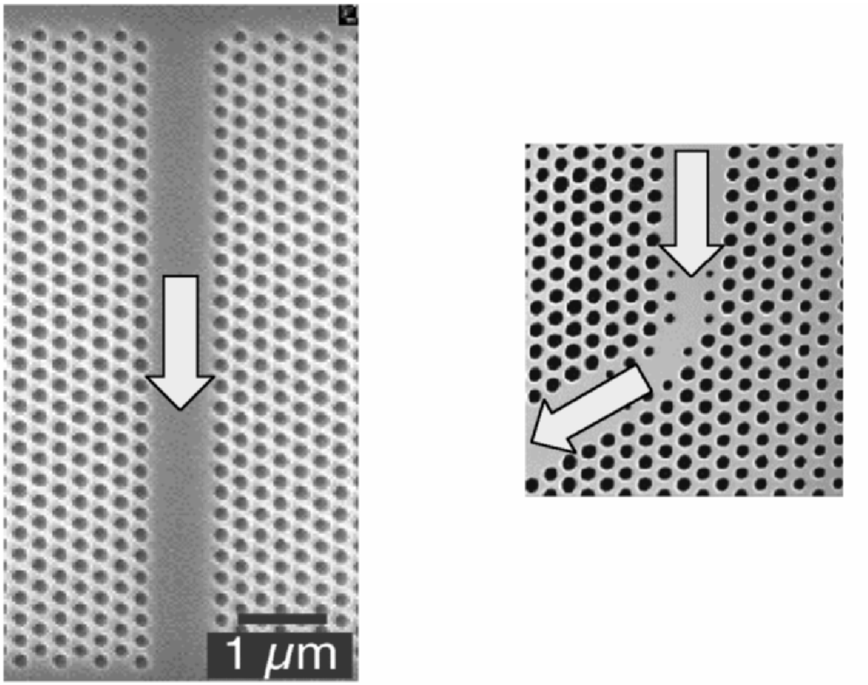

Fig. 2. Channel optical waveguide (*left*) and light bend (*right*) fabricated in a two-dimensional photonic crystal

[2] Kittel C. *Introduction to Solid State Physics,* J. Wiley & Sons, 1971

While two-dimensional photonic crystals are more difficult to fabricate than one-dimensional crystals, they nevertheless remain of a moderate complexity (Fig. 1, *middle*). The strong interest in these structures originates from their potential applications to planar integrated optics and to 'photonic circuitry'. Basically, two different types of such structures exist: the first one consists of disconnected dielectric cylinders (Fig. 1, *middle top*), while the other is formed by air pores drilled in a dielectric matrix (Fig. 1, *middle bottom*). If the in-plane confinement of light could be achieved in a thin slab of such a photonic crystal, then the propagation of light could be totally controlled along two directions. This is illustrated in Fig. 2, which shows how to obtain either a channel waveguide or a light bend by removing a series of patterns from a two-dimensional photonic crystal. This leads to the possibility of envisioning planar photonic circuits that would be analogous to electronic circuits fabricated on silicon wafers. Such circuits would be of particular interest for obviating the shortcomings of the ultraminiature microelectronic chips which are expected to appear in the future. We shall later see that one of the main problems in this context is actually to prevent the light from escaping out of the plane, i.e. out of the dielectric slab. This issue has been addressed in a number of studies. Theoretical investigations often remain complex due to both the finite thickness of the crystal slab and to the local disruptions of the periodicity of the crystal.

Actually, only three-dimensional photonic crystals really allow for omnidirectional photonic band gaps. The last decade has been marked by two main types of structures, represented in the right-hand part of Fig. 1. The so-called Yablonovite Fig. 1, *top right*) was promoted by the famous experiments conducted by Eli Yablonovitch and his group in 1991 (Yablonovitch 1991). Indeed, the fabrication of the first prototype at centimetre scales and the subsequent demonstration of a complete photonic band gap around 12 GHz aroused tremendous interest in photonic crystals within the scientific community. The second emblematic three-dimensional photonic crystal (Fig. 1, *bottom right*), which is referred to either as a ‘woodpile’ or ‘layer-by-layer’ structure, consists of a multilayer stack where each layer is formed by a one-dimensional array of dielectric rods. Existing methods of fabrication, i.e. those used in semiconductor technology, can be applied successfully for the realization of such structures. Actually, both the Yablonovite and the woodpile photonic crystals present the same crystalline structure as diamond or silicon. Indeed, in the first case, the periodic array of pores drilled in the dielectric matrix with an angle of 120° between one another reproduces the empty <110> galleries of the face centred cubic (fcc) lattice with two atoms per cell. In the second case, the intersections between the dielectric rods are organized into two fcc lattices in the same way as carbon atoms are in the diamond crystal.

In practice, the similarity with solid state crystals can be neglected, and photonic structures can be considered as specific instances of two or three-dimensional diffraction gratings. This more traditional optical approach can be quite useful, and therefore it will be adopted at various points in this book.

Objectives of this Book

The growing interest for photonic crystals has generated an extensive literature on this subject. Some websites have tried to maintain an exhaustive bibliography as long as it has been possible, but most of them have given up due to the explosion of the studies on the subject. Contrary to the valuable books which have already been published on this subject, this book does not intend only at describing ideal photonic structures with infinite dimensions in all directions of space, but rather aims at going from photonic crystals to the realization of actual optical devices, and beyond to the development of a photonic circuitry. In this respect, the confinement of light in a 'photonic cage' can be viewed as a first step towards the design of optical devices at the wavelength scale with ultimate properties for storing, filtering, guiding and emitting light. It is also part of a tendency towards the extreme miniaturization of devices and systems, which is made necessary by the manipulation of an ever increasing number of data.

From a more academic point of view, the study of photonic crystals has been, and still remains, a unique opportunity of bringing together a large diversity of skills from such different fields as solid state physics, optics, microwaves and microelectronics. The 'Groupe de Recherche' (GDR) on 'Microcavities and Photonic Crystals' organized by the CNRS in the period from 1996 to 2001 has been the French example of a cooperation between researchers from such different fields. The present book can be seen as the result of this cooperation.

The six authors, coming from different scientific fields, have joined efforts to provide students and researchers with the necessary theoretical background on photonic crystals and their optical properties, while at the same time presenting a large variety of optical and microwave devices to which photonic crystals can be applied.

The book is divided into three parts which can be independently approached. In the first part, the reader will become familiar with photonic band diagrams and theoretical models for both infinite and finite photonic crystals. We address the problem of analysing the presence of local disruptions in the periodicity of photonic crystals, which are also referred to as crystal defects in analogy with solid state physics. We finally consider different issues related to quasi-crystals as well as the main specificities of periodic metallic structures.

The second part of this book is devoted to the specific properties of photonic structures in terms of optical confinement, guiding, refraction and optical nonlinearity. Novel concepts of mirrors, waveguides and optical resonators based on photonic crystals will then be discussed. A particular attention shall be devoted to the problem of a solid state emitter in a microcavity and to the control of its spontaneous emission, which remains one of the major issues in nanophotonics. A detailed bibliography, covering all topics addressed in this book, will allow the reader to delve deeper in the subject, and should provide him with a precise idea of the most recent advances in research.

The last part of the book will be devoted to a review of the potential applications of photonic crystals and of the different methods which have been developed for their fabrication and their characterization. We shall successively consider semiconductor devices in planar integrated optics, light microsources and photonic crystal fibres. In most cases, photonic crystals will be compared to other technical solutions implemented with existing devices. A specific chapter will be devoted to three-dimensional photonic crystals in optics. Finally, the potential applications of photonic crystals to microwave and THz devices and antennas will also be presented in order to complete this review and to show the many common aspects shared by optics and microwaves.

As can be seen, we have tried throughout this book to capture the strong multidisciplinary character of photonic crystal research, which is an essential part of its appeal to everyone with a broad curiosity.

Orsay, January 2008 Jean-Michel Lourtioz

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