Slow-Light Trapping in a Photonic Crystal Slab

Frédéric Bordas,[1] M. J. Steel,[2,3] Christian Seassal,[1] and Adel Rahmani[4]

[1]*Institut des Nanotechnologies de Lyon, UMR CNRS, Ecole Centrale de Lyon, 69130 Ecully, France*
[2]*RSoft Design Group, Inc., 65 O'Connor Street, Chippendale, NSW 2008, Australia*
[3]*Centre for Ultrahigh bandwidth Devices for Optical Systems (CUDOS), School of Physics, University of Sydney, NSW 2006, Australia*
[4]*CUDOS and Centre for Lasers and Applications, Department of Physics, Macquarie University, North Ryde, NSW 2109, Australia*

Abstract: We present a general scheme to trap slow-light in a photonic crystal slab and achieve high Q/V ratio with a fabrication tolerant design, well suited for low-threshold microlasers and cavity quantum electrodynamics.

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The two major strategies when devising photonic crystal slab optical devices are the introduction of defects, and the exploitation of the critical points of the band dispersion diagram of the perfect crystal. The former approach creates a defect state in the band gap, the defect constituting a cavity for photons. However, these cavities draw their properties of confinement from an astute management of losses which relies on the careful control of the optical reflections at the boundaries of the cavity. This means that the fabrication of such structures often requires state-of-the-art technological processes, capable of accommodating minute adjustments to the structure of the crystal.

The second approach considers the perfect crystal (without defects) and builds upon the enhanced local-density of electromagnetic states associated with the critical points of the band dispersion diagram. At these points, the slope of the band is zero and the crystal supports slow light modes (SLMs). Owing to their small group velocity, SLMs experience a stronger effective electromagnetic interaction with their environment than conventional modes with a larger group velocity. They are also more resilient with respect to fabrication imperfections [1].

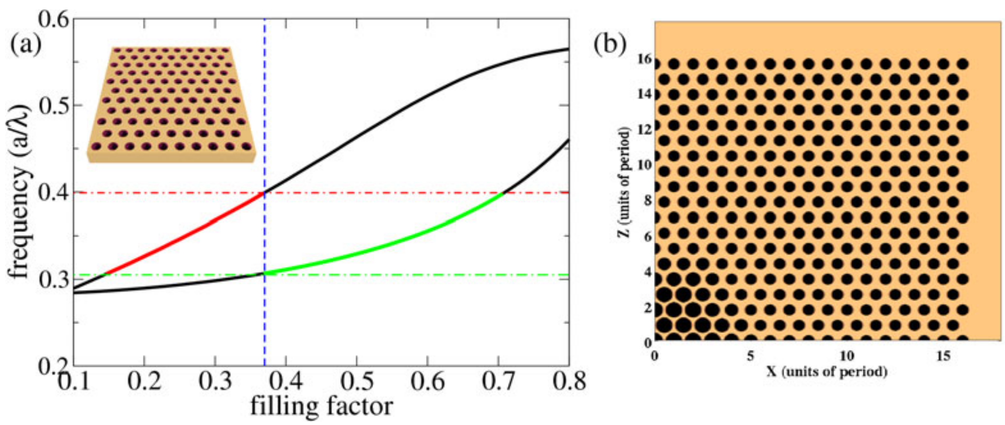

Fig. 1. (a) Generic photonic crystal slab geometry and frequency of the band edges along the *M-K* direction versus the filling factor computed by the plane wave method [3]. The horizontal lines mark the edges of the bandgap for a crystal with f=0.37. (b) Upper-right quadrant of the computational domain in a plane parallel to the slab for a V_4^2 cavity.

This property makes SLMs an asset in achieving enhanced nonlinear effects or low-threshold laser emission [2]. However, one problem inherent to modes of a defect-free crystal is that they are delocalized. This leads to practical problems in the design of compact photonic microstructures. It also implies a more fundamental problem, if the mode size is only limited by its losses, how can one design a structure exploiting band-edge SLMs with a high ratio of the quality factor to the mode volume? We will present a general approach allowing one to confine the SLM spatially without inducing drastic losses.

How can a slow photon be confined efficiently? To answer this question we consider a photonic crystal slab (PCS) with refractive index 3.17 The PCS contains a pattern of circular air holes arranged over a triangular lattice

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with period *a* and filling factor *f* (Fig. 1). The thickness of the slab is 11*a*/26, ensuring monomode operation. For these parameters, the perfect (infinite) crystal supports two band-edge modes. Below the bandgap, the valence band edge is at the *K* point of the Brillouin zone (hereafter referred to as the valence mode), whereas above the bandgap, the band edge lies at the *M* point (conduction mode). Using the RSoft photonics modeling suite [3], we plot in Fig. 1 the frequency of the band edges as a function of the filling factor.

Consider a PCS with $f=f_{\text{mirror}}=0.37$ (vertical dashed line in Fig. 1). If we alter the filling factor in a region of the PCS, we create an effective core that has either its valence ($f_{\text{core}} > f_{\text{mirror}}$), or its conduction ($f_{\text{core}} < f_{\text{mirror}}$) band edge lying within the bandgap (delimited by horizontal dashed lines). The outer region of the PCS thus acts as a mirror. This approach yield cavities capable of sustaining a confined SLM which results from the balance between confinement (maximized at the center of the bandgap) and scattering losses (minimized at the edges of the bandgap of the mirror). Therefore, the out-of-plane scattering losses due to the lattice mismatch at the core/mirror interface imposes an upper limit to the efficiency of the confinement. Nevertheless, this limit can be circumvented by including adaptation (*i.e.,* transition) layers between the core and mirror regions. We will show that this strategy can enhance the quality factor *Q* of the structure by one order of magnitude or more, without any drastic increase in the mode volume *V*. An example of this effect is illustrated in Fig. 2 for a V_4^2 cavity which consists of a core of 4 rings and 2 adaptation layers.

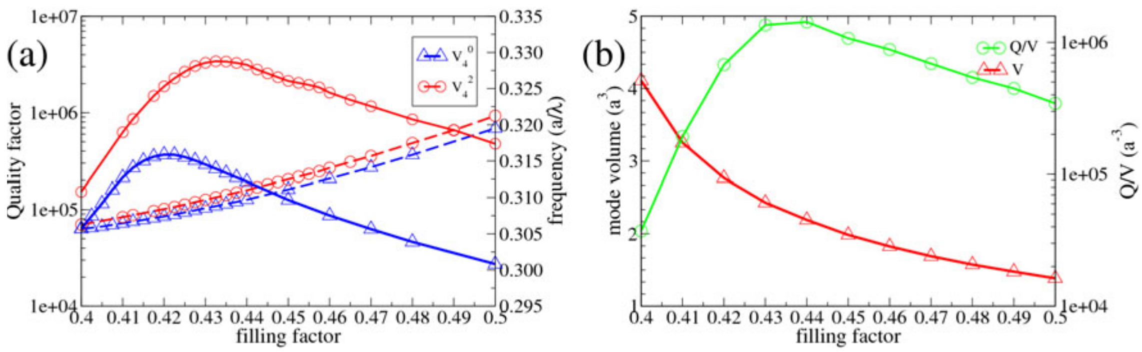

Fig. 2: (a) Quality factor (solid lines) and frequency (dashed lines) for the confined slow light mode for a V_4^0 and a V_4^2 cavities as a function of the filling factor of the core. (b) Mode volume and *Q/V* ratio versus the filling factor of the core region for a V_4^2 structure.

We plot in Fig. 2 (a) the evolution of the quality factor *Q* (and the frequency) of the core SLM as a function of the filling factor for cavities with a core consisting of 4 rings of holes. We first note that while the V_4^0 cavity has a large quality factor to start with, it can be increased by more than an order of magnitude by the use of two adaptation layers. Furthermore, the quality factor reaches a maximum not at the middle of bandgap of the mirror, but rather for a value of the filling factor closer to that of the mirror. This is due to the fact that the optimal slow-light cavity structure is one that balances spatial confinement, maximal for large filling factors (i.e., deep in the bandgap of the mirror), and out-of-plane scattering losses, minimal for smaller lattice mismatch between the core and the mirror. This is illustrated further in Fig. 2 (b) where we plot the evolution of the mode volume and the ratio *Q/V* for a V_4^2 cavity. As one can see, because of the evolution of *Q,* the maximum of *Q/V* does not occur for the filling factor for which the mode is most confined spatially but closer to the band edge of the mirror region.

In summary, we will show that drastic enhancements of the *Q/V* ratio are achievable by using our approach on photonic crystal slabs. We will explore the influence of core and mirror size, the number of adaptation layers and we will present efficient, fabrication tolerant slow-light cavity designs, and discuss their application to compact ultralow-threshold microlasers and enhanced radiation dynamics.

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[3] http://www.rsoftdesign.com/

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