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Photonic Crystals¹

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Abstract

Photonic Crystals are considered to day as the « must » for the ultimate control of light in spatial and spectral domains (trapping of light in the photonic band gap regime, slowing down of photons in the slow Bloch mode regime). This seminar concentrates on two dimensional Photonic Crystals (2DPC): it is shown that they provide unmatched tools for the ultimate engineering of electromagnetic field which is required in nanophotonic devices of quantum information. Special emphasis is put on devices where light control is provided by slow Bloch mode confinement scheme.

1. Introduction: solid state quantum optics and nano-photonics

Harnessing the interaction or coupling between the electromagnetic field and the matter, where the latter is meant to provide, absorb or exchange limited numbers of photons, constitutes one of the main challenges of quantum optics. This implies the control or confinement of photons within the tiniest possible space (as referred to the wavelength) during the longest possible time (as referred to the period of oscillation of the electromagnetic field), which is precisely the purpose of nano-photonics for wave-length in the micro-meter range (visible or near-visible range): we will concentrate on this wave-length range, where it is usually appropriate to speak in terms of solid state quantum optics.

The general approach for the control of light consists in structuring the space where it is meant to be confined, via a high contrast modulation of the optical index. For that purpose high index dielectrics or semiconductors, as well as metals are used: we will concentrate on the former, the latter being relevant to the domain of plasmonics, which is not within the scope of the present chapter.

The next section gives a brief reminder of the principal requirements which should be met when it comes to achieve light-matter interaction in solid state quantum optics, where the

¹ This series of lectures was delivered at Ecole Prédoctorale des Houches, session XXIV, Quantum Optics, September 10-21, 2007. The session was directed by Nicolas Treps and Isabelle Robert-Philip.

photon providers-absorbers are formed by quantum boxes (see chapter [n](#), by Isabelle Robert and chapter [n+1](#) by Philippe Roussignol).

In section 3, we present a brief overview of the basic concepts which underlie Photonic Crystals, which are considered to day as the « must » for the ultimate control of light in spatial and spectral domains, with emphasis on two-dimensional Photonic Crystals (2DPC).

Solid state quantum optics is usually considered as very promising in the prospect of future quantum integrated circuits: we argue in section 4 that quantum optical devices based of solid state quantum boxes do not lend themselves to easy integration and should be restricted, at least in the medium range, to discrete configurations.

In section 5, it is shown that 2DPC have definitely entered within the realm of practical devices: discrete devices for quantum information processing, based on 2DPC formed in wave-guiding membranes are presented.

2. Electromagnetic field engineering in solid state quantum optics

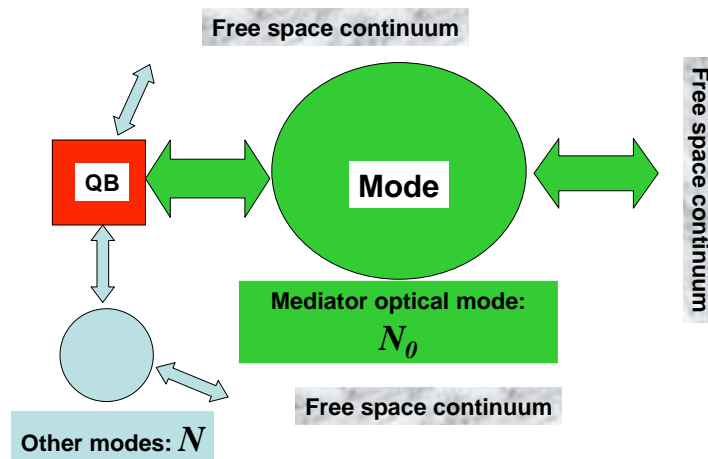


Figure 1: principle of collection (from) and addressing of photons to the quantum box (QB)

The reader will have understood that quantum optics solid state devices involve active quantum box material for the one by one generation and/or detection of photons. One crucial issue is to achieve efficient optical addressing (to) or collection (from) a single quantum box. The general approach consists in the coupling of the quantum box to an intermediary optical mode mediator, which is meant to insure the optical communication with external world: the difficulty lies in the fact that the quantum box is offered multiple optical tracks toward or from the latter. This is illustrated in figure 1 which shows, schematically, the various opportunities of photon transfers between the quantum box and the external world. Engineering of the mode mediator has therefore to meet a variety of requirements, which are dictated by its role of providing the main avenue for the quantum box communication with the external world, while other parasitic shortcuts are minimized. First, the optical mode must be tuned, spectrally and spatially, with the quantum box, in order to maximize its “local” density of states, which should, secondly, dominate the total density of states seen by the quantum box. Those conditions can be gathered in the so called coupling factor β which must be maximized. β can be expressed simply as:

$\beta = \frac{N_0}{N_0 + N}$, where N_0 is the mediator mode density of states and N the density of states of other modes to which the quantum box may be coupled. $N_0 + N$ is the total density of states felt by the quantum box.

$N_0 = \frac{1}{\delta\omega \times V_{mode}}$, where $\delta\omega = \frac{1}{\tau_{mode}}$ is the spectral width of the mode and τ_{mode} its lifetime.

In summary, for the coupling factor β to be as close as possible to unity, it is highly desirable to achieve large N_0 or large $\frac{\tau_{mode}}{V_{mode}}$ ratio of the mediator mode². In other words, it is requested to engineer mediator optical modes endowed with outstanding photon confinement characteristics.

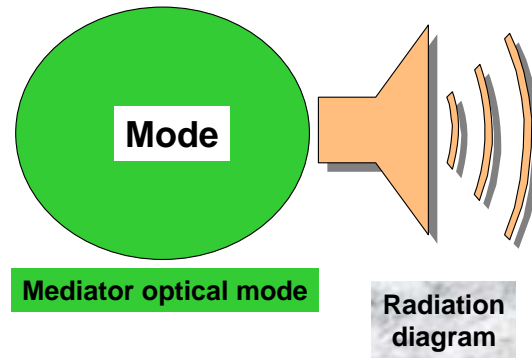


Figure 2: schematic representation of the radiation diagram of the collector/addressable optical mode

The above condition is necessary but not sufficient. Efficient communication with the quantum box implies, in addition, that the mediating optical mode can be efficiently addressed, which means that its radiation diagram can be formatted accordingly, as illustrated in figure 2.

Weak and strong coupling

Two regimes of coupling between the quantum box and the mediating optical mode are contemplated, depending upon the conditions requested for the targeted application. In the so called *weak regime*, the optical mode fully plays its role of mediator, in that it is widely opened to the external world, while it is meant to be the sole optical mode accessible to the quantum box: in other words, the coupling strength between the quantum box and the optical mode is weaker than the coupling strength between the latter and the free space radiated modes. In this particular regime, the function of the optical mode lies principally in speeding up the spontaneous emission rate of the quantum box, which is highly desirable for the production of indistinguishable photons (see chapter n, by Isabelle Robert). This is obtained when the $\frac{\tau_{mode}}{V_{mode}}$ ratio (or the Purcell factor) is large enough to result in a homogeneous emission spectral width of the quantum box, which is then dominated by the spontaneous emission rate (at the expense of other induced de-coherency phenomena). Large $\frac{\tau_{mode}}{V_{mode}}$ ratio

² Or to maximize the so called Purcell factor F of the mode (see section 3).

can be achieved by maximizing τ_{mode} and minimizing V_{mode} . The so called *strong coupling regime* is reached when the optical mode lifetime τ_{mode} is large enough for its coupling strength with the quantum box to overcome its coupling strength with free space radiated modes (which is proportional to $\frac{1}{\tau_{mode}}$). In the strong coupling regime, the quantum box and the optical mode form an isolated system, resulting in new hybrid photon-exciton states (see chapter n+1 by Philippe Roussignol).

In brief, the development of quantum optics solid state devices makes it necessary to control the electromagnetic field environment with very high spatial as well as temporal resolution, which implies the engineering of optical modes with large $\frac{\tau_{mode}}{V_{mode}}$ ratio and accurately controllable radiation pattern. The subsequent sections are meant to convince the reader that two-dimensional Photonic Crystals (2DPC) should be considered as the best candidates for that purpose.

3. Photonic Crystals: a brief overview of basic concepts

3.1 What are photonic crystals?

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 200%): this specific feature is central for the control of the spatial-temporal trajectory of photons at the scale of their wavelength and of their periodic oscillation duration.

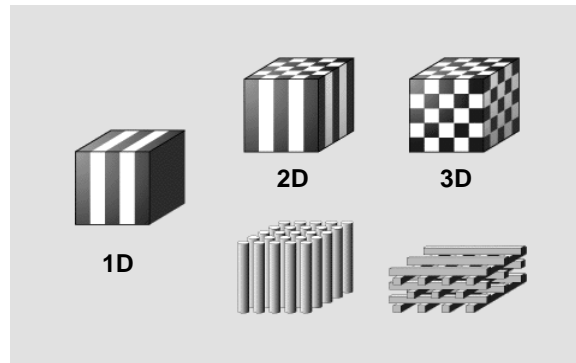


Figure 3: schematic view of Photonic Crystals with different dimensionalities

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

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 (initially introduced by E. Yablonovitch [1]), from the fabrication point of view.

A real 2DPC consists in considering a 2D structuring of a planar dielectric waveguide where photons are “index guided”, that is to stay vertically confined by the vertical profile of the optical index. Figure 4 shows schematic and SEM views of a real typical 2DPC, consisting in a triangular lattice of holes formed in a semiconductor slab.

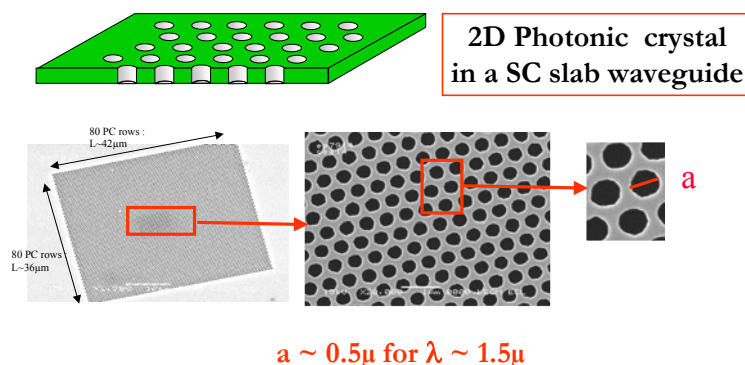


Figure 4: schematic and SEM views of a real 2DPC, consisting in a triangular lattice of holes formed in a semiconductor slab

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: see figure 5). In mono-mode 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 fibre 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. Another essential asset of the membrane approach will be fully appreciated in section 5, 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 wave-guided operation and that they may be opened to the third dimension, particularly along the so called 2.5D micro-nano-photonics schemes.

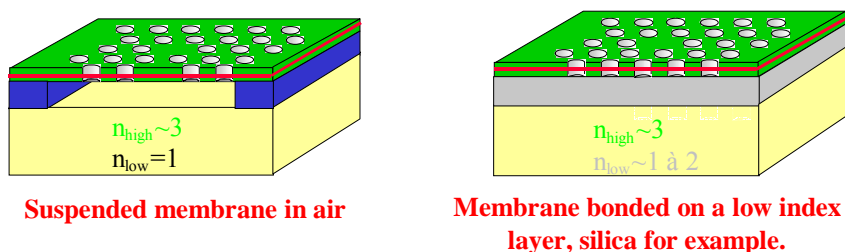


Figure 5: The basic building blocks of the membrane approach.

3.2 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 / photons within the tiniest space V during the longest possible period of time τ , which means the engineering of optical modes with the largest possible $\frac{\tau}{V}$ merit factor.

The merit factor 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 when normalized to the ratio $\frac{T}{\lambda^3}$, where T is the period of oscillation and λ the wavelength in vacuum.

$$F = \frac{\tau}{T} \times \frac{\lambda^3}{V} \quad (1)$$

With:

$$Q = \frac{2\pi\tau}{T} \quad (2)$$

where Q is the traditional quality factor of the mode.

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 (see section 2 and chapter n; see also, for example, [2])

It should be pointed out that there exists a variety of ways for the structuring 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. 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.

3.3 Photonic Crystals: how does it work? [3]

The principal characteristics of the photonic crystal manifest themselves in the so called dispersion characteristics of the periodically structured medium, which relate the pulsation ω (eigen value) to the propagation constants k (eigen vector) of optical modes, and which are the eigen solutions of Maxwell equations, corresponding to a stationary spatial distribution of the electromagnetic field. 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 surfaces relate classically to the wave-guided modes of the slab waveguide and show a circular symmetry.

For photonic crystals, which are strongly corrugated periodic structures, strong diffraction coupling between wave-guided modes 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 (figure 6):

- 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 form 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.

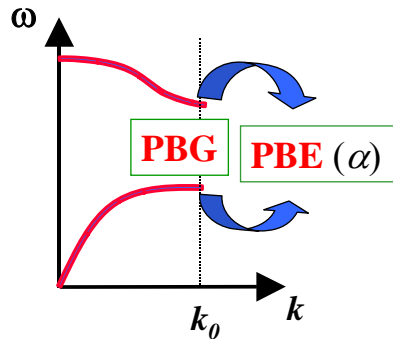


Figure 6: schematic representation of a photonic band gap (PBG) and of related photonic band edges (PBE) in the dispersion characteristics of a photonic crystal.

PBG confinement scheme using localized “defect” or cavity modes

In the PBG scheme, the propagation of photons is forbidden at least along 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 *average* group velocity of optical *slow 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 which

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 $\alpha\tau$ [4]. It can then be straightforwardly derived that the merit factor of the Bloch mode is simply proportional to

$\frac{1}{\alpha}$ 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 and large merit factor of the corresponding slowed down optical modes.

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 [5].

The PBE scheme provides weaker confinement efficiency than with the PBG approach, while resulting in an improved control over the angular resolution in the reciprocal space or, in other words, over the directionality of the radiation pattern.

The issue of vertical confinement in 2DPC: below and above light-line operation

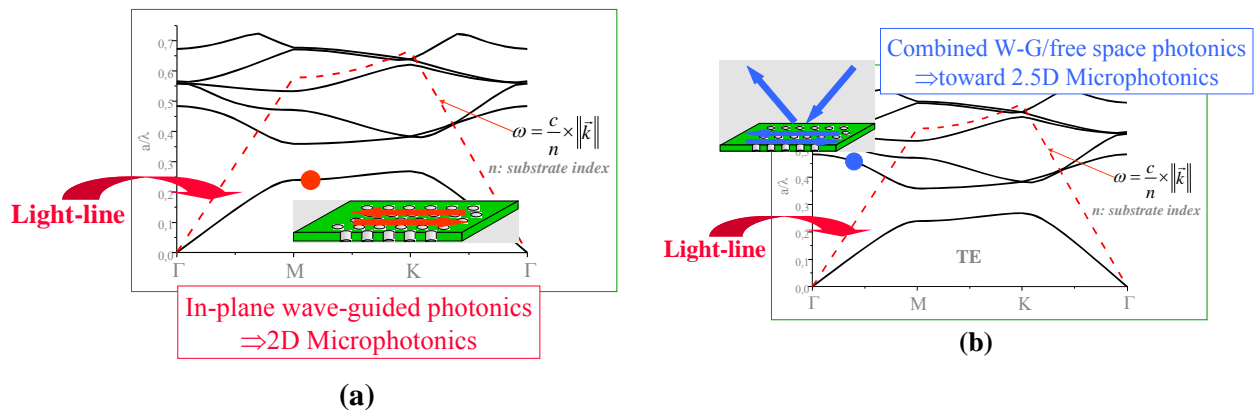


Figure 7: below (a) and above (b) light-line operation of photonic structures based on 2D photonic crystals

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 (see figure 7a). 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-nano-photonics.

For wave-guided modes whose dispersion characteristics happen to lie above the light line, where 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 figure 7b). This is the world of 2D-3D micro-nano-photonics, which we will quote later in this paper as 2.5D micro-nano-photonics.

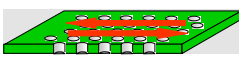
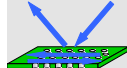
3.4 Photonic crystals : principal categories of devices

Following the pioneering and triggering work of E. Yablonovitch [1], it took quite a few years for the modelling 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.

³ Which is also proportional to the density of photonic modes at the band edge extreme.

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.

This classification is further detailed in the tables of figure 8, which provides a non-exhaustive list per category of the principal device structures demonstrated so far. In the first column, one finds the devices which operate exclusively below the light line, according to the PBG confinement scheme (first line) or the PBE confinement scheme (second line): this is the domain of planar photonic integration, where the photons/optical modes are solely wave-guided and where a rather large number of devices are integrated and may communicate, on a single chip. In the second column, the devices may operate above the light line and can be used for free space photonics: it is here more appropriate to think in terms of discrete devices.

												
PBG	<ul style="list-style-type: none"> • Micro-cavities (QED) • Micro-lasers • Guiding / bends • Cavity-guide cascading (add-drop filters) • ... 	<ul style="list-style-type: none"> • Drop filters • ... 	<table border="1"> <tbody> <tr> <td>PBG</td> <td></td> <td></td> </tr> <tr> <td></td> <td>INTEGRATED PHOTONICS</td> <td>FREE SPACE PHOTONICS</td> </tr> <tr> <td>PBE</td> <td></td> <td>----- DISCRETE DEVICES</td> </tr> </tbody> </table>	PBG				INTEGRATED PHOTONICS	FREE SPACE PHOTONICS	PBE		----- DISCRETE DEVICES
PBG												
	INTEGRATED PHOTONICS	FREE SPACE PHOTONICS										
PBE		----- DISCRETE DEVICES										
PBE	<ul style="list-style-type: none"> • Directional add-drop filters • Micro-lasers • Super-prism • Pulse compression • ... 	<ul style="list-style-type: none"> • Compact reflectors/filters • Non-linear optics : fully optical micro-switches • Surface emitting Micro-lasers • ... and other devices 										

(a)

(b)

Figure 8: classification of 2D PC based devices in four main categories (a), divided in two wide domains of applications (b).

In the following section, we discuss the issue of photonic planar integration, as a viable (or not) approach for quantum optics, in the short to medium range.

4. Quantum Micro-Nano-Photonics: integrated or discrete devices

4.1 The minimum requisite for quantum photonic integration

The simplest photonic integrated circuit consists in an optical link, where a (single) photon source is linked, via a waveguide, to a (single) photon “detector” as shown schematically in figure 9. The source and the detector are formed by quantum boxes coupled to mediator optical modes confined in nanophotonic structures (as described in section 2), which can communicate through the waveguide. Here, the function of the detector is wider than a plain detection of photons: it is to be viewed as a non-linear device, which optical characteristics can be strongly affected, following the absorption of a single photon; it is then more appropriate to speak in terms of quantum optical gate.

In this (quantum) regime of operation, strong constraints are requested for the active materials of the source and of the detector: the active materials should be formed by quantum boxes

which are spectrally matched, which means that they should operate at the same wave-length and that their line-widths are also the same.



Figure 9: schematic view of a quantum optical link

A first step toward the realization of the optical link of figure 9 has been reported by the group of Jelena Vuckovic [6], with the demonstration of a single phonon emitter coupled to a wave-guide. However it remains that the integration of a single quantum photonic link, and, *a fortiori*, of a large number of such links on the same chip, requires the resolution of further far more demanding technological steps: the principal difficulty lies in the achievement of a sufficient degree of spectral matching between the quantum boxes, as discussed in the following section.

4.2 Spectrally matched “identical” quantum boxes

Let us assume, for sake of simplicity, that the photonic structure has been successfully designed to insure the appropriate optical confinement and coupling to the quantum boxes of the mediator optical modes, resulting in similar optical line-widths (regime of homogeneous broadening, controlled by the Purcell effect enhanced spontaneous emission rate), as requested when it comes to manipulate indistinguishable photons⁴. One is left to meet the first constraint, which is to produce quantum boxes with the same operation wave-lengths, that is with controlled individual sizes: “same” means wave-lengths spanning over a range which should not exceed the line-width. Given that the line-width is around 10^{-4} to 10^{-5} times the operation wave-length, this means that the latter should set with a relative accuracy of around 10^{-5} . It can then be easily inferred that, if the average size of the quantum boxes is a few times 10nm, their individual size should be controlled with accuracy better than 10^{-2} to 10^{-1} Å. This means that the quantum boxes should be strictly identical.

The fabrication of semiconductor quantum boxes, normally considered as very good candidates to form the active material for quantum photonic integration, is usually based on growth procedures (MBE, MOCVD) which require growth conditions far from thermal equilibrium. These procedures do not lend themselves to the production of identical and well organized nanostructures. The target of quantum photonic integration based on semiconductor quantum boxes is therefore likely to appear rather elusive, at least in the short-medium range.

In the following paragraphs, we will concentrate on discrete devices, for free space operation, which are deemed to be the matter of the principal developments in the field for coming up years.

5. Discrete photonic devices based on 2DPC membranes for free space quantum optics

⁴ The reader will have certainly anticipated that this is not an easy task. This task implies, among other constraints, to localize accurately the quantum boxes within the optical mode electromagnetic field.

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 wave-guided modes with the radiation continuum. When it comes to use 2DPC for free space operation devices, the problem of optical losses is approached from a completely different perspective: instead of attempting to confine the light entirely within wave-guiding structures, the 2D structures are deliberately opened to the third space dimension by *controlling* the coupling of the wave-guided modes with the radiation continuum. In this approach, the exploitation of the optical power is achieved by accurately tailoring the optical radiation into free space. A detailed account of the physical concepts which underlie the manipulation of wave-guided modes in time and space can be found in [1, 7] and references there in. In brief, the general target is to generate the wave-guided modes with the appropriate temporal (lifetime) and spatial (lateral extension or confinement, radiation diagram) characteristics. Discrete quantum photonic devices based on 2D PC membranes, which have been so far or are being developed, principally consist in single (or few) photon emitters. They are meant to operate in free space or fibre pigtailed. They belong to the two categories of the second column of the table in figure 8a; they may be also classified along the line of the table in figure 10, depending upon whether the lateral confinement of photons in the membrane is achieved in a micro-cavity (PBG lateral confinement scheme) or with the use of slow Bloch modes (PBE lateral confinement scheme).


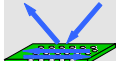
		
PBG	[Hatched Area]	Devices based on 2D PC micro-cavities
PBE		Devices based on Slow Bloch modes

Figure 10: the two categories of single discrete photon emitters based on 2D Photonic crystals, for free space operation

5.1 Photon emitters based on a 2D PC micro-cavity

The production of indistinguishable photons using single photon emitters based on 2D PC micro-cavities has been recently demonstrated by I Robert et al [8]. Confinement of photons was achieved along the PBG scheme in so called H1 cavities, provided by a one missing hole single defect formed in a triangular lattice 2D PC. The gain material consisted in strained InAs quantum boxes grown on GaAs.

The principal drawback of this approach however lies in the fact that, for operation above the light line, that is in free space, angular resolution is requested, which is hardly offered by the PBG scheme. 2DPC based micro-cavity sources do not indeed lend themselves to a directional emission diagram in free space, given that all k components are available for the modes of the cavity, which behaves like a localized defect. As a consequence free space collection efficiency of emitted photons is rather poor, which is not affordable, when it comes

to collect single of very few photons. In that respect nano-pillar based single photon emitters are superior [9], at the expense, however, of a far more demanding technological fabrication process.

5.2 Photon emitters using 2D PC slow Bloch modes: micro-lasers

Photon emitters using 2D PC slow Bloch modes for photon confinement along the PBE scheme, do not suffer from poor low directional resolution which plagues the operation of micro-cavity devices: this is owing to the fact that slow Bloch modes are “delocalized” states, which lends them to provide angular resolved emission diagram. In that respect, they should be considered, to day, as very strong contender to nano-pillar based photon emitters.

Use of slow Bloch modes has been made for the demonstration of very low threshold and compact surface emitting Bloch mode laser [10]. The photonic crystal consists in a graphite lattice (figure 11).

This particular 2D PC exhibits band edge extremes at the Γ point with very low curvature (figure 11). One of these extremes is exploited for vertical laser emission. The coupling between wave-guided slow Bloch modes and radiated modes is authorized, but its rate is controlled accurately by the design of the 2D PC membrane, allowing for the vertical emission, while retaining the strength of the resonance and, therefore, achieving a weak threshold power.

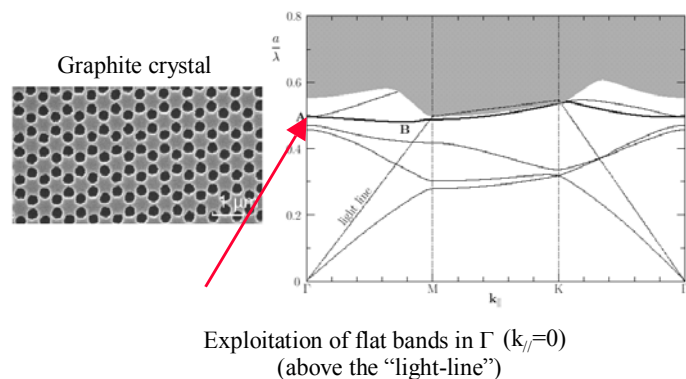


Figure 11: band structure of a surface emitting Bloch mode laser formed in a graphite 2D PC.

Emission spectra of the laser are shown in figure 12 for different hole filling factors f , as well as the spontaneous emission spectrum of the non-structured membrane. The device is optically pumped in a quasi-steady state regime and operates at room temperature. The peak intensity for the optimum filling factor ($f = 19\%$) is larger than the spontaneous emission power by 5 orders of magnitude. For increasing f , as expected, the emission peak is blue shifted as a result of the reduction of the effective optical index of the membrane; in the same time, the emission yield drops rapidly due to the decrease of the modal gain (not shown in the figure). The effective threshold pumping power, for the optimized device, is very weak and does not exceed $40 \mu\text{W}$. 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 2D PC to confine laterally slow Bloch modes, along the PBE scheme. Let us mention that active research work is presently ongoing, where the production of highly directive emitters of indistinguishable single photons based on this 2D PC structure is targeted.

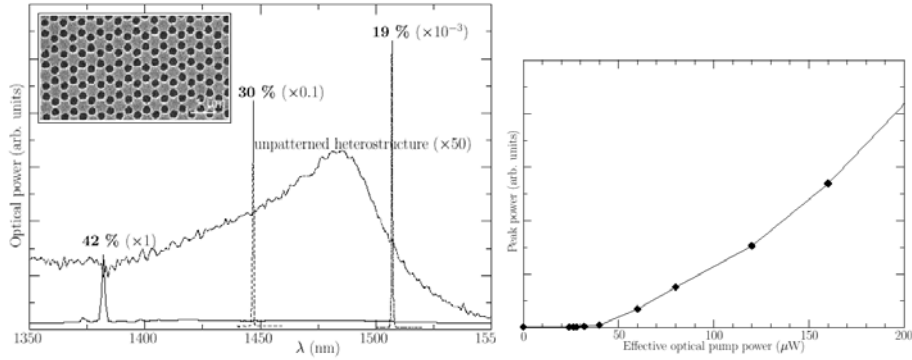


Figure 12: emission spectra of the surface emitting laser formed in a graphite lattice 2D PC, for different hole filling factors (f). The plot of the emitted power versus the pumping power indicates a threshold power of 40 μW for $f = 19\%$.

5.3 The step further: 2.5D Micro-Nano-Photonics

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 a 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 [4,1].

The simplest illustration of this approach is the use of a plain Photonic Crystal Membrane as discussed above. 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.

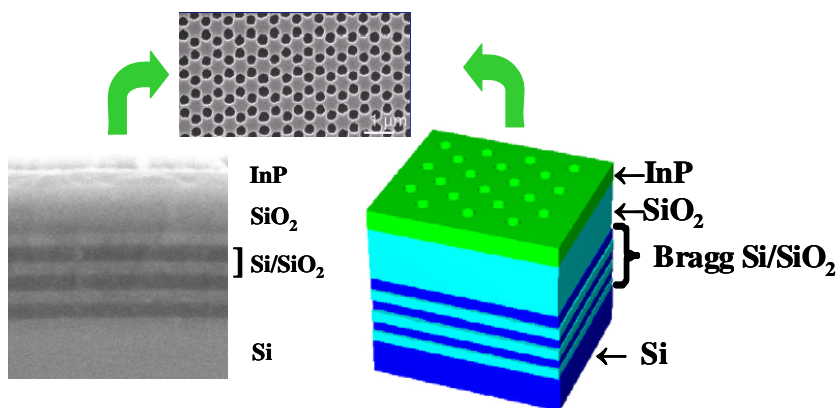


Figure 13: Photonic Crystal membrane bonded on top of a Bragg

In summary, 2.5D Micro-Nano-photonics, combining lateral 2D PC and vertical 1D PC, 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 technology schemes to be adopted are

compatible with technological approaches which are normally describable 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 inter-connections; its use for micro-nano-photonics extends far beyond, from the viewpoint of widening considerably the range of new accessible functionality and performances.

The 2.5D Micro-nano-photonics approach has been successfully applied recently for the production of very low threshold power microlasers [11] and of a new class of optical bistable devices based on the Kerr effect [12]. The basic common building block for these devices is shown in figure 13. 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 SiO₂-Si quarter wavelength pairs. It can be shown that the thickness t_G of the top SiO₂ “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. This is due to the fact that the resonant coupling rate at the Γ point of the wave-guided slow Bloch mode which is 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).

This is illustrated in a spectacular manner in figure 14, which shows the gain characteristics of the micro-laser for the two (quarter-wavelength or half wave-length) t_G values.

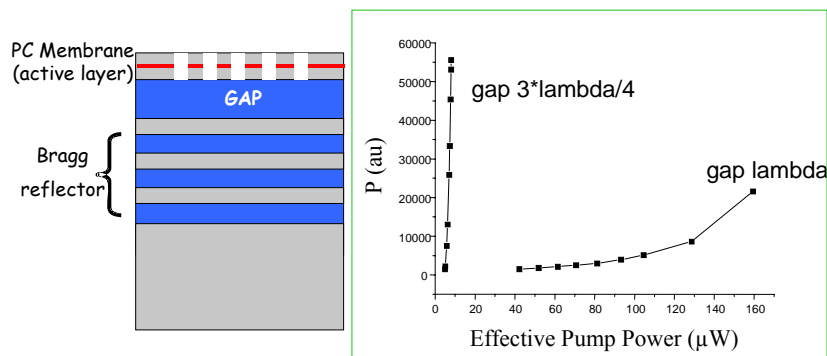


Figure 14: 2.5D Photonic Crystal micro-laser: the thickness of the top silica “gap” layer has a wide impact on the threshold power of the micro-laser

Optical bi-stability could be demonstrated for the sole quarter-wavelength t_G case (see figure 15), 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 wavelength at the Γ point lies close to the gain maximum of the active quantum well medium, whereas, for the bi-stable device, it is located within the Urbach tail of the quantum well material. Needless to say, therefore, that the building block shown in figure 15 is very generic.

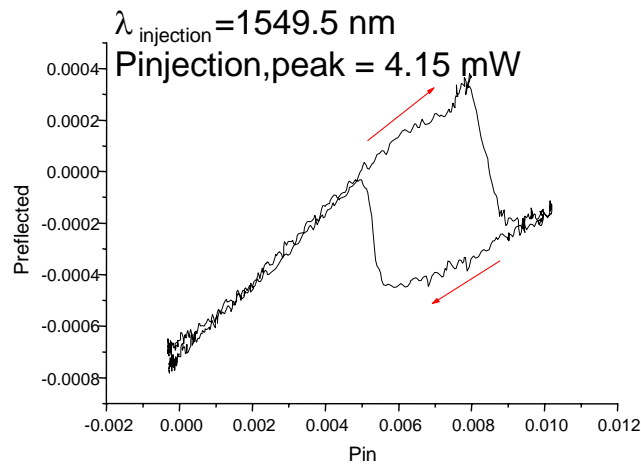


Figure 15: Optical bi-stability effect in a 2.5D PC structure as shown in figure 13

6. Conclusion

The flow of innovations whose threshold has been triggered 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 : 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 3D micro-nano-photonics based on full 3D PC will be significantly delayed, as a result of technological constraints. We hope that the reader will have been convinced that, on the other hand, 2D PC are fully engaged in the process of innovation and that we are living, in that respect, a true micro-nano-photonics revolution. We have shown, in particular for the so called 2.5D Micro-nano-photonics, 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. We hope also that the reader will have been convinced that, among the numerous domains which should profit from the micro-nano-photonics revolution initiated by Photonic Crystals, quantum optics should be in the forefront.

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