Photonic Crystal based photonic Integration

Pierre Viktorovitch
Institut des Nanotechnologies de Lyon, CNRS, Ecole Centrale de LYON, Ecully, France
Pierre.Viktorovitch@ec-lyon.fr

Abstract. *Fundamental properties of Photonic Crystals, as well as the basic physical concepts which are relevant to their practical exploitation are presented. The tutorial focuses on two dimensional Photonic Crystals (2DPC), which are shown not only to have a great potential in the prospect of the development of 2D Microphotonics in the wave-guided in-plane configuration, but to open the way to other brilliant developments, where 2D Microphotonics is extended to out of plane operation.*

Introduction

The principal motivations for the emergence of Photonic Crystals can be summarized in one single word, that is "λ-Photonics", whose definition could be *the control of photons within the tiniest possible space during the longest possible time*: this implies to structure space at the wavelength scale, which means 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 matter, so far, of most of the new applications in terms of device demonstrations. It will be shown in the subsequent section that 2DPC have definitely entered within the realm of practical devices. A special attention will be given to surface addressable devices, which have been the matter 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 presented.

Photonic crystals : a brief overview of basic concepts

<u>What are photonic crystals?</u>

A Photonic Crystal is a medium which the 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.

We will restrict the rest of this paper to 2DPC, which have been the matter of most of the recent developments in the field of Micro-Nano-Photonics and are far more accessible than 3DPC [1], from the fabrication point of view.

A real 2DPC consists in considering a 2D structuration of a planar dielectric waveguide where photons are "index guided", that is to say vertically confined by the vertical profile of the optical index. In the rest of this chapter we will concentrate on the so called membrane approach, where the vertical confinement is strong: 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). 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 2D PC (holes with a shape ratio around unity). 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. It should be mentioned, at this stage, that most of the recent achievements reported 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 silicon substrate [2]. This approach presents a definite advantage: it lends itself to heterogeneous integration of active III-V optical devices with silicon based passive optical devices and microelectronics.

Why photonic crystals?

Refraction phenomena have been widely used in opto-electronics for the guiding of photons or for their confinement within micro-cavities. The control of photon "trajectory" is based upon the total internal reflection that they experience at the boundary between the external world and the higher index medium where they are 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.

Photonic crystals : how does it work?

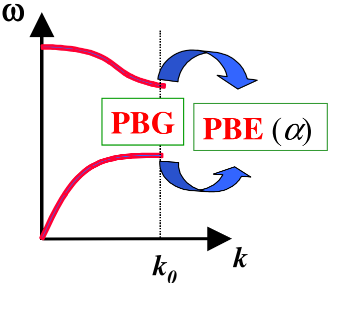

Figure 1 : schematic representation of a photonic band gap (PBG) and of related photonic band edges (PBE) in the dispersion characteristics of a photonic crystal.

In photonic crystals, which are strongly corrugated periodic structures, strong diffraction coupling between waveguided modes occurs; these diffraction processes affect significantly the surface dispersion characteristics, or the so called band structure, according to the solid state physics terminology. The essential manifestations of these disturbances consist in (figure 1):

- 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) $\alpha \approx \frac{1}{PBG}$.

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.

PBG confinement scheme using localized "defect" or cavity modes

In the PBG scheme, 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.

PBE confinement scheme using delocalized slow Bloch modes

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* of optical modes (so called Bloch modes for a periodical structure), which remain however *de-localized.* It can be shown that the lateral extension of the area S of the slowing down Bloch mode during its lifetime τ is proportional to $\alpha\tau$ [3]. As mentioned above, one essential virtue of PC is to achieve very low curvature α at the band edge extremes, thus resulting in very efficient PBE confinement of photons.

The most efficient confinement of photons can be achieved with the PBG scheme. The PBE scheme provides weaker confinement efficiency than with the PBG approach, while resulting in an improved control over the directionality or spatial/angular resolution.

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 wave-guiding slab is achieved only for those optical modes which operate below the light-line. 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 is 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. This is the world of 2D-3D microphotonics, which we will quote later in this paper as 2.5D microphotonics.

Photonic Crystals: devices

Following the pioneering and triggering contributions of E. Yablonovitch [1], it took quite a few years for the modeling and technological tools to reach the degree of maturity requested by 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.
In order to help the reader to find his way within this jungle, 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.

	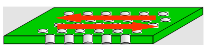	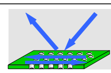
PBG	• Micro-cavities (QED) • Micro-lasers • Guiding / bends • Cavity-guide cascading (add-drop filters) • …	• Drop filters • ...
PBE	• Directional add-drop filters • Micro-lasers • Super-prism • Pulse compression • ...	• Compact reflectors/filters • Non-linear optics : fully optical micro-switches •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

Figure 2: classification of 2D PC based devices in four main categories.

This classification is further detailed in the table of figure 2, which provides a non-exhaustive list per category of the principal device structures demonstrated so far. In the following sections we emphasize devices making use of slow Bloch modes along the PBE confinement scheme and specifically those devices belonging to the fourth category, that is to say devices operating in the wave-guided regime while being also opened to the third direction of space: these devices include in their functionality the coupling of wave-guided to radiated modes.
Photonic devices based on 2D PC have been principally aimed, so far, at forming the basic building blocks of integrated photonics and are usually designed for in plane wave-guided operation. We remind that the operation of photonic integrated circuits based on 2D PC may be deeply affected by optical losses resulting from unwanted diffractive coupling of waveguided modes with the radiation continuum.

Instead of attempting to confine the light entirely within 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.

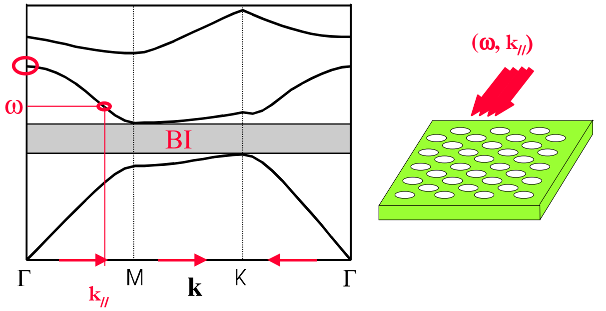

Fig.3. Illustration of the resonant coupling between a waveguided mode and a radiated mode.

A simple illustration of this approach is the use of a plain Photonic Crystal Membrane as a wavelength selective transmitter / reflector: when light is shined 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 [4], 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 the wave vector of the guided modes (figure 3). Accurate tailoring 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,…). In addition and very importantly, 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, allows for the production of very compact, yet very efficient, 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 [5].
The 2DPC membrane can be also designed in such a way as to result in very strong Fano resonances, that is to say with a very narrow spectral bandwidth. Use of such strong Fano resonances has been made for the demonstration of very low threshold and very compact surface emitting Bloch mode laser [6]. The photonic crystal consists in a graphite lattice (figure 4), which can be viewed as an array of H_1 coupled cavities, formed in a triangular lattice.
The graphite lattice 2D PC active membrane used for surface laser emission is very 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 and fully optical micro-switches [7, 8]. For the latter it is made use of electronic Kerr

effect, via photo-injection of carriers in quantum wells, to manipulate the Fano resonance wave-length.
All these devices are convincing illustrations of a planar technological approach resulting in 2DPC devices freed from the bi-dimensional universe.

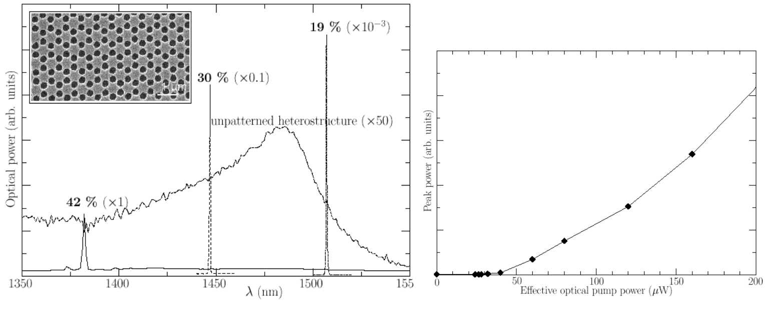

Fig.4. Emission spectra of the surface emitting laser formed in a graphite lattice 2D PC, for different hole filling factors (f). The plot of the emitted power versus the pumping power indicates a threshold power of 40 μW for f = 19%.

Towards 2.5D Micro-Nano-Photonics

It has been proposed 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 [3]. The simplest illustration of this approach is the use of a plain Photonic Crystal Membrane as discussed in the previous section. 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.
The technology schemes to be adopted are compatible with technological approaches which are normally describable as planar and are familiar to the world of silicon microelectronics.
The 2.5D Microphotonics approach has been successfully applied recently for the production of very low threshold power microlasers [9] and of a new class of optical bistable devices based on the Kerr effect [10].
The basic common building block for these devices is shown is figure 5. It consists in a graphite lattice 2D PC 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. The thickness t_G of the top SiO_2 "gap" layer, which supports the bonded 2D PC membrane, is essential for the performances of both types of devices, in terms of the requested threshold power : the coupling rate of wave-guided photons with the radiation continuum 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 Fano 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).

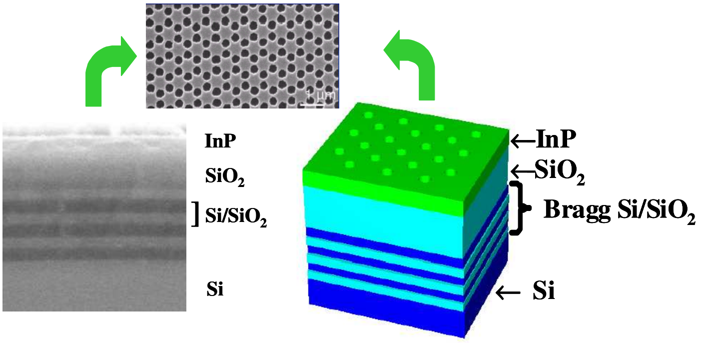

Fig.5. Photonic Crystal membrane bonded on top of a Bragg

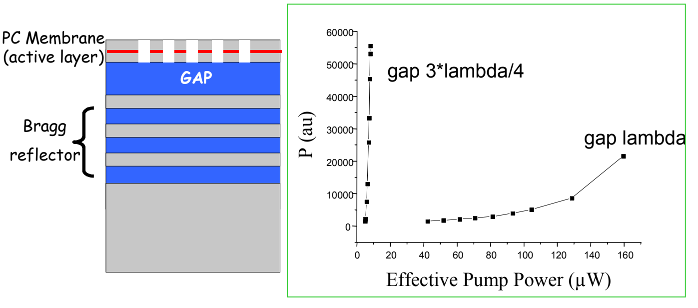

Fig.6. 2.5D Photonic Crystal micro-laser: the thickness of the top silica "gap" layer has a wide impact on the threshold power of the micro-laser

This is illustrated in a spectacular manner in figure 6, which shows the gain characteristics of the micro-laser for the two (quarter-wavelength or half wave-length) t_G values. Optical bistabity could be demonstrated, as expected, for the sole quarter-wavelength t_G case, 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: needless to say, therefore, that the building block shown in figure 5 is very generic.

Other domains of photonics should take advantage of the 2.5D microphotonics approach. For example, the introduction of 2D PC 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.

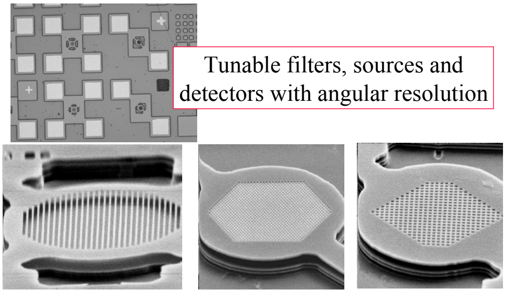

Fig.7. New class of MOEMS devices: structures including several InP membranes suspended in air, with a 1D and 2D PC formed in the top membrane (SEM view).

Figure 7 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-2D PC). Highly selective and widely tunable 2.5D MOEMS filters have been demonstrated recently [11]. Also, a new family of hybrid VCSEL, where one of the traditional Bragg reflectors is replaced by a PC membrane reflector, has been reported both in the GaAs and InP systems [12, 13].

Conclusion

The flow of innovations, whose threshold has been initiated in the late 1980 by the introduction of the concept of photonic crystals [1], is still very close to its source and will inflate in the future to an extent which is certainly beyond our full consciousness. We hope that the reader will have been convinced that 2D PC are fully engaged in the process of innovation and that we are living, in that respect, a true microphotonic revolution. We have shown, in particular for the so called 2.5D microphotonics, where 2D PC are deliberately opened to the third dimension of space, convincing demonstrations 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.

This work was partly supported by the EC FP6 network of excellence ePIXnet.

References

[1] E. Yablonovitch, "Inhibited spontaneous emission in solid – state physics and electronics", Phys. Rev. Lett., vol. 58, pp. 2059-2062, 1987.

[2] C. Monat, C. Seassal, X. Letartre, P. Viktorovitch, P. Regreny, M. Gendry, P. Rojo-Romeo, G. Hollinger, E. Jalaguier, S. Pocas and B. Aspar, "InP 2D photonic crystal microlasers on silicon wafer : room temperature operation at 1.55µm", Electron. Lett. vol. 37 pp. 764-766, 2001.

[3] X. Letartre, J. Mouette, C. Seassal, P. Rojo-Romeo, J.-L. Leclercq, P. Viktorovitch, "Switching devices with spatial and spectral resolution combining Photonic Crystal and MOEMS structures", Journal of Lightwave Technology, vol. 21, pp. 1691-1699, 2003.

[4] VN Astratov, DM Whittaker, LS Culshaw, RM Stevenson, MS Skolnick, TF Krauss and RM De La Rue. “Photonic band-structure effects in the reflectivity of periodically patterned waveguides”, Phys. Rev. B, vol. 60 pp. R16255-R16258, 1999.

[5] S. Boutami; B.B. Bakir; H. Hattori; X. Letartre; J.-L. Leclercq; P. Rojo-Romeo; M. Garrigues; C. Seassal; P. Viktorovitch, “Broadband and compact 2-D photonic crystal reflectors with controllable polarization dependence”, Photonic Technology Letters, vol. 18, 835-837, 2006.

[6] J. Mouette, C. Seassal, X. Letartre, P. Rojo-Romeo, J.-L. Leclercq, P. Recgreny, P. Viktorovitch, E. Jalaguier, P. Perreau, H. Moriceau, “Very low threshold vertical emitting laser operation in InP graphite photonic crystal slab on silicon”, Electron. Lett vol.39, pp. 526-528, 2003.

[7] Crina Cojocaru, F. Raineri, P. Monnier, C. Seassal, X. Letartre, P. Viktorovitch, A. Levenson, R. Raj, “Ultrafast nonlinear dynamics of a two-dimensional InP-based photonic crystal response”, Appl. Phys. Letters, vol. 85, pp. 1880-1882, 2004.

[8] F. Raineri, G. Vecchi, A. M. Yacomotti, C. Seassal, P. Viktorovitch, R. Raj, A. Levenson, “Doubly resonant photonic crystal for efficient laser operation: Pumping and lasing at low group velocity photonic modes”, Appl. Phys. Letters vol. 86, pp. 011116-118, 2005.

[9] B. Ben Bakir, Ch. Seassal, X. Letartre, P. Viktorovitch, M. Zussy, L. Di Cioccio, And J. M. Fedeli, “Surface-emitting microlaser combining two-dimensional photonic crystal membrane and vertical Bragg mirror”, Appl. Phys. Lett. Vol. 88, pp. 081113-115, 2006 and Virtual Journal on Nanoscale Science & Technology, 13 n°10, 2006.

[10] A. M. Yacomotti, F. Raineri, G. Vecchi, R. Raj, A. Levenson, B. Ben Bakir, C. Seassal, X. Letartre, P. Viktorovitch, L. Di Cioccio, J. M. Fedeli, “All-optical bistable band-edge Bloch modes in a two-dimensional photonic crystal”, Appl. Phys. Lett. vol. 88, pp. 231107-109 2006.

[11] S. Boutami, B. Ben Bakir, J.-L. Leclercq, X. Letartre, P. Rojo-Romeo, M. Garrigues, P. Viktorovitch, I. Sagnes, L. Legratiet, And M. Strassner, “Highly selective and compact tunable MOEMS photonic crystal Fabry-Perot filter”, Optics Express, vol. 14, pp. 3129-3137, 2006.

[12] C. Y. Huang, Y. Zhou, and C. J. Chang-Hasnain, “A surface-emitting laser incorporating a high-index-contrast subwavelength grating”, Nat. Photonics vol. 1, pp. 119-122, 2007.

[13] S. Boutami, B. Ben Bakir, J.-L. Leclercq, P. Viktorovitch, “Compact and polarization controlled 1.55µm vertical-cavity surface emitting laser using sinble-layer Photonic Crystal mirror”, Appl. Phys. Lett. vol. 91, pp. 071105-107, 2007.