# Slow Bloch mode confinement in 2D photonic crystals for surface operating devices

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**Abstract:** 2D photonic crystal (2DPC) structures consisting in 2D silicon nanopillar arrays in silica are investigated. The main motivation of this work lies in that 2D rod arrays should be easily combined with refractive structures (e. g. micro-wire waveguides), unlike 2DPC consisting in hole lattices. Such an association is expected to lead to both new functionalities and larger scale integration. In this paper, we study the loss mechanism for non degenerated Bloch modes located at Γ-point in a 2DPC slab constituted by a square lattice of silicon rods in silica. For such modes, we show that the quality factor is mainly governed by the lateral losses. To further inhibit the lateral losses, a photonic heterostructure is used. 3D FDTD calculations show that quality factors of 4000 are achieved. To reduce the vertical losses, the 2DPC heterostructure is associated with a vertical Bragg mirror, thus resulting in very high quality factors (>40000).



**OCIS codes:** (350.4238) Nanophotonics and photonic crystals; (230.5750) Resonators; (250.7270) Vertical emitting lasers.

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## 1. Introduction

Most of two dimensional (2D) photonic crystal (PC) devices operate below the light line, where the waveguided modes do not undergo losses and remain confined in the slab. For such modes, the only losses are lateral losses and are due to the finite size of the photonic crystal or

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to technological imperfections. On the other hand, above the light line, waveguided modes suffer from out-of-plane coupling with the radiated modes into free space.

In order to allow the opening to free space of integrated photonics, devices based on photonic crystals have to possess a directive emission diagram. This can be achieved by using in a controlled way the 2DPC waveguided modes, above the light line of the dispersion diagram. Especially, by using Slow Bloch Modes (SBM) close to the Γ-point (the center of the first Brillouin zone where $k_{//}$-vector=0), 2DPC slabs can be designed to emit light vertically. SBM at the Γ-point combine several advantages: first, at this high symmetry point, photonic bands with very low curvature can be achieved leading to a strong lateral confinement of the SBM owing to the efficient slowing down of the group velocity; secondly, Γ-point SBM can couple both with radiated modes (in the vertical direction) and to waveguided modes through their k-vector components in the second Brillouin zone; finally, coupling of SBM with free space modes can also be adjusted by structuring space in the vertical direction [1].

In a 2DPC slab, the coupling between a SBM at Γ-point and radiated modes is determined by the mode symmetry properties. Indeed, Γ-point SBM in a square lattice can be classified into two categories: the degenerated SBM that can couple to the radiated modes for symmetry reasons and the non-degenerated SBM for which the coupling to the radiated modes at Γ-point is forbidden [2]. These symmetry properties related to degenerated or non degenerated Bloch modes lead to different use of the photonic crystal device.

The degenerated SBM can be exploited for applications such as very efficient reflectors [3]. In that case, the photonic crystal is designed to support a degenerated Bloch mode around Γ-point that can couple preferentially in the vertical direction than in the lateral one. These modes are usually weakly resonant in the 2DPC and possess very low quality factor. Contrary to degenerated SBM, very high quality factors can be achieved by using a non-degenerated SBM. This property can lead to the realization of devices requiring strong light-matter interaction such as vertical emitting lasers [4].

The non degenerated Bloch modes at the Γ-point of the square lattice of dielectric rods have infinite lifetime in a photonic crystal slab with infinite lateral sizes. In a 2DPC with finite sizes, the SBM wave vector k is not defined exactly at the Γ-point, but has an extent Δk in the reciprocal space. Around the Γ-point, a parabolic approximation of the dispersion diagram can thus be applied: $\omega = \omega_0 + \frac{1}{2}\alpha k_{//}^2$ where α is the second derivative of the dispersion characteristic that is the curvature of the corresponding band. A SBM cycling in a cavity of length L constituted by two mirrors with perfect reflectance, exhibits a mean k// fixed by the phase matching condition $k_{//}L = p\pi - \phi_r$, where p is an integer, $\phi_r$ the phase of the modal reflectivity at the 2DPC edges. The mean group velocity can then be expressed as: $v_g = \frac{d\omega}{dk} = \alpha k_{//}$ where k// can be related to real space by: $k_{//} \approx \frac{1}{L}$ (assuming p=1 and $\phi_r$=0), L being the lateral size of the 2DPC. To reduce the lateral losses, it is necessary to increase the time requested by the SBM to reach the 2DPC boundaries. This can be achieved by exploiting a flat extreme (small α) of the dispersion curve leading to a strong lateral confinement of photons. In addition to lateral losses occurring in a 2DPC with finite sizes, vertical losses may appear as well since the SBM can couple with the free space modes around the Γ-point. The overall quality factor for such modes, defined by the product of the angular frequency ω and the lifetime of photons τ inside the 2DPC, is then given by: $Q^{-1} = Q_{lateral}^{-1} + Q_{vertical}^{-1}$. $Q_{llateral} = \omega\tau_l$, where $\tau_l$ is the lifetime of photons inside the 2DPC membrane before their lateral escape at the 2DPC edges and is directly related to the group velocity $v_g$ from previous

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considerations. $Q_{vertical} = \omega\tau_r$ describes the vertical losses and $\tau_r$ stands for the photons lifetime before they are reemitted in free space.

For SBM above the light line of the dispersion characteristic, the mode confinement in a 2DPC slab with finite sizes is thus due to two mechanisms: one related to the coupling between SBM and free space modes, the other one to the in-plane propagation of the SBM inside the 2DPC membrane. These two effects arise from the finite size of the 2DPC slab.

In this paper we focus on the first non-degenerated SBM at Γ-point, which we call A1, in a finite size square lattice of silicon rods (n=3.5) embedded with silica (n=1.44), as shown in Fig. 1. We study first the loss mechanisms by analysing the quality factor for such modes as a function of the size of the 2DPC, by using 3D finite-difference time-domain (FDTD) calculations. We distinguish the vertical and the lateral losses to highlight the parameters involved in the mode confinement for a non degenerated SBM located above the light cone. We then work out a strategy to reduce the lateral and vertical leakages of the non degenerated SBM at Γ-point in order to increase the quality factor without increasing the mode volume.

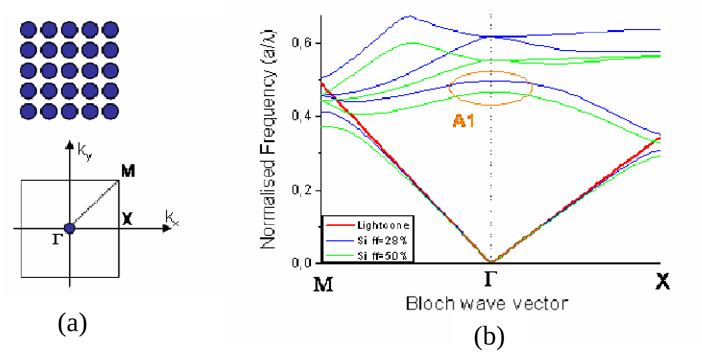


Fig. 1. (a). View of the studied square lattice of silicon rods (top): the number of rows N is 5 in the figure. Reciprocal space associated to the square lattice (bottom). (b). Band diagram for TE polarization and for two silicon filling factors (28% and 50%): the studied A1 SBM is circled.

## 2. Quality factor of the non-degenerated SBM at the Γ-point in a 2DPC slab with finite sizes

In this section we compute the quality factor by using 3D FDTD for the A1 SBM at the Γ-point of the 2DPC slab as the structure size increases. The membrane thickness is 0.3µm.

The band diagram for TE polarization calculated using the MIT Photonic Bands software (MPB) is given in Fig. 1(b) for two silicon filling factors (ff): 28% which corresponds to a rod radius of 0.3*a* and 50% for a rod radius of 0.4*a*, where *a* is the lattice constant. The A1 SBM exhibits a low band curvature and its central frequency is located into a bandgap in the X direction.

The quality factor of the A1 mode as a function of the 2DPC slab size and for silicon filling factors ranging from 19% (*r*=0.2*a*) to 62% (*r*=0.45*a*) is plotted in Fig. 2. The 2DPC surface is evaluated by: $((N-1)\cdot a + 2\cdot r)^2$ where N is the number of rod layers in the X direction, *r* the rod radius and where *a*=1µm.

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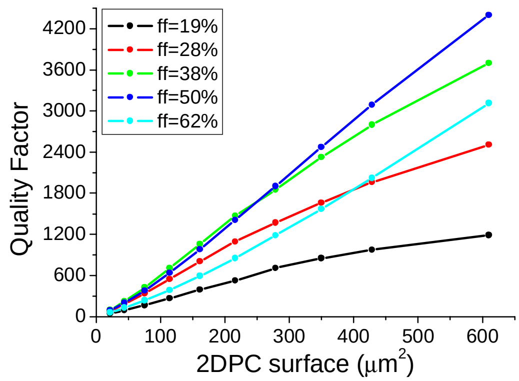


Fig. 2. A1 quality factor as a function of the 2DPC slab surface and for filling factors ranging between 19 and 62%.

As it has been explained in the introduction, the A1 SBM does not couple with radiated modes at Γ-point and thus its quality factor increases to infinity as the structure size grows. However, when the 2DPC surface is finite, vertical as well as lateral losses appear and the quality factor is a combination of a vertical quality factor and a lateral quality factor. The Fig. 3 shows the Hz and Ex components of the magnetic and electric field respectively in a 11*11 silicon pillar array in silica for the studied fundamental A1 SBM. The filling factor is 50%, the rod radius 0.4*a* and the resonance wavelength is 1.53µm. A large part of the losses are lateral losses due to the coupling between the SBM and a propagating wave in X directions at each 2DPC edges [2].

In the following, qualitative results for the value of $Q_{vertical}$ and $Q_{lateral}$ will be given for the A1 mode. The parameters that govern the A1 SBM confinement in the 2DPC will be also emphasized.

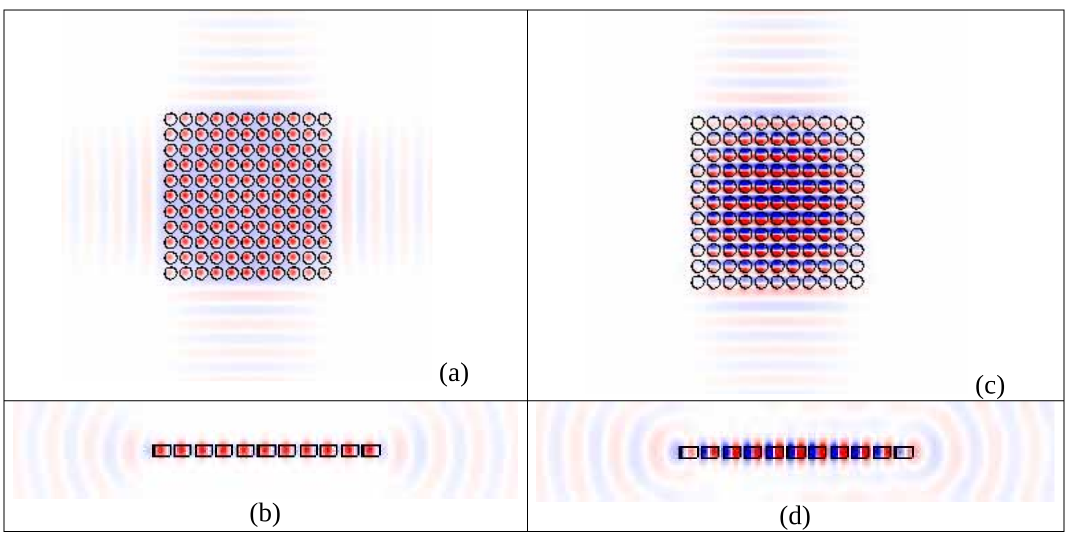


Fig. 3. (a). Hz component of the magnetic field in the x-y plane and the y-z plane (b). (c) and (d) are the same for Ex component of the electric field in a 11*11 silicon pillar array in silica at 1.53µm for the fundamental A1 SBM.

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*2.1. Vertical losses*

The band diagram in complex frequency (using MEEP, the MIT 3D FDTD software [5]) for the A1 SBM in a 2DPC with infinite lateral sizes is given in Fig. 4. In the vertical direction, the simulation cell is limited by perfectly matched layers. The band diagram is calculated in the X direction, for silicon filling factors in the range 19 to 62%. The imaginary part of the frequency is increasing when going away from the Γ-point. This means that vertical losses appear at k-point different from Γ, and are increasing if $k_{//}$ increases. The quality factors around the Γ-point, for 2DPC of infinite lateral size, can be derived from the complex frequency: $Q_{vertical} = -\frac{\omega_{real}}{2\omega_{im}}$, where $\omega_{real}$ is the real part of the frequency, $\omega_{im}$ the imaginary part. In order to roughly estimate the vertical quality factor of a finite size 2DPC, one can consider that a 2DPC of lateral size L support a mode with a mean in-plane $k_{//}$ vector on the order of $k_{//} \propto \frac{1}{L}$. Using this approximation, the variation of $Q_{vertical}$ as a function of the 2DPC size can be calculated and is given in Fig. 5.

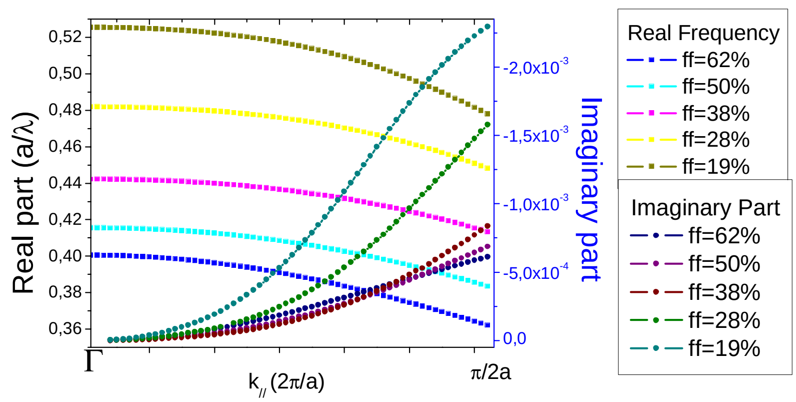


Fig. 4. Band diagram in complex frequency for the A1 SBM in the X direction of the reciprocal space. Results are given for filling factors ranging between 19 and 62%

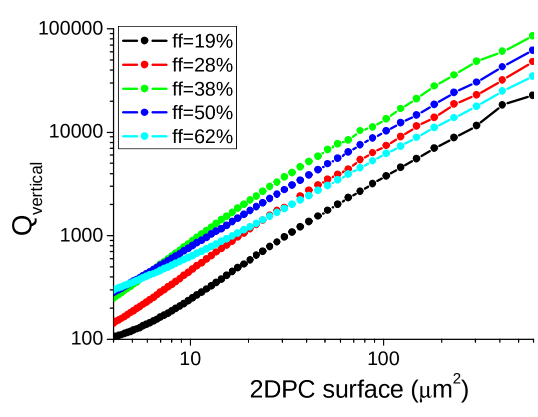


Fig. 5. A1 vertical quality factor as a function of the 2DPC slab size and for filling factors in the range 19 to 62%.

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For a given surface, the vertical quality factor is much higher than the overall quality factor of the A1 mode given in Fig. 2. The quality factor of the A1 SBM is thus mainly determined by the lateral losses.

*2.2. Lateral losses*

We apply the phenomenological Fabry-Perot model developed in [6] to express the lateral quality factor of the studied 2DPC slab. By rewriting the quality factor expression of the SBM as a function of the band curvature, using the expression of $v_g$ and the phase matching condition for the SBM inside the PC cavity given previously, one obtains: $Q_{lateral} = \frac{\pi}{(1-R(\lambda_0))}\left[\frac{2c}{\lambda_0}\frac{L^2}{\alpha}\left(\frac{1}{p\pi-\phi_r}\right)-\frac{\lambda_0}{\pi}\frac{d\phi_r}{d\lambda}\bigg|_{\lambda_0}\right]$, where R(λ) is the modal reflectivity, p an integer and $\phi_r$ the phase of the modal reflectivity at the 2DPC edges.

This expression is composed by two terms in the bracket: the second term is related to the lifetime of photons out of the 2DPC boundaries before they are reflected back inside the cavity. The effect of the modal reflectivity at band edges on the SBM quality factor is explained in [7].

The first one is related to the lifetime of photons inside the 2DPC membrane before the photons reach the boundaries. It depends on the 2DPC size and the band curvature. Figure 6 shows the band curvature, calculated from the obtained bands with MPB, in each reciprocal space direction X and M for the studied square lattice as a function of the silicon filling factor. The band curvature is not a monotonic function of the filling factor, but an optimum value exists between 30 and 40%. As it has been seen previously, for finite size 2DPC, the SBM mean group velocity $v_g$ is proportional to α, so the SBM will propagate slower if it exhibits a flat band curvature. In other words, using a simple kinetic model [8], S/α, S being the size of the SBM, represents the mean time needed for a photon to reach a boundary of the 2DPC.

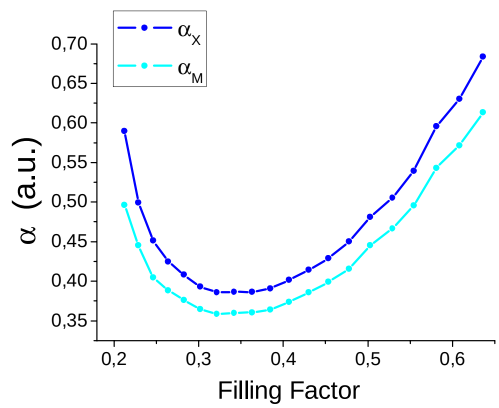


Fig. 6. A1 band curvature around the Γ-point as a function of the 2DPC filling factor (19 %< ff<62%).

The lateral quality factor for the non degenerated SBM at Γ-point is thus strongly related to the value of the band curvature α given in the Fig. 6: the highest quality factors should thus be obtained for the smallest values of α. This is indeed confirmed in Fig. 2: the structures having filling factors of 38% and 50% have the highest quality factors.

For applications in photonic integrated circuits, the devices exploiting SBM at the Γ-point (such as vertical emitting micro-lasers) should operate on structures with limited size, yet retaining high quality factors. In the following, strategies to reduce the lateral and vertical leakages, while keeping a small structure size, are presented.

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## 3. Reduction of the lateral leakages

In order to inhibit lateral losses, we use a heterostructure as depicted in Fig. 7. This concept was first studied in [9] to confine light in a modified W1 waveguide. In a recent paper [10], band-edge SBM below the light line are laterally confined using a 2D photonic heterostructure in a triangular lattice of air holes. Following this work, we used a heterostructure to reduce the lateral losses without increasing the size of the 2DPC structure for a SMB located at Γ-point.

By varying the filling factor of the outer rows of the 2DPC slab, keeping the same lattice constant, we can create a *barrier* for the photons inside the *well*. Indeed, if we refer to the Fig. 1(b), the centred frequency of the A1 mode inside the well is located in the gap in the X direction of the barrier.

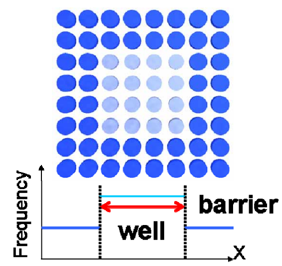


Fig. 7. Studied heterostructure and schematic band diagram showing the heterostructure effect.

We computed, using 3D FDTD, the quality factor of the A1 mode inside the well as a function of the barrier parameters, such as the number and the filling factor of the rows. Results are plotted in Fig. 8. The well is constituted by an 11*11 pillar cavity arranged on a square lattice with a filling factor of 38% (8a) and 50% (8b), embedded in silica.

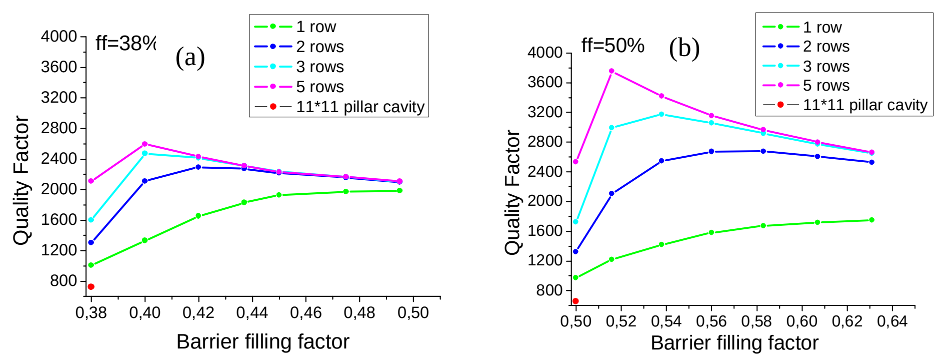


Fig. 8. Quality factor of the A1 SBM in the investigated heterostructure constituted by a 11*11 pillar well of filling factor 38% (a) and 50% (b) as a function of the barrier parameters : row number (1,2,3, 5) and filling factor, keeping the same lattice constant.

The quality factor of the A1 SBM inside the well is controlled by the vertical losses, the lateral leakages inside the barrier and diffracted losses at the edge between the well and the barrier.

For more than 2 outer rows, the highest quality factor is obtained for a small difference between the filling factor of the well and the barrier. Beyond this optimum, when the barrier filling factor increases, the quality factor decreases because of the geometry mismatch between the well and the barrier. An amount of losses are then due to diffracted losses occurring at the edges of the well and are growing with the silicon filling factor of the barrier. In that case, the lateral losses are completely inhibited and when the barrier silicon filling factor keep increasing, the photon lifetime is only limited by the diffracted losses (and the vertical ones that still exist). Therefore, for a large row number of the barrier, large enough to

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inhibit completely the lateral leakages, the largest quality factor is obtained, as expected, for filling factor close to the well filling factor.

For less than 2 outer rows, the quality factor still increases when the barrier filling factor increases, in spite of the fact that diffracted losses occur. In that case, a large difference between the well and the barrier rod radius is required to inhibit the lateral losses, that is to say a high barrier filling factor. The lateral losses through the barrier are much higher than the diffracted ones. Thus, for a small number of barrier rows, to enhance the quality factor of the A1 SBM inside the well, it is necessary to increase the barrier rod radius to inhibit the lateral leakages.

The Fig. 9 shows the Hz and Ex components of the magnetic and electric field respectively for a heterostructure constituted by an 11*11 pillar cavity of ff=50% surrounded by 5 barrier rows with filling factor = 52%. Contrary to the Fig. 3 without a heterostructure, we can see that the field is laterally confined.

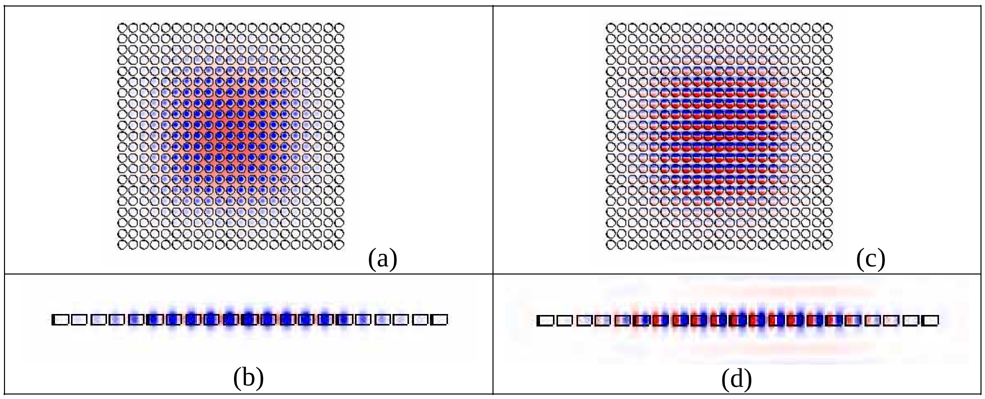


Fig. 9. (a). Hz component of the magnetic field in the x-y plane and the y-z plane (b). (c) and (d) are the same for Ex component of the electric field.

When the lateral losses are inhibited, the quality factor of the A1 mode reaches 4000 that is on the order of the vertical quality factor given by the Fig. 5 for the same 2DPC surface. For applications requiring high quality factors, it is necessary to further reduce these vertical losses.

## 4. Reduction of the vertical leakages

The lateral losses are inhibited thanks to the use of a heterostructure. However, the main leakages are now the vertical losses around the Γ-point. To reduce these leakages, we then associate the studied photonic heterostructure with a vertical multilayer Bragg mirror as shown in Fig. 10. This association strongly modifies the electromagnetic field distribution in the structure. The coupling rate between the A1 SBM inside the 2DPC and the radiated mode is thus affected by the Bragg mirror. Indeed, it can be shown [1] that if the gap between the 2DPC and the Bragg mirror equals $2p\lambda/4n$, p being an integer, constructive interferences occur with the radiated modes resulting in a drop of the quality factor. Inversely, if the gap equals $(2p+1)\lambda/4n$, the SBM electromagnetic field interferes destructively with the radiated modes. This results in an increase of the SBM quality factor of the 2DPC slab.

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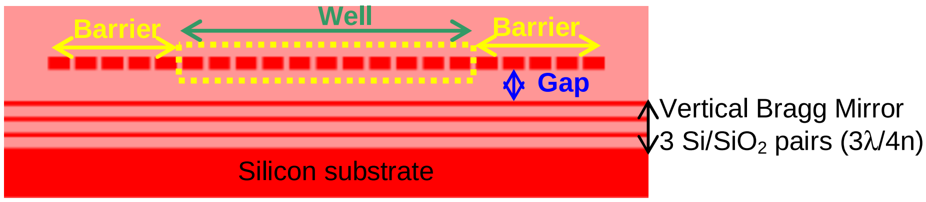


Fig. 10. Association between a photonic heterostructure and a vertical Bragg mirror.

The A1 SBM quality factor is calculated, using 3D FDTD, as a function of the gap size. The studied photonic heterostructure is constituted by an 11*11 pillar well with a filling factor of 50%, and 5 outer rows with a filling factor of 53.8%. Results are given in Fig. 11 and show that quality factors of 40000 are obtained for a gap size g=740nm. From the previous model, the highest quality factor should have been found for a gap size g=790nm. The difference between the 3D calculations and the theoretical model is due to the approximation made on the model: it is calculated using an infinite PC excited by a plane wave. In our case, the 2DPC has finite lateral sizes and is excited by a dipole located inside the membrane allowing for the existence of $k_{//}\neq 0$. The Fig. 12 shows the Hz and Ex components of the magnetic and electric field respectively for the same heterostructure as in Fig. 9 associated with a vertical Bragg mirror for g=740nm.

The lifetime of photons inside the heterostructure can then be adjusted by adding a vertical Bragg mirror.

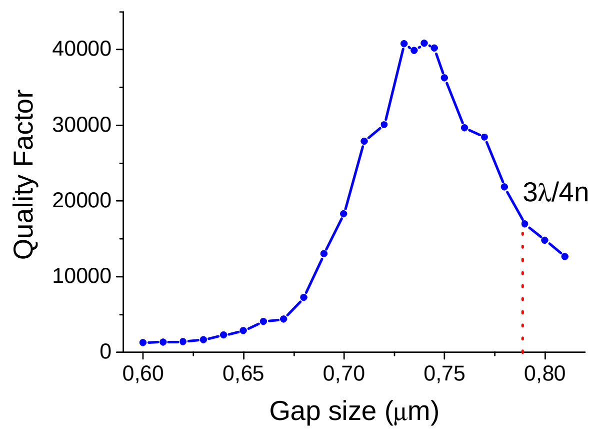


Fig. 11. Quality factor of the A1 SBM in the photonic heterostructure of Fig. 8(b) with 5 surrounding rows, as a function of the gap size between the heterostructure and the vertical Bragg mirror.

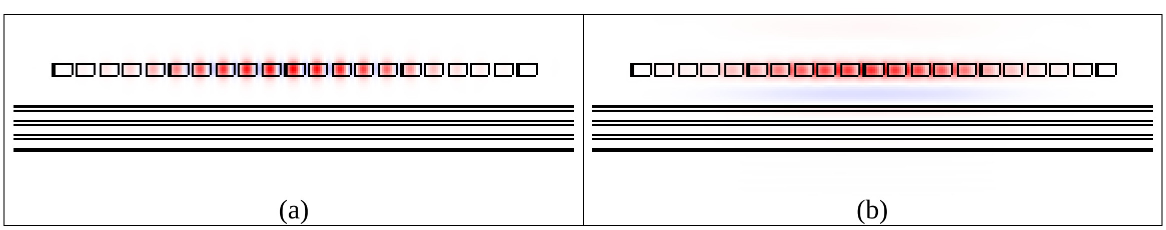


Fig. 12. Hz component of the magnetic field (a) and Ex component of the electric field (b) in the heterostructure.

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## 5. Conclusion

In this paper, we propose a general approach for the spatial and time confinement of SBM in 2DPC: we focused on non degenerated SBM above the light cone in a 2DPC slab constituted by a square array of silicon pillars in silica. For such modes, we have first shown that the quality factor can be enhanced by increasing the structure size and by optimizing the value of the band curvature and the modal reflectivity. We have also shown that the main losses are lateral losses. We used a heterostructure to reduce these leakages and obtained quality factor of around 4000, which is suitable for the realization of small vertical emitting lasers. To reduce further the vertical losses, we have associated the heterostructure to a vertical Bragg mirror. The gap size between the heterostructure and the Bragg mirror can be adjusted in such a way as to generate SBM resonator structures with very high quality factor (40000) and limited modal volume. Such an association can lead to the production of active devices with very low energy threshold (vertical emitting lasers, non-linear devices), while lending itself to an excellent spatial (angular) resolution.

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