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Confinement of photons and control of their emission using surface addressable photonic crystal membrane

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ABSTRACT

High index contrast periodic structures can be exploited to perform an arbitrarily adjustable spatio-temporal molding of light at the wavelength scale. This tight control of photons is obtained through a shaping of resonant modes and a suitable adjustment of their coupling with propagative modes. In this talk, surface addressable (or above the light line) Bloch modes in photonic crystal membranes (PCMs) will be investigated. The concepts governing the properties of these modes will be first presented. It will be demonstrated that simple models can be considered to understand their behavior and, more specifically, their ability to capture photons during the desired lifetime. Bloch modes with a very large band width or a very high Q factor can be easily designed this way. The wide application range of these PCMs will be illustrated by different devices. Low Q Bloch modes will be first used as efficient and broadband reflectors and exploited to realize compact and efficient vertical cavity lasers with unprecedented functionalities. In addition, it will be shown that this kind of mirrors can be bent in order to confine photons in the 3 directions even in low index materials, opening the way to a new class of emitters and sensors. Finally, the exploitation of high Q Bloch modes to design highly directional thermal emitters with wavelength selectivity will be presented.

Keywords: Nanophotonics, Photonic Crystal Membranes, microlasers, 3D microresonators

1. INTRODUCTION

During the last decades, Photonic Crystals have played a fast growing role in nanophotonics. This success relies in their ability to harness the light at the wavelength scale leading to a spatial and spectral control of photons. In practice the fabrication of 3D PhCs is very difficult, and most of the developments have concerned the production of 1D and 2D PhCs formed in wave-guiding dielectric slabs as they can be fabricated using conventional planar technological approaches. The resulting structures are called Photonic Crystal Membrane (PCM) where the light can be “index guided” in the vertical direction. The spectro-spatial trajectory of this guided modes are then controlled through a high contrast 1D or 2D periodic modulation of the optical index. In most of the reported works, the PCM is meant to operate in this waveguiding regime, which gave rise to numerous demonstrations like strongly confining resonators (high Q/V), slow light and superprism phenomena...

In this paper, we will concentrate on most recent developments where PCM are used to control photons not only in the waveguiding configuration but also in the free space regime. In this case, the PCM can be seen as a high index contrast grating (HCG) which enables the coupling between in plane waveguided and out of plane free space modes, leading to an efficient 3D harnessing of light.

2. PCMs: MAIN PROPERTIES AND APPLICATIONS

A PCM (or HCG) is basically a membrane of high index (n_H) dielectric embedded in a low index (n_B) dielectric, and patterned to form a 1D or 2D grating with high index contrast (Figure 1, left). When operating above the light line, it behaves as a resonant reflector with 100% reflectivity at the resonant wavelength and with a bandwidth which can be adjusted through the geometric parameters of the PCM (thickness (h), duty cycle (DC), period (Λ)). It is illustrated on the right of Figure 1 where the reflectivity spectra of a 1D PCM are plotted as a function of the membrane thickness. It is shown that very narrow (close to zero) or very broad (up to 20%) bandwidths can be reached.

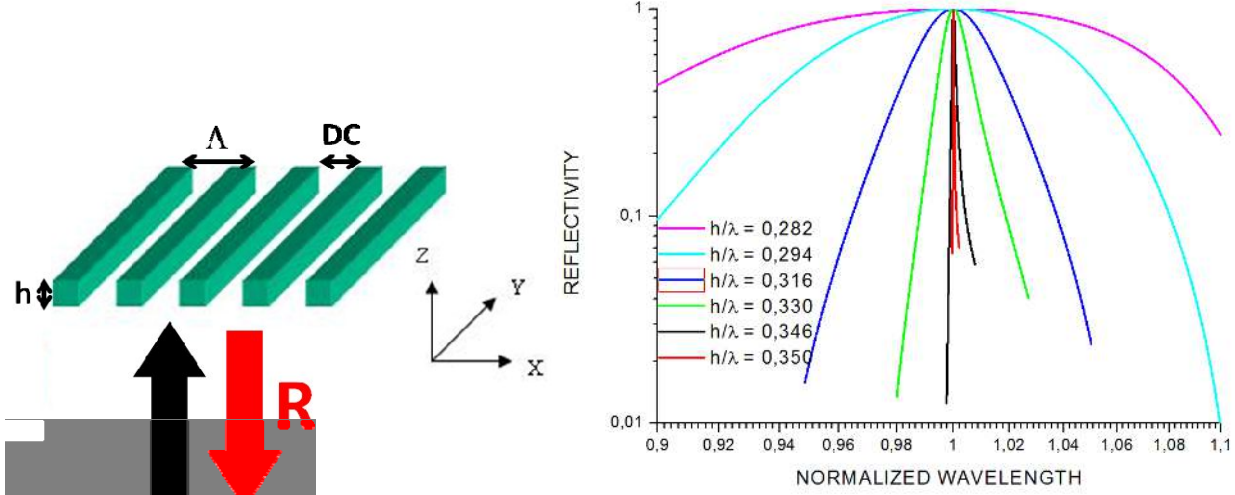


Figure 1: left: schematic view of a 1D PCM, right: reflectivity spectra, at normal incidence, of a 1D PCM as a function of the membrane thickness (h) ($n_H=3.481$, $n_L=1.528$, $DC=50\%$, Λ is modified for each spectrum in order to renormalized the resonant wavelength)

This plasticity allows for application in a wide range of optical devices:

- Narrow band PCMs (or high Q resonators) have been extensively used for surface addressable optoelectronic devices where an active material is embedded into the membrane, leading to the demonstration of low threshold surface emitting lasers¹, nonlinear bistables², optical traps³...
- A broadband PCM^{4,5} represents an ideal mirror to form compact vertical microcavity with 3D confinement of photons⁶ and polarization selectivity⁷. Among numerous devices, low threshold VCSELs with remarkable and tunable modal properties have been demonstrated in our group^{8,9} and at Berkeley University¹¹.

3. PCMs WITH CONTROLLABLE Q-FACTOR: PHYSICAL INSIGHTS

It has been shown in the previous section that PCMs are resonant reflectors whose bandwidth (or Q factor) can be widely adjusted in order to match the requirements of a given application. It is therefore of prime importance to establish the physical rules which govern the lifetime of photons in these resonant modes.

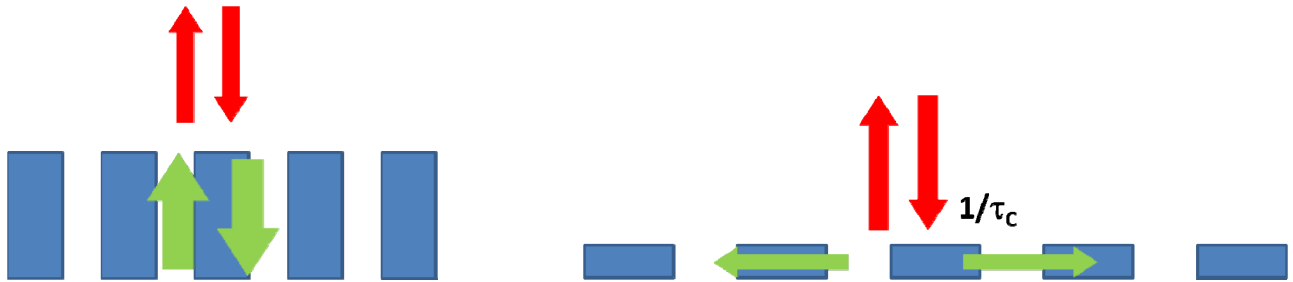


Figure 2: two approaches to understand the physics of PCMs: left: "Fabry-Perot" approach, right: "guided mode" approach

In the literature, two main models have been developed to address this point. In the first one^{12-15]} the PCM is considered as a periodic array of waveguides carrying Bloch modes which propagate in the vertical direction (Figure 2, left). When impinging the bottom and top surfaces of the PCM, these modes can be transmitted, reflected or can couple to each others. Then the PCM acts, for each resulting hybrid modes, as a Fabry-Perot vertical cavity. It has been demonstrated in Ref.15 that the Q factor of the PCM modes is strongly determined by the interferences between these Fabry-Perot modes.

In the second approach, which can be qualified as “orthogonal” to the previous one, the PCM is seen as a planar, periodically patterned, waveguide whose guided modes interact, through the corrugation, with the free space ones (Figure 2 right). In other words, the Bloch modes of the planar photonic crystal are first considered, disregarding their out of plane losses, even if they are located above the light line. In this last case, which is the only of interest in this study, the diffraction coupling to free space modes is characterized by a phenomenological parameter $1/\tau_C$, where τ_C is the lifetime of photons before escaping out of the membrane¹⁶. This point of view has been popularized by R. Magnusson and co-workers¹⁷ who have exploited these “Guided Mode Resonances” to achieve a new class of optical filters. In this frame, the Q factor of the PCM (or the coupling rate $1/\tau_C$) is determined, to the first order, by the integral overlap between the electromagnetic field distributions of the guided and free space modes and of the dielectric periodic perturbation which is applied to the homogeneous membrane to get the photonic crystal. It turns out that the symmetries of these distributions are of prime importance for the strength of the resonance. The impact of the in plane symmetry of Bloch modes on their coupling strength with radiated modes had been recognized by J. M. Pottage and co-workers¹⁸ who reported on 2D PCM supporting wave-guided modes, resonantly coupled with radiated modes, with very high Q factors. The effect of the vertical symmetry has been less studied but is also significant. As an illustration, we have recently emphasized the fact that the strong dependence of the Q factor with the PCM thickness can be understood by symmetry considerations¹⁹. More specifically, the “guided mode” approach can be analysed using the model developed by Kazarinov and Henry for shallow gratings^{20,21} where the coupling between guided and free space modes, for a vertically symmetric grating, is shown to be proportional to:

$$|M|^2 = \int e^{ik_z z} \phi(z) dz \quad (1)$$

Where $\phi(z)$ is the guided mode distribution in the unpatterned membrane and $e^{ik_z z}$ stands for a plane wave in the same membrane. Strictly speaking, the Kazarinov-Henry model is only valid for small index contrast gratings. However, even for PCM/HCG, it remains very efficient to calculate the thickness dependence of the Q factor. It is worth noticing that, with this approximate model, the coupling rate tends to zero (and the Q to infinity) for specific values, $(h/\lambda)_0$, of the membrane optical thickness, which do not depends on the photonic crystal itself but only on the optical index of the membrane. To illustrate this point, Fig.3 plots the first $(h/\lambda)_0$ value, calculated by RCWA, as a function of the duty cycle (DC) of the 1D grating: up to DC as large as 75%, $(h/\lambda)_0$ is approximately constant and very close to the value given by the approximate model (solution of $|M|^2 = 0$).

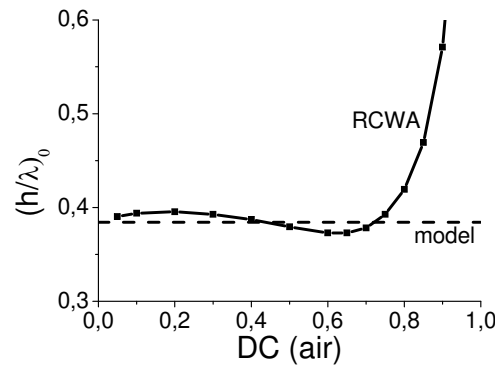


Figure 3: normalized thickness of a PCM (period=1μm, membrane optical index=3, embedded in air) for zero coupling rate as a function of the PCM duty cycle, calculated by RCWA (square) and by the model (dashed line)

As a concluding remark for this section, the “Fabry-Perot” model is clearly more rigorous, allowing for an accurate calculation of the optical properties of a PCM. However, as it has been shown above, the “guided mode” approach is, from our point of view, more intuitive (or phenomenological) and represents a very efficient guideline for designing a wide class of devices, as it will be illustrated in the next section.

4. EXAMPLES OF APPLICATIONS OF PCM BASED STRUCTURES

In this section, the functionalities of PCMs will be illustrated on selected devices which exploit low or high Q PCMs. For each device, we will show how the “guided mode” vision is helpful to improve the design.

4.1 Broadband PCM mirrors for 3D confinement of light

As discussed in the introduction, a low Q PCM is a mirror which leads to the design of planar microcavities where photons are confined in the vertical direction. However it will be demonstrated in this section that their specific properties allow for a 3D light trapping.

PCMs based VCSELs

When two 1D PCMs are used to form a vertical cavity, as illustrated in Figure 4 (left), the resulting resonant modes can be seen, in the “guided mode” approach, as hybrid modes with a waveguided component into the PCMs and a vertically radiated component in between the PCMs. Therefore, for a finite size microcavity, the confinement properties of the structure results not only from the reflectivity of the PCMs but also from the in-plane photons kinetics.

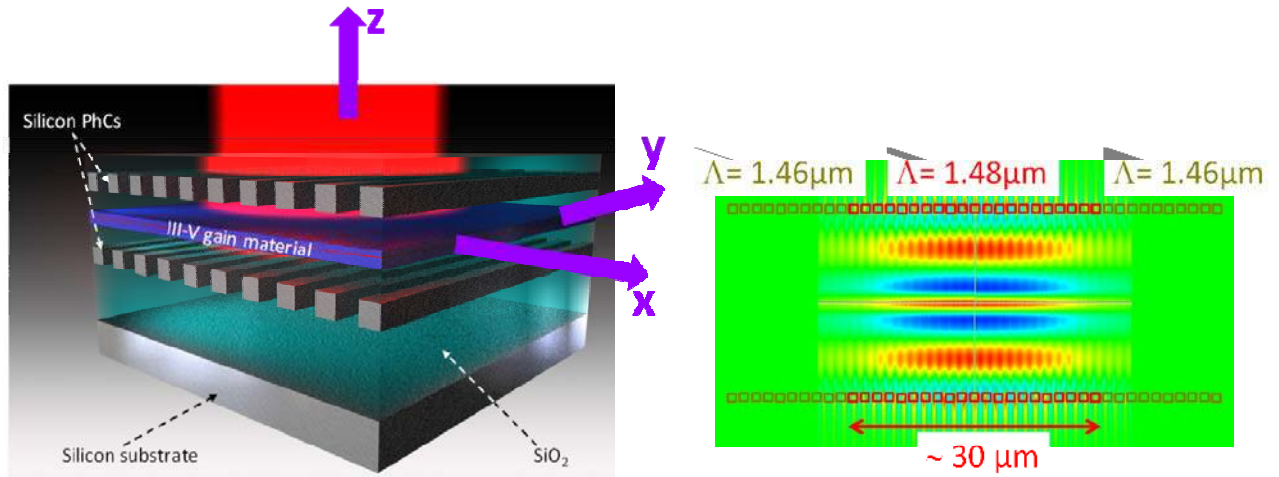


Figure 4: left: artistic representation of a PCMs based VCSEL, right: electric field distribution (y-cut) of the resonant mode and main parameters of the PCMs (DC=48%, the length of the bars constituting the PCMS is $L_Y=30\mu\text{m}$)

This point can be exemplified through the design of the PCM-VCSEL depicted on Figure 4 (right). This cavity aims at achieving laser emission at $2.3\mu\text{m}$ (TE polarized: electric field along z) for application in mid infrared sensing. An antimony based active heterostructure is inserted between two broadband PCM mirrors and separated from the latter's by silica layers. The lifetime of photons in such a resonator is governed by the loss rates in the three directions of space, which can be quantified by the quality factors Q_X , Q_Y , Q_Z . FDTD simulations have been used to calculate them:

- 2D FDTD (in xz plane) calculations with absorbing (resp. periodic) boundary conditions in the z (resp. x) direction leads to $Q_Z > 10^6$, indicating the very high reflectivity of the PCMs.
- 3D FDTD calculations with absorbing (resp. periodic) boundary conditions in the y and z (resp. x) directions leads to $Q_Y = 9 \times 10^4$, for L_Y as small as $30\mu\text{m}$ ($< 15\lambda$). This strong confinement can be explained by the very low group velocity of photons in the direction parallel to the slits, which is a well known property of 1D periodic structure (see e.g. Ref. 22).
- In the x direction, following the approach described in Ref. 23, we can fully take advantage of the waveguided nature of the resonant modes by trapping photons inside an optical well formed by slightly modifying the geometrical parameters (in this case the period) of the PCMs at its lateral edges. Then, 2D FDTD (in xz plane) with absorbing boundary conditions in both x and z directions gives $Q_X = 1.9 \times 10^4$.

Finally a full 3D FDTD with absorbing boundary conditions allows for calculating the Q factor of the real device, leading to $Q = 1.5 \times 10^4$. It is worth noticing that $Q^{-1} \approx Q_X^{-1} + Q_Y^{-1} + Q_Z^{-1}$, which confirms the hybrid nature of this resonant mode.

Photon cages

We have recently shown²⁴ that hollow microresonators can be achieved by simply bending a broadband PCM mirror in order to get a 2D cylindrical cavity (Figure 5 left). High Q resonant modes have been demonstrated with a very strong confinement of light in the embedded air region (Figure 5 right). These performances are explained by the high reflectivity of the PCM even if it is bent. Again, this behaviour can be easily understood within the “guided mode” approach. Indeed, the reflectivity of the PCM is due to the resonant interaction of free space modes with a waveguided mode propagating laterally inside the membrane. Thanks to the high index contrast patterning, this mode exhibits a low group velocity⁴ and, therefore, a flat dispersion curve. This property results in mirrors with a large angular acceptance¹⁹.



Figure 5: left: schematic view of the formation of a photons cage. right: 3D electric field distribution (TE polarization) into the photons cage

This approach can be applied to 2D and 3D resonators²⁵ which can be fabricated either by conventional “top-down” technologies or by a controlled mechanical relaxation of pre-stressed planar microstructures²⁶.

These photons cages could be used for applications where light confinement in low index materials is required, e.g. sensing in fluidic environment or microsources based on nano-emitters embedded in a polymer matrix.

4.2 High Q PCM resonators for the management of thermal radiation

Since the seminal work of J.J. Greffet and coworkers²⁷, the possibility to get a directive and wavelength selective light source from a simple heated object has been extensively investigated. To achieve such a spatial and spectral coherence, the electromagnetic environment of the emitter must be engineered in order to get, at the targeted wavelength and in the desired direction, an emissivity close to one, when it is small for all other wavelengths and directions. This process is the exact equivalent of a filtering of a perfect blackbody radiation. Examining Kirchhoff’s law, this molding of the density of optical modes can be exploited either for thermal emitters or detectors.

Then, let us consider a non absorbing highly resonant PCM. As explained at the end of section 3, the Q factor of the resonance can be strongly dependent on the membrane thickness (h). Indeed a change of the PCM optical thickness results in a modification of the overlap integral (1), i.e. of the coupling between the waveguided mode and the free-space one. It is straightforward that this effect can also be observed by changing the angle of incidence of the incoming beam.

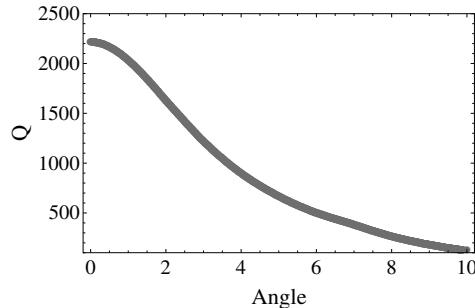


Figure 6: evolution of the Q factor of the PCM resonance, calculated by FDTD.

As an example, for a 540nm thick Si/SiO₂ PCM with a 50% duty cycle and a period of 750nm, a resonance at 1.51 μm with $Q = 2200$ is obtained, at normal incidence, by 2D FDTD calculations, which provide also the evolution of this Q factor as a function of the angle of incidence, as depicted on Figure 6.

To go further, a small absorption coefficient (corresponding to an imaginary index of a few 10^{-4}) is inserted into the membrane (obtained e.g. by doping the Si). This absorption losses is adjusted in order to get an absorption lifetime τ_{abs} such as $\omega_0\tau_{\text{abs}} = 2200$. It corresponds, for normal incidence, to the so called critical coupling regime where the absorption is maximum, reaching 50%, as it can be shown using Coupled Modes Theory (CMT). As the angle of incidence increases, the Q factor decreases and the absorption drops. This behaviour is fully confirmed by approximate CMT calculations and by ab initio FDTD simulations (Figure 7).

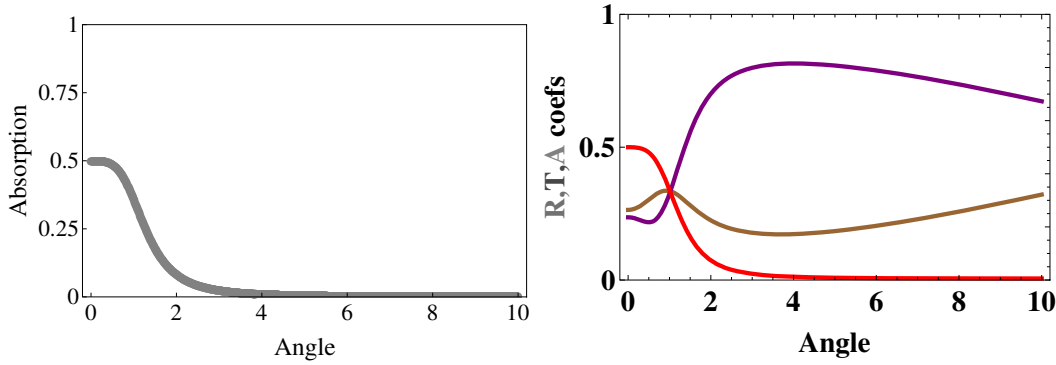


Figure 7: Absorption @1.51 μm as a function of the angle of incidence calculated by CMT (left) and by FDTD (right)

To summarize these results, a coloured map is plotted in Figure 8 showing the spectral and angular selectivity of the PCM absorber.

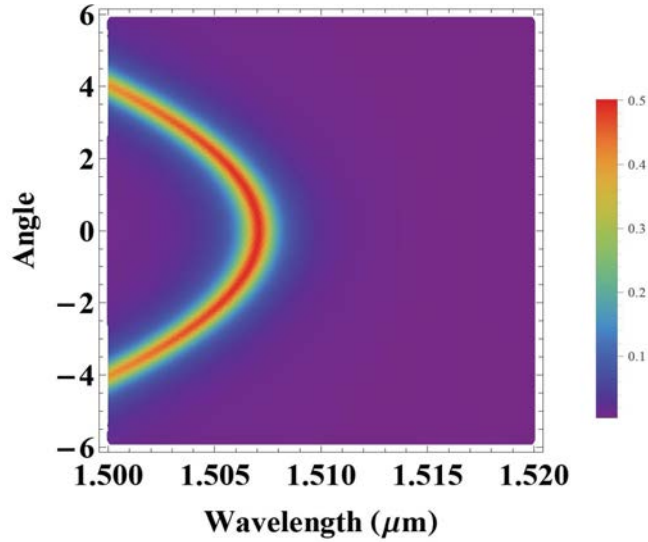


Figure 8: Absorption of the PCM as a function of the wavelength and the angle of incidence (FDTD simulation)

5. CONCLUSION

In the present communication, surface-addressable photonic crystal membrane resonators are shown to constitute generic enablers for 3D harnessing of light. Conceptual approaches used to analyse their optical properties are briefly presented and natural routes leading to simple design rules of those structures are given. The application of PCMs to a wide range of devices is described, showing the versatility of these simple periodic structures.

6. ACKNOWLEDGEMENTS

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