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C. R. Physique 8 (2007) 253–266
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Recent advances in crystal optics/Avancées récentes en optique cristalline

Photonic crystals: basic concepts and devices

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Available online 28 August 2006

Invited Paper

Abstract

The art of microphotonics consists in confining photons, in one or more directions, in structures having dimensions about the wavelength, and doing this for the longest possible duration. The objective is then to associate these microstructures in order to carry out a photonic integration allowing data processing in very compact systems and using low optical powers. Photonic crystals have largely showed these last years their capacity to achieve these goals. ***To cite this article: P. Viktorovitch et al., C. R. Physique 8 (2007).***

Résumé

Cristaux photoniques : concepts de base et des composants. L'art de la microphotonique consiste à confiner les photons, selon une ou plusieurs directions, dans des structures ayant des dimensions de l'ordre de la longueur d'onde et ceci, pour une durée la plus longue possible. L'objectif est alors d'associer ces microstructures afin de réaliser une intégration photonique permettant le traitement de l'information dans des systèmes de faible encombrement en utilisant de faibles puissances optiques. Les cristaux photoniques ont largement démontré ces dernières années leur capacité à atteindre ces objectifs. ***Pour citer cet article : P. Viktorovitch et al., C. R. Physique 8 (2007).***

Keywords: Photonic crystals; Microphotonics

Mots-clés : Cristaux photoniques ; Microphotonique

1. Introduction

The principal motivations for the emergence of Photonic Crystals can be summarized in one single word, that is 'λ-Photonics', which means the control of photons at the wavelength scale. The harnessing of light has always been central in the field of human endeavor: one may quote, for example, the destruction of the Roman fleet by the blazing mirrors of Archimedes at the siege of Syracuse in 215 BC.

Generally speaking, the harnessing of light consists in *structuring the space* where it is meant to be confined: however, there are intrinsic limitations which are related to the undulatory nature of the light and which have been

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1631-0705/$ – see front matter
doi:10.1016/j.crhy.2006.04.005

formulated in the famous equations of Maxwell in 1873, providing a consistent picture of the experimental data available then. These limitations are in the heart of the λ-Photonics, whose definition could be *the control of photons within the tiniest possible space during the longest possible time*: this implies structuring space at the wavelength scale, which in the sub-micron range for the optical domain.

The next section will present a brief overview of the basic concepts which underlie Photonic Crystals, with a special emphasis on two-dimensional Photonic Crystals (2DPC), which have been the subject, so far, of most of the new applications in terms of device demonstrations; the presentation proposed is phenomenological and does not leave much room for theoretical models of Photonic Crystals. Focus is put, instead, on the deep changes of the spatial–temporal characteristics of photons as a result of their 'immersion' in the periodic medium formed by the Photonic Crystal. Section 2 will conclude with the presentation of the essential building blocks of the 2DPC based Integrated Micro-Nano-Photonics, which is presently developed along planar technological schemes and is considered as the principal domain of applications of Photonic Crystals.

It will be shown in Section 3 that 2DPC have definitely entered within the realm of practical devices; although 2DPC have not yet reached the maturity allowing for the mass production and transfer to the market of devices, it must be pointed out the extraordinary flourishing of laboratory demonstrations of Micro-Nano-Photonic devices, at a rate which had not been anticipated a few years back. Given the wide variety of achievements reported in the literature, a classification of the devices in four main categories is proposed, depending on their mode of operation and on the confinement scheme in use. Special attention will be given to surface addressable devices, which have been the subject of very recent developments. In that respect, the concepts of 2.5 Microphotonics based on 2DPC, which can be considered as a major extension of planar technology through exploitation of the third ('vertical') dimension, will be also presented in Section 3, which will be followed by the concluding section.

2. Photonic crystals: a brief overview of basic concepts

2.1. What are photonic crystals?

A Photonic Crystal is a medium whose optical index shows a periodical modulation with a lattice constant on the order of the operation wavelength. The specificity of Photonic Crystals inside the wider family of periodic photonic structures, lies in the high contrast of the periodic modulation (generally more than that 200%); this specific feature is central for the control of the spatial-temporal trajectory of photons at the scale of their wavelength and of the their periodic oscillation duration.

Fig. 1 shows schematic views of a variety of photonic crystals with dimensions ranging from 1 to 3.

One-dimensional photonic crystals (1DPC) have been around for quite a long time in the very fertile field of thin film optics; however, the periodic structuration has been limited to only one direction in space, and devices based on 1DPC suffer from a limited angular resolution and their 'lateral' size cannot be made very compact.

The concept of 3DPC has been introduced in 1987 by E. Yablonovitch [1] and demonstrated experimentally for the first time in the micro-wave regime in a photonic crystal, called 'Yablonovite' [2]. The initial motivation was the full

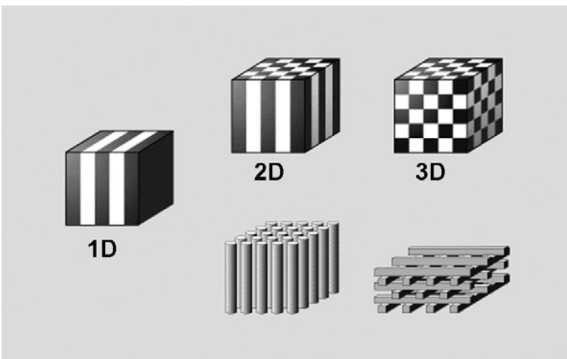

Fig. 1. Schematic view of Photonic Crystals with different dimensionalities.

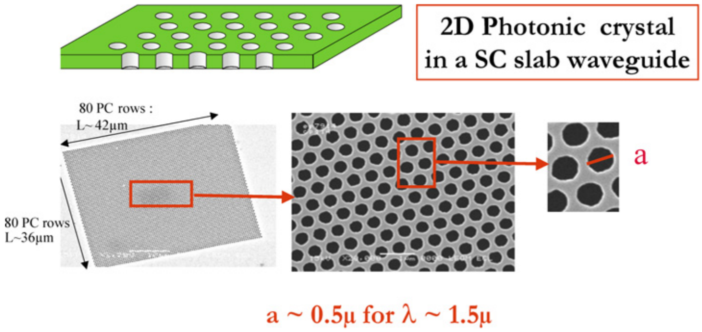

Fig. 2. Schematic and SEM views of a real 2DPC, consisting in a triangular lattice of holes formed in a semiconductor slab.

control of the spontaneous emission of an active emitting material. 3DPC are potentially the best candidates for this purpose and for many other applications where the best control of photons in space and time is required.

However, fabrication technology of 3DPC in the optical domain is extremely complex. The only examples of mass production of such structures can be found in nature, owing to miracles (or to the 500 million years of research) of the natural morphogenesis.

In between, 2DPC are far more accessible than 3DPC, since they may be fabricated using planar technological schemes which are familiar to the world of integrated optics and micro-electronics. They provide, in addition, a considerable amount of new degrees of freedom with respect to 1D structures. We will restrict the rest of this article to 2DPC, which have been the subject of most of the recent developments in the field of Micro-Nano-Photonics.

An ideal 2DPC (two-dimensional object in a two-dimensional world) has no, formally, real existence and a representation closer to reality would be to imagine, in a real 3D space, a 2D structuration of the latter, where the only directions of propagation to be considered would be along the index 'gradient vector'. This implies an 'infinite' shape ratio of the structuration, which is not realistic, either. A last step toward a real 2DPC consists in considering a 2D structuration of a 2D object in a 3D real space; the 2D object is a planar dielectric waveguide where photons are 'index guided', that is they stay vertically confined by the vertical profile of the optical index. Fig. 2 shows schematic and SEM views of a typical real 2DPC, consisting in a triangular lattice of holes formed in a semiconductor slab.

2.1.1. Strategies for the vertical confinement in 2DPC in the waveguided configuration

Two approaches are used to insure the guiding or vertical confinement of photons. In the so called 'substrate' approach, the vertical confinement is 'weak', which means that the vertical structuration of the optical index is achieved by a low index contrast between the dielectric cladding and core layers. Typically the core guiding layer is a semiconductor layer (through which the 2DPC is etched), epitaxied onto a semiconductor substrate, with a slightly lower optical index. A semiconductor cladding or barrier layer (with a slightly weaker optical index than the substrate) may be inserted in between for a fine adjustment of the vertical electromagnetic distribution. This is the usual configuration for classical integrated optoelectronics based on III–V compound semiconductors. The substrate approach is therefore fully compatible with the classical technology currently in use. It takes advantage of the well controlled coupling schemes between the devices and input-output optical fibers, owing to the relatively comfortable thickness (around 1–2 µm, for monomode operation in the 1.5 µm wavelength range) of the guiding or vertical confinement zone. There are, however, drawbacks with this approach: it requires first to control the fabrication of the holes of the 2DPC with a very large shape ratio; the depth of the holes must, indeed, exceed significantly the thickness of the guiding zone in such a way as to minimize optical losses in the semiconducting substrate (Lalanne and Benisty [3]); also, the large index of the cladding substrate results in a rather weak slope of the so-called light-line (it is like the inverse of the optical index), which leaves very little room for the pure loss-less waveguided modes, which are not allowed to couple, via diffraction processes induced by the PC structuration, with radiated modes below the light-line.[1] In the so-called 'membrane' approach, the vertical confinement is strong; the guiding of light is achieved in a high index semiconductor membrane surrounded with low index cladding or barrier layers (for example an insulator like silica or simply air).

[1] See, for example, [4] for a thorough presentation and discussion of the concept of light-line. We will come back to this point later on in the present contribution.

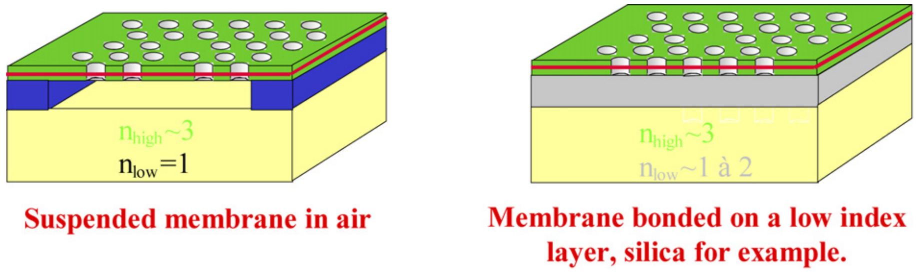

Fig. 3. The basic building blocks of the membrane approach.

The virtues and drawbacks of the substrate approach become precisely the drawbacks and virtues of the membrane approach: in monomode operation conditions, the thickness of the membrane is very thin, around a fraction of μm; it results that low loss coupling schemes with an optical fiber are not easily achievable, but, the positive counterpart lies in the relaxed technological constraints for the fabrication of the 2DPC (holes with a shape ratio around unity). In addition, one may rely on a 'reservoir' of wave-guided modes below the light-line, far more comfortable than with the substrate approach. Also, the strong vertical confinement, leading to a reduced volume of the optical modes, lends itself to the production of very compact structures, which is essential for active devices to operate at the cost of very low injected power. Another essential asset of the membrane approach will be fully appreciated in Section 3, where the attention of the reader will be strongly driven to the fact that a brilliant future should be promised to 2DPC provided that they are not strictly restricted to in-plane waveguided operation and that they may be opened to the third dimension, particularly along the so called 2.5D microphotonics schemes.

In the rest of this section we will concentrate on the membrane approach, which, in addition, lends itself to more accessible optical objects from the conceptual point of view. A schematic view of basic building blocks for the membrane approach is shown in Fig. 3.

The membrane including the 2DPC may be suspended in air; this is the 'ideal' situation from the basic study point of view. For practical applications, where the thermal budget should be considered carefully, bonding of the membrane on a low index substrate (silica for example) is to be applied. In the latter situation, advantage can be drawn, in addition, from an improved mechanical stability as well as from easier technological conditions (for the electrical contacting of the devices, for example).

2.2. *Why photonic crystals?*

The principal motivation for high index contrast periodical structuring of space, thus resulting in the formation of a photonic crystal, lies in the general objective of Micro-Nano-Photonics, which is the control of optical modes, i.e., photons within the tiniest space V during the longest possible period of time τ.

According to the above definition of Microphotonics, it appears natural to grant the optical mode with a merit factor F, which quantifies the properties of the optical mode in terms of the ratio of the time τ during which it remains under control (or its lifetime from the observer/user view-point), over the average real space volume which it fills up during its lifetime.

To put it differently and more precisely, the lifetime τ is the time interval when the user may count on a coherent mode, whose phase remains deterministic, within the volume where he tries to control and confine it. The merit factor can be made dimension-less if normalized to the ratio T/λ^3, where T is the period of oscillation and λ the wavelength in vacuum.

$$F = \frac{\tau}{T} \times \frac{\lambda^3}{V} \tag{1}$$

with:

$$Q = \frac{2\pi\tau}{T} \tag{2}$$

where Q is the traditional quality factor of the mode.

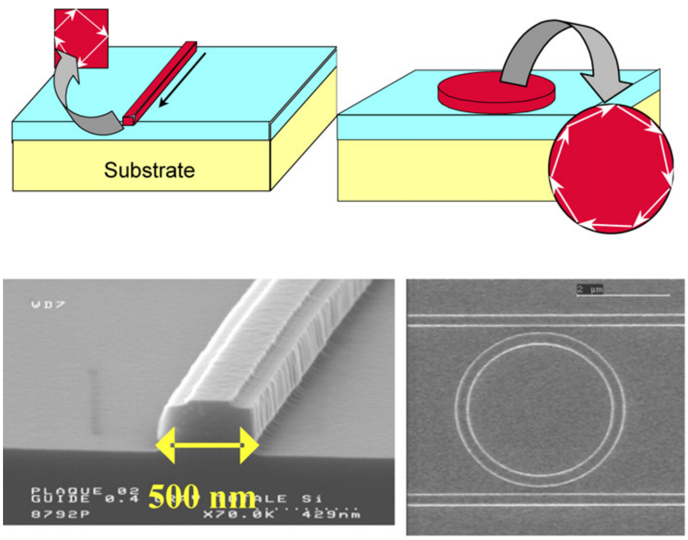

Fig. 4. Guiding and trapping of photons based on refraction phenomena confinement schemes.

The reader will have noticed that F is proportional to the Purcell factor, which expresses the relative increase of the spontaneous recombination rate of an active medium as a result of its coupling to the optical mode, as compared to the non structured vacuum [5].

It should be pointed out that there exists a variety of ways for the structuration of space, consisting in preventing the propagation of photons along one or several directions, thus resulting in photonic structures with reduced 'dimensionality' and optical mode confinement. Refraction phenomena, for example, have been widely used in opto-electronics for the guiding of photons or for their trapping within micro-cavities, as illustrated in Fig. 4. The control of the photon 'trajectory' is based upon the total internal reflection that it experiences at the boundary between the external world and the higher index medium where it is meant to be confined. Photonic crystals offer a new strategy for optical mode confinement based on diffraction phenomena. The new avenue opened up by Photonic Crystals lies in the range of degrees of freedom which they provide for the control of photon kinetics (trapping, slowing down), in terms of angular, spatial, temporal and wavelength resolution.

2.3. Photonic crystal: how does it work?

The principal characteristics of the photonic crystal manifest themselves in the so called dispersion characteristics of the periodically structured medium, relating the pulsation ω (eigenvalue) to the propagation constants k (eigenvector) of optical modes, which are the eigen solutions of Maxwell equations, corresponding to a spatial distribution of the electromagnetic field which is stationary in the time scale. It is appropriate here to speak in terms of dispersion surfaces $\omega(k) = \omega(k_x, k_y)$, real space being two-dimensional.

In a non structured homogeneous dielectric membrane, the dispersion surface relates classically to the wave-guided modes of the slab waveguide and show a circular symmetry.

For photonic crystals, which are strongly corrugated periodic structures (large magnitude of the periodic modulation of the optical index), strong diffraction coupling between waveguided modes (induced by the high index contrast 2D periodic structuration) occurs; these diffraction processes affect significantly the dispersion surfaces, or the so called band structure, according to the solid state physics terminology. The essential manifestations of these disturbances consist in:

– the opening of multidirectional and large photonic band gaps (PBG);
– the presence of flat photonic band edge extremes (PBE), where the group velocity vanishes, with low curvature (second derivative) $\alpha \approx \frac{1}{\mathrm{PBG}}$.

These are the essential ingredients which are the basis of the two optical confinement schemes provided by photonic crystals (PBG/PBE confinement schemes) and which make them the most appropriate candidates for the production of a wide variety of compact photonic structures.

2.3.1. PBG confinement scheme

In the PBG scheme (Fig. 5), the propagation of photons is forbidden at least in certain directions. This is in particular true when they are trapped in a so called localized defect or micro-cavity and the related optical modes are *localized:* in this case the propagation of photons is fully prohibited. Opening of large PBG (in the spectral range) provided by the PC, allows for a very efficient trapping of photons, which can be made strongly localized in free space. Fig. 6 shows a typical example of trap or localized state, consisting in an hexagonal shaped micro-cavity formed in a triangular lattice. This micro-cavity can embed a variety of localized optical modes, whose electromagnetic distributions are also shown.[2] A very large merit factor $F = \frac{\tau}{T} \times \frac{\lambda^3}{V}$ of the localized optical modes may be achieved with the PBG confinement scheme, given that the mode volume which practically coincides with the volume of the micro-cavity can be made very small (a fraction of λ^3), and that the photon trapping time or the lifetime of the localized optical mode τ can be adjusted finely and be made very large. A record quality factor $Q = \frac{2\pi\tau}{T}$, in excess of 10^5, has been demonstrated recently in small micro-cavities by Noda and collaborators [6].

2.3.2. PBE confinement scheme

In the PBE scheme, the PC operates around an extreme of the dispersion characteristics where the group velocity of photons vanishes. It should be noted, however, that the dispersion characteristics apply strictly for infinite periodic structure and time and that the concept of zero group velocity is fully true only under these particular extreme conditions. The real common world is actually finite and transitory. It is therefore more appropriate to speak in terms of *slowing down*[3] of optical modes (so called Bloch modes for a periodical structure), which remain however *delocalized*.

It can be shown that the average group velocity of optical Bloch modes in a photonic structure operating around an extreme of the dispersion characteristics decreases with time t like $V_g \approx \sqrt{\frac{\alpha}{t}}$ (assuming that the dispersion characteristics are isotropic at the extreme whose curvature is α). If we put it in a different way, the lateral extension of the area S of the slowing down Bloch mode during its lifetime τ is proportional to $\alpha\tau$ [7]. It can then be straightforwardly derived that the merit factor of the Bloch mode is simply proportional to $\frac{1}{\alpha}$.[4] As mentioned above, one essential virtue

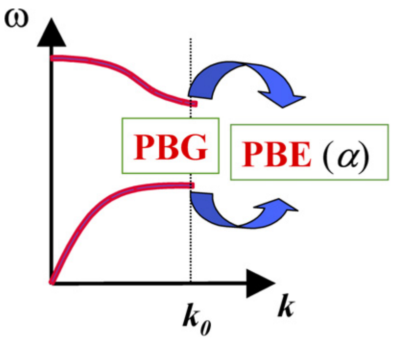

Fig. 5. Schematic representation of a photonic band gap (PBG) and of related photonic band edges (PBE) in the dispersion characteristics of a photonic crystal.

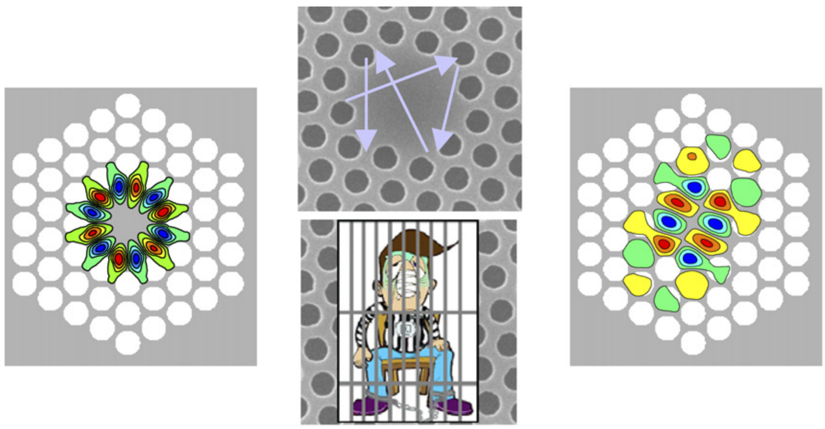

Fig. 6. PBG scheme: photons are trapped in an hexagonal microcavity formed in a triangular lattice photonic crystal, in the spectral range where the latter behaves as a PBG.

2 As determined by FDTD simulation.

3 Not in terms of slow Bloch modes, as this is usually done in the literature.

4 This is also proportional to the density of photonic modes at the band edge extreme.

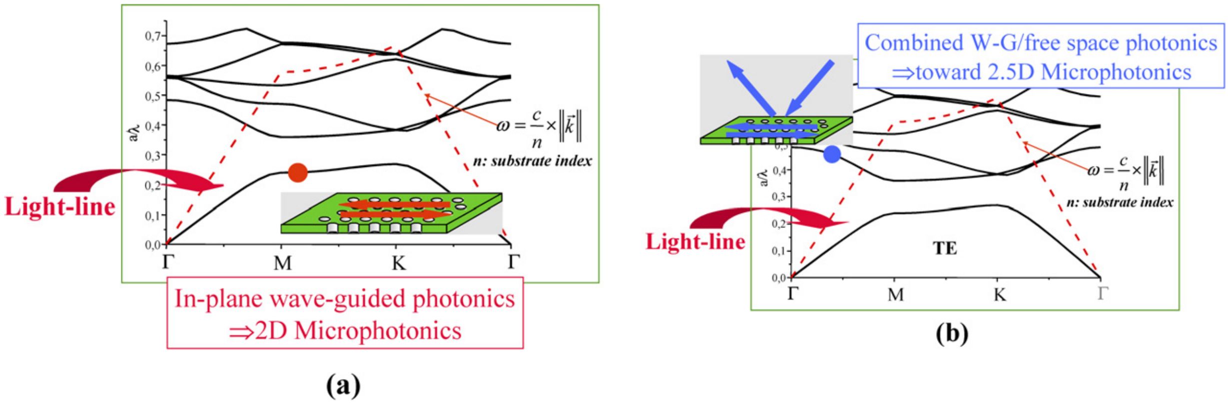

Fig. 7. Light-line operation of photonic structures based on 2D photonic crystals.

of PC is to achieve very low curvature α at the band edge extremes, thus resulting in very efficient PBE confinement of photons and large merit factor of the corresponding slowed down optical modes.

2.3.3. Respective merits of the PBG and PBE confinement schemes in brief

The most efficient confinement of photons can be achieved with the PBG scheme. Record merit factors have been reported in the literature along this way [6].

The PBE scheme provides a weaker confinement efficiency than the PBG approach, while resulting in an improved control over the directionality or spatial/angular resolution.

2.3.4. Flash back to the issue of vertical confinement in 2DPC: below and above light-line operation

It has been explained earlier in this contribution that the vertical confinement of photons is based on refraction phenomena. However, full confinement of photons in the membrane waveguiding slab is achieved only for those optical modes which operate below the light-line (see Fig. 7(a)). This mode of operation is restricted to devices which are meant to work in the sole wave-guided regime, where wave-guided modes are not allowed to interact or couple with radiated modes. This the territory of 2D micro-photonics.

For wave-guided modes whose dispersion characteristics happen to lie above the light line, coupling with the radiated modes is made possible, the wave-guided 'state' of the related photons is transitory, and the photonic structure can operate in both wave-guided and free space regimes (see Fig. 7(b)). This the world of 2D–3D microphotonics, which we will quote later in this article as 2.5D microphotonics.

3. Photonic crystals: devices

Following the pioneering and triggering contributions of S. John [8] and E. Yablonovitch [1], it took quite a few years for the modeling and technological tools to reach the degree of maturity required for the production of the first elementary building block devices, essentially based on 2DPC. This gradual start has been followed, around 2000, by an ever growing wave of new device demonstrators, so much so that it may be stated, to day, that Photonic Crystals have entered within the realm of practical devices (Fig. 8).

In order to help the reader to find his way within this jungle (as illustrated in Fig. 8), we choose to classify the wide range of devices produced so far into four main categories, depending upon whether they operate singly in the wave-guided regime or not, and upon whether they make use of the PBG or of the PBE confinement scheme.

This classification is further detailed in the table of Fig. 9, which provides a non-exhaustive list per category of the principal device structures demonstrated so far. We will span in the following sections these different categories, given that the emphasis will be specifically put on the fourth category (devices operating, along the PBE confinement scheme, in the wave-guided regime while being also opened to the third direction of space, that is including in their functionality the coupling of wave-guided and radiated modes), which has been the matter of attractive new developments in the recent literature.

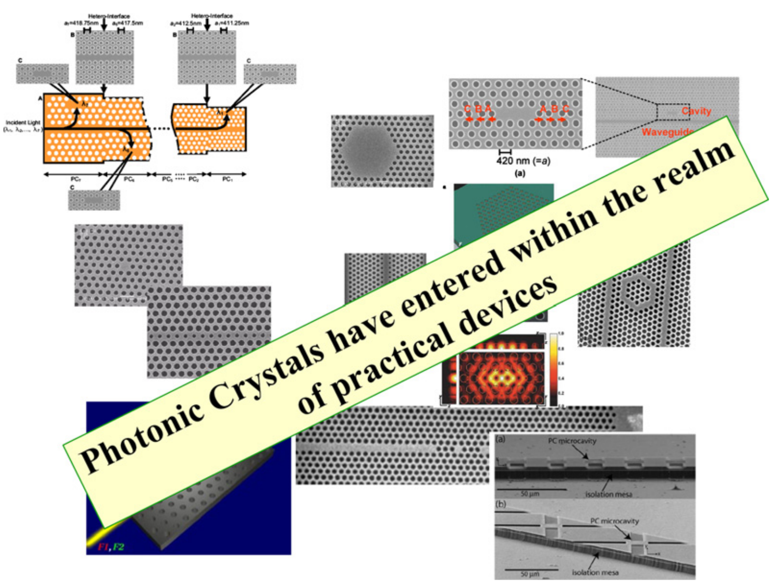

Fig. 8. Illustration of the variety of photonic device structures based on 2DPC.

	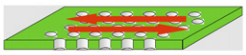	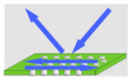
PBG	• Micro-cavities (QED) • Micro-lasers • Guiding / bends • Cavity-guide cascading (add-drop filters) • …	• Drop filters • ...
PBE	• Directional add-drop filters • Micro-lasers • Super-prism • Pulse compression • ...	• Compact reflectors/filters • Non-linear optics : fully optical micro-switches • Surface emitting Micro-lasers • … and other devices

Fig. 9. Classification of 2DPC based devices in four main categories.

It should be mentioned, at this stage, that most of the recent reported achievements in the literature, in terms of device demonstrations, are based on the membrane approach. For passive devices silicon is often used for the membrane material, especially in the silicon on insulator (SOI) configuration, which is fully available in the world of microelectronics. For active devices, III–V semiconductor membranes have been principally used so far: the thin membrane is generally bonded by the molecular bonding procedure on the low index material, such as silica on a silicon substrate [9]. This approach presents a definite advantage lending itself to heterogeneous integration of active III–V optical devices with silicon based passive optical devices and microelectronics. We will concentrate, in the following sections, on the membrane approach.

3.1. PBG scheme and in plane wave-guiding operation (below the light line)

The basic building blocks of photonic components for in plane operation along the PBG scheme are micro-cavities [10] and waveguides [11]. These building blocks were among the earliest structures based on 2DPC reported in the field: they have been the matter of a considerable amount of publications since the late nineteen nineties and have resulted in the production of a variety of devices including very high Q factor nanoresonators for Quantum Electrodynamics [6], very low loss wave-guides [12], micro-lasers [9,13], channel drop filters [14], etc.

3.2. PBE scheme and in plane wave-guiding operation (below the light line)

The PBE confinement scheme has been the matter of a later and less extensive use than the PBG confinement scheme. However, it has already resulted in a variety of devices reported in the recent literature. Active as well as passive devices have been demonstrated. For the former, Bloch mode micro-lasers[5] designed for in-plane emission have been reported in a triangular lattice 2PC formed in an InP active membrane (see, for example, [15]). In Section 3.4, we will come back in more details to Bloch mode micro-lasers designed to operate above the light cone, that is for surface emission. Such passive structures as channel drop filters making use of the PBE scheme have also been proposed; the principal advantage over their counterpart based on the PBG scheme, lies in their 'natural' propensity to provide a directional dropping [16]. A convincing illustration of the strong spatial/angular resolution offered by 2DPC operating around a PBE of the dispersion characteristics is given by the so-called super-refraction or super-prism effect, which manifests itself, in term of a strong angular dispersion of the spectral components of a multicolor incident beam impinging onto the photonic crystal. This phenomenon may possibly be used for an efficient spatial separation of the different wavelength components of the multicolor in coming beam [17]. Another exploitation of these dispersion phenomena has been proposed for the tight control of photon group velocity or dynamics, resulting in the demonstration of compact pulse reshaping devices [18].

3.3. PBG scheme and above the light line operation

Only few reports of devices operating in this particular regime may be found in the literature. The principal reason lies in the fact that, for operation above the light cone, that is in free space, angular resolution is requested, which is hardly offered by the PBG scheme. For example, 2DPC based micro-cavity sources do not lend themselves to a directional emission in free space, given that all k components are available for the modes of the cavity, which behaves like a localized defect (see Section 3.1). Asano et al. [19] have proposed the extraction of wavelengths from a waveguide by using radiation optical losses in free space of localized defect coupled to the guide; although attractive, this approach is hardly expected to result in directional operation. In the beautiful work reported by the group at Kaist [20], it is shown, however, that the emission diagram in free space of a micro-cavity (which can be viewed as a micro-antenna) can be shaped on demand via a careful design of the structure, implying a very good control over the size and the position of the holes around the cavity.

3.4. PBE scheme and wave-guiding/free space operation (above the light cone): surface addressable 2DPC devices

Photonic devices based on 2DPC have been principally aimed, so far, at forming the basic building blocks of integrated photonics and are designed for in plane waveguided operation.

The problem of optical losses, which are considered as hindering the operation of 2D photonic integrated circuits based on 2DPC, can be approached from a completely different perspective: instead of attempting to confine the light entirely within the waveguide structures, the 2D structures can be deliberately opened to the third space dimension by *controlling* the coupling between wave-guided and radiation modes. In this approach, the exploitation of the optical power is achieved by accurately tailoring the optical radiation into free space.

A simple illustration of this approach is the use of a plain Photonic Crystal Membrane as a wavelength selective transmitter/reflector: when light is shone on this photonic structure, in an out-of-plane (normal or oblique) direction, resonances in the reflectivity spectrum can be observed. These resonances, so called Fano resonances [21], arise from the coupling of external radiation to the guided modes in the structures, whenever there is a good matching between the in-plane component of the wave vector of the incident wave and of the guided modes (see Fig. 10). Accurate tailoring

[5] The so called DFB classical lasers are also Bloch mode lasers; the novelty of 2DPC lies first on their compactness, as extensively explained in this chapter and, second, on the extra dimension which they offer.

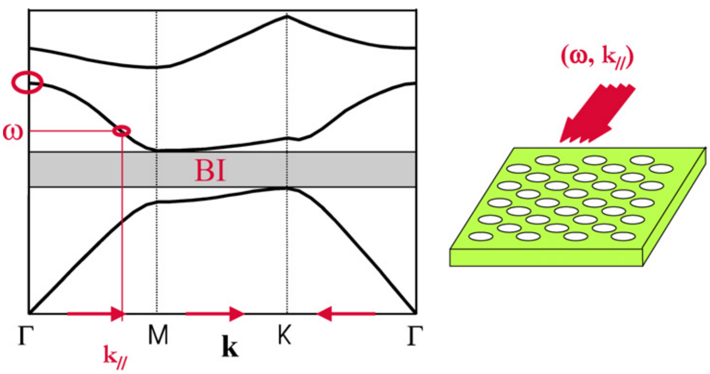

Fig. 10. Illustration of the resonant coupling between a waveguided mode and a radiated mode.

of the spectral characteristics of the Fano resonances (shape, spectral width) is made possible by the design of the 2DPC membrane (type of 2DPC, membrane thickness, ...). If the lateral size of the illuminated membrane is infinite, the spectral width of the resonance is like the inverse of its lifetime τ, that is the lifetime of the waveguided mode, with $\tau = \tau_c$, where τ_c is simply the coupling time constant between waveguided and radiated plane-wave modes.[6] In real devices, the lateral size of the illuminated area is limited, and the lifetime of the resonance is also controlled by the lateral escape rate $1/\tau_g$ of the waveguided mode out of this area; this escape rate can be considered as a loss mechanism for devices which are designed and meant to operate 'vertically'. In these real conditions the lifetime of the resonance can be written, under certain conditions as:

$$\frac{1}{\tau} = \frac{1}{\tau_c} + \frac{1}{\tau_g} \approx \delta\omega \tag{3}$$

where $\delta\omega$ is the spectral widening of the resonance [7]. The ability of high index contrast PC to slow down photons and to confine them laterally, especially at the high symmetry points (or extremes) of the dispersion characteristics, as explained in previous sections, allows for a very good control over the lateral escape losses and results in very compact devices.

A variety of passive as well as active devices has been demonstrated in the recent literature. For example, very compact passive reflectors showing a large bandwidth (a few hundreds of nanometers) and consisting in a plain 2DPC membrane formed in Silicon on silica have been reported [22]. The large bandwidth is obtained for specific designs of the 2DPC which allow for a very strong coupling rate $1/\tau_c$ of waveguided modes with the radiation continuum.

The 2DPC membrane can be also designed in such a way as to result in very strong Fano resonances, that is for weak coupling rate $1/\tau_c$. Use of such strong Fano resonances has been made for the demonstration of very low threshold and very compact surface emitting Bloch mode laser [23]. The photonic crystal consists in a graphite lattice (Fig. 11), which can be viewed as an array of H_1 coupled cavities, formed in a triangular lattice. This particular 2DPC exhibits band edge extremes at the Γ point with very low curvature (Fig. 11). One of these extremes is exploited for vertical laser emission. The coupling between waveguided modes and radiated modes is authorized, but its rate is controlled accurately, allowing for the vertical emission, while retaining the strength of the resonance and, therefore, achieving a very weak threshold power (40 μW): the device is optically pumped in a quasi-steady state regime and operates at room temperature. The pumped area where the stimulated emission process takes place is very limited and does not exceed 2 to 4 μm in diameter: this is a clear demonstration of the outstanding ability of 2DPC to confine laterally slow Bloch modes, along the PBE scheme.

The graphite lattice 2DPC active membrane used for surface laser emission is extremely generic and can apply for a large variety of other types of active devices, at the very cheap expense of slight changes in the design of the 2DPC. Along this line spectacular demonstrations of diverse devices have reported recently, including optical amplifiers [24] and fully optical micro-switches [25]: for the latter use is made of the electronic Kerr effect, via photo-injection of carriers in quantum wells, to manipulate Fano resonances in the spectral domain (the design of the 2DPC results

[6] Various factors contribute to the control of the coupling time constant, such as the strength of the periodic corrugation, the membrane thickness, the symmetry of the waveguided mode, ...

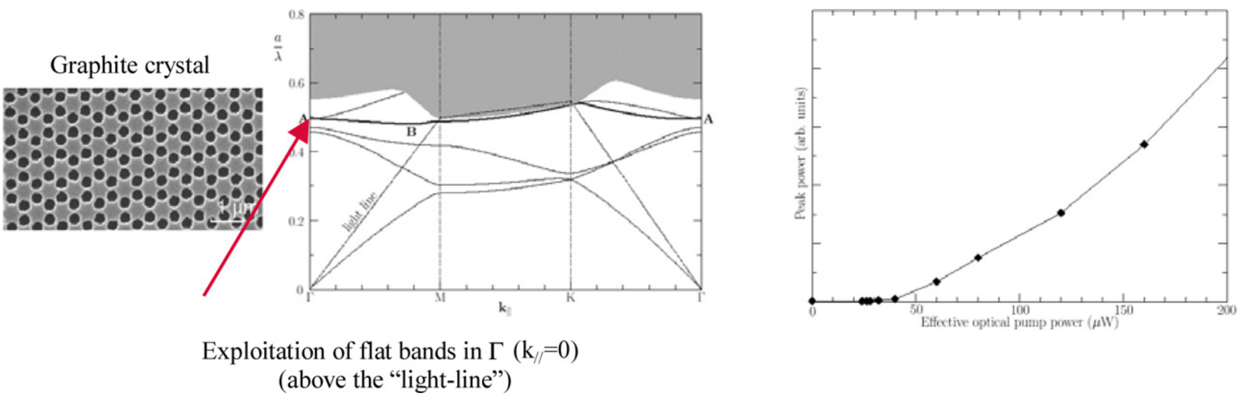

Fig. 11. Band structure and of a surface emitting Bloch mode laser formed in a graphite type 2DPC. The plot of the emitted power versus the pumping power indicates a threshold power of 40 μW.

in Fano resonances lying in the Urbach tail of the quantum wells, instead of the gain maximum as in the case of micro-lasers).

All these devices are convincing illustrations of a planar technological approach resulting in 2DPC devices freed from the bidimensional universe.

3.5. Toward 2.5D microphotonics

It has been proposed recently a major extension of planar technology, through exploitation of the third ('vertical') dimension by using a so-called multi-layer approach, where the lateral high index contrast patterning of layers would be combined with the vertical 1D high index contrast patterning: it is here more appropriate to think in terms of '2.5-dimensional' photonic structures, in which an interplay between wave-guided-confined photons and radiated photons propagating through the planar multilayer structure occurs [7].

The simplest illustration of this approach is the use of a plain Photonic Crystal Membrane as discussed in the previous Section 3.4. If one considers now a multilayer structure, the strong vertical 1D modulation of the optical index allows for a fine and efficient 'carving' of the density and vertical field distribution of radiated modes, using a limited number of layers. As a result, the variety of coupling schemes between optical modes is considerably widened, thus opening large avenues toward new photonic functionality.

In summary, 2.5D Microphotonics, combining lateral 2DPC and vertical 1DPC, should provide a very good control over the electromagnetic environment, that is over the distribution of optical modes in 3D real space and time, at a much lower cost than the full 3D approach in terms of technological feasibility: the technological schemes to be adopted are compatible with approaches which are normally described as planar. This multi-layer or multi-level approach is familiar to the world of silicon microelectronics, when it comes, for example, to fabricate the multiple levels of electrical interconnections; its use for microphotonics extends far beyond, from the viewpoint of widening considerably the range of new accessible functionality and performances.

The 2.5D Microphotonics approach has been successfully applied recently for the production of very low threshold power microlasers [26] and of a new class of optical bistable devices based on the Kerr effect [27]. The basic common building block for these devices is shown in Fig. 12. It consists in a graphite lattice 2DPC active membrane, similar to that presented in the previous section, bonded on to the top of a Bragg reflector formed by high index contrast SiO_2–Si quarter wavelength pairs. It can be shown that the thickness t_G of the top SiO_2 'gap' layer, which supports the bonded 2DPC membrane, is essential for the performances of both types of devices, in terms of the requested threshold power. This is due to the fact that the resonant coupling rate at the Γ point of the wave-guided slow Bloch mode which are used in these devices, is strongly dependent of t_G: the coupling rate is inhibited for t_G on the order of an odd integer number of quarter wavelength, which results in an increased strength of the slow Bloch mode resonance and, therefore, in a significantly reduced threshold power of the device (and vice versa for t_G on the order of an integer number of half wavelength).

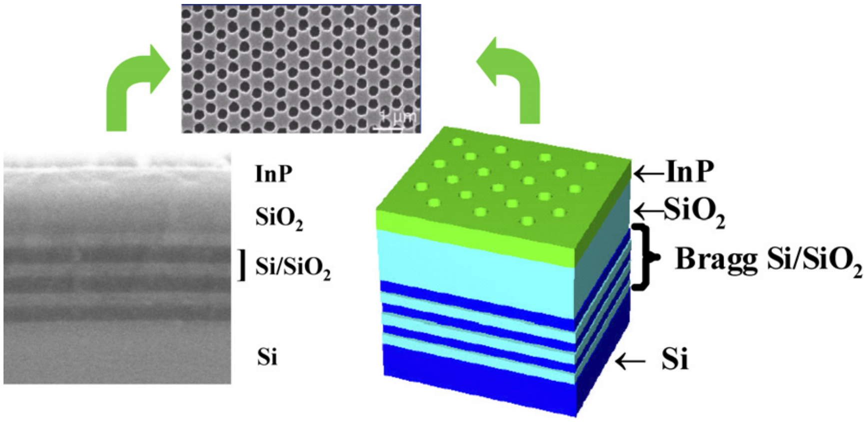

Fig. 12. Photonic Crystal membrane bonded on top of a Bragg Reflector.

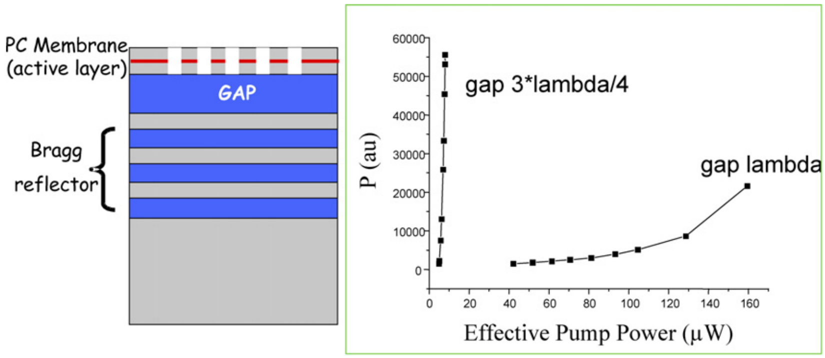

Fig. 13. 2.5D Photonic Crystal micro-laser: the thickness of the top silica 'gap' layer has a wide impact on the threshold power of the micro-laser.

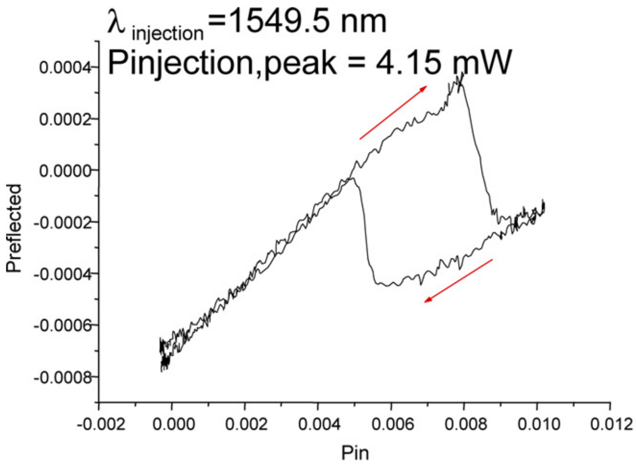

Fig. 14. Optical bistability effect in a 2.5DPC structure as shown in Fig. 12.

This is illustrated in a spectacular manner in Fig. 13, which shows the gain characteristics of the micro-laser for the two (quarter-wavelength or half wave-length) t_G values. Optical bistability could be demonstrated for the sole quarter-wavelength t_G case (see Fig. 14), corresponding to the strongest mode confinement (inhibition of coupling to the radiation continuum). It should be pointed out that the only difference between these two categories of devices lies in the particular design of the 2D graphite PC: for the micro-laser, it is managed that the slow Bloch mode resonance

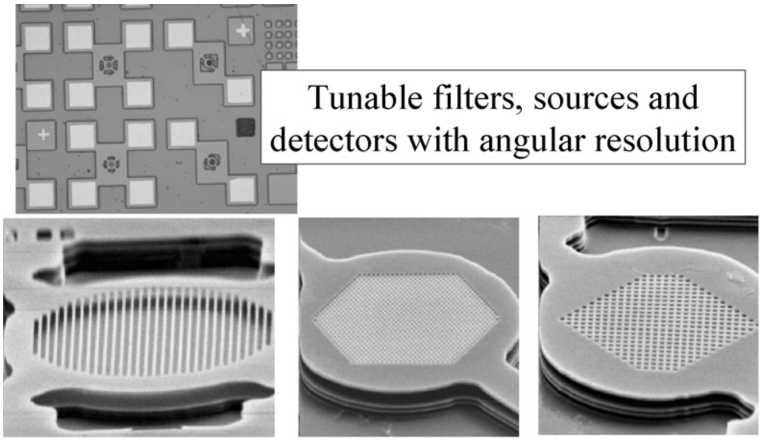

Fig. 15. New class of MOEMS devices: structures including several InP membranes suspended in air, with a 1D and 2DPC formed in the top membrane (SEM view).

wavelength at the Γ point lies close to the gain maximum of the active quantum well medium, whereas, for the bistable device, it is located within the Urbach tail of the quantum well material. Needless to say, therefore, that the building block shown in Fig. 12 is very generic.

Other domains of photonics should take advantage of the 2.5D microphotonics approach. For example, the introduction of 2DPC in MOEMS (Micro Opto Electro Mechanical) devices shows great promises in terms of widening of the spectrum of (electromechanically actuable) optical functions, achievable with further enhanced compactness structures.

Fig. 15 shows examples of such 2.5-dimensional MOEMS structures. These new types of photonic structures should be applied in various domains, including Optical Telecommunications (tunable or switchable wavelength selective devices, taking advantage of the extra angular resolution provided by the in-plane 1D–2DPC). Highly selective and widely tunable 2.5D MOEMS filters have been demonstrated very recently [28].

4. General conclusion

The flow of innovations whose threshold has been initiated in the late 1980 by the introduction of the concept of photonic crystals [1,8] is still very close to its source and will inflate in the future to an extent which is certainly beyond our full consciousness: it was simply proposed to extend to the three dimensions of space the field of optics, which was rather confined, yet with very successful outcomes, to the one dimensional world of multilayer optical structures. It is now established that the emergence of 3D microphotonics based on full 3DPC will be significantly delayed, as a result of technological constraints. We hope that the reader will have been convinced that, on the other hand, 2DPC are fully engaged in the process of innovation and that we are living, in that respect, a true microphotonic revolution. We have shown that 2DPC are very promising for 2D microphotonic integration; there is however a lot left to be done, before 2DPC devices are fully introduced in the world of optoelectronic integration, especially in connection with the appropriate solutions requested for the control of radiation optical losses. As to the so called 2.5D microphotonics, where 2DPC are deliberately opened to the third dimension of space, convincing demonstrations have been recently reported of their ability to generate, in the short run, a wide range of photonic devices (‘killer applications’), combining compactness, spatial (angular) and spectral resolution, and whose fabrication meets the standards of the planar technology, familiar to the world of microelectronics.

It appears that the rising trajectory of photonic crystals will not be inhibited in the long term, provided that appropriate tools are made available for their evolution. In that respect, bottlenecks are still to be eliminated and important R&D will have to be deployed for that purpose: this is true for the modeling and design aspects (especially 3D), whose fast and convivial tools are yet to be built; the technological constraints, dictated by the necessity to control the size of the devices at the nanometer scale, are far from being overcome. From the latter point of view, it can be stated that one has really entered within the *Nanophotonic* era.

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