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# Slow Light Dispersion Engineering of Active Photonic Crystal Cavities for Compact and Integrated Mode-Locked Lasers

Malik Kemiche, Jérémy Lhuillier, Thomas Wood, Aziz Benamrouche,  
Philippe Regreny, Radosław Mazurczyk, Pedro Rojo-Romeo,  
Xavier Letartre, Ségolène Callard, Christelle Monat

Institut des Nanotechnologies de Lyon, Université de Lyon, CNRS UMR 5270, École Centrale de Lyon, 36 Avenue  
Guy de Collongue, 69134 Écully Cedex, France

email: malik.kemiche@doctorant.ec-lyon.fr, phone: +33 4 72 18 60 40, fax: +33 4 78 43 35 93

**Abstract:** We realize compact active photonic crystal cavities for miniaturized chip-based pulsed lasers. We experimentally validate our approach relying on slow-light dispersion engineering for sustaining the intended regular comb of modes from a  $30\ \mu\text{m}$  long cavity.

**OCIS codes:** 130.3120, 130.5296, 140.3945.

Mode-locked lasers capable of generating short optical pulses in the near-infrared are a key enabler to various applications including high data rate optical interconnects. However, the related technology mostly consists of bulky and stand-alone devices, which tends to hinder their widespread use. The integration of such devices onto chip-based platforms could bring advantages in terms of robustness and stability, while offering new prospects for the realization of advanced hybrid photonic-electronic architectures. There has recently been some progress regarding the miniaturization of fast pulsed lasers [1], but the underlying cavity typically remains in the millimeter range and their integration on a chip is still a challenge [2]. Here, we propose an extremely compact cavity design ( $\approx 30\ \mu\text{m}$ ) based on a dispersion-engineered photonic crystal (PhC) etched in an active InP slab on silica, as depicted on figure 1(a). Note that, as compared with suspended slabs, this vertically asymmetric heterostructure is more robust and improves heat dissipation, although it may introduce additional optical losses.

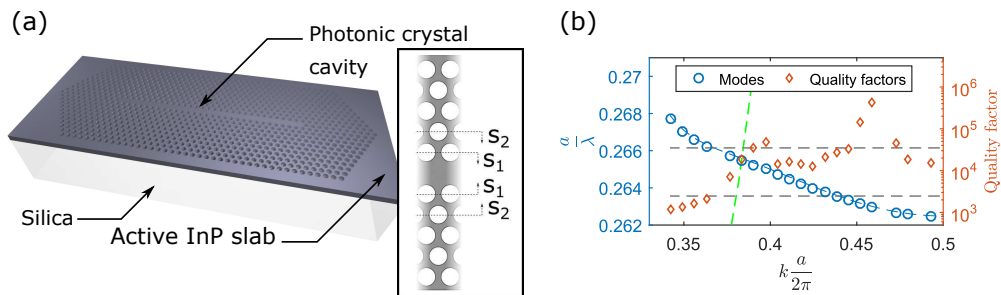


Fig. 1. (a) Schematic of the PhC cavity design for the integrated mode-locked laser consisting of a  $300\text{nm}$ -thick active InP slab on top of a silica substrate. (b) Cavity modes of a  $30\ \mu\text{m}$  long L73 PhC cavity from 3D FDTD simulations along with their quality factors.

Laser mode-locking relies on a frequency equidistant comb of modes that jointly sustain the emission of short optical pulses, whose shape quality and peak power directly increase with the number of cavity modes. Our approach to generate numerous modes despite the reduced size of our cavity is to exploit slow light modes (with a high group index) in PhC structures so as to increase the effective optical path. In particular, we applied dispersion engineering techniques [3] to our asymmetric InP/silica PhC structures, relying on the local shift of air holes around the cavity defect (see fig. 1(a)). This allowed us to achieve low-dispersion bands of slow light in otherwise highly dispersive PhC waveguides. These dispersion-engineered cavities yield a frequency-equidistant comb in very compact geometries as intended for mode-locking operation.

We performed 3D FDTD simulations to design PhC structures with the adequate dispersion, i.e. a mode with a high group index that is relatively constant across a substantial band. As an example, a 30  $\mu\text{m}$  long PhC cavity associated with a group index of 28 could provide at least 9 equally-spaced modes with quality factors above 10,000 over 11.5nm (see figure 1(b)), which could sustain the generation of sub-picosecond pulses. The cavity length can hence be reduced by almost an order of magnitude compared to a standard strip waveguide-based cavity [1] presenting a similar spectral signature. Furthermore, group indices ranging from 15 to 40 can be readily achieved with other designs, depending on whether further miniaturization or shorter pulses are sought for.

Based on these designs, PhC active structures including InAsP/ InP quantum wells or InAs/InP quantum dashes were fabricated using molecular beam epitaxy, III-V/silica bonding, e-beam lithography and reactive ion etching. As theoretically expected, the spectral signature of a 30  $\mu\text{m}$  long PhC cavity measured by micro-photoluminescence exhibits equally-spaced modes (see fig. 2.(a)). From the free spectral range of these comb lines, the group index of the underlying elongated PhC cavity can be inferred, which is shown to be relatively high ( $\approx 36$ ) and constant between 1486 and 1492 nm. Furthermore, the narrow linewidth of the peaks suggests that the experimental quality factors of our cavity modes are high enough to sustain stimulated emission, as predicted by simulations. To unambiguously identify the origin of these modes, we measured their intensity maps along the cavity by near-field scanning optical microscopy (see fig. 2.(b)). NSOM cartographies confirm that these comb lines correspond to modes that are tightly confined along the cavity with different longitudinal orders. Our experimental results thus validate the feasibility of our approach, showing that slow light PhC based active cavities can be effectively exploited for the realization of miniaturized integrated mode-locked lasers.

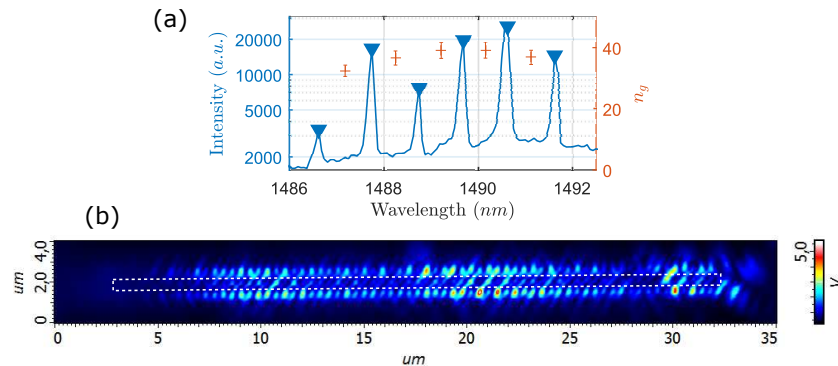


Fig. 2. (a) Photoluminescence spectrum of a slow light dispersion-engineered L73 PhC cavity ( $L = 30.2 \mu\text{m}$ ) with quantum wells and the corresponding group index inferred from the spectral signature, and (b) near-field  $|E|^2$  total intensity map (spectrally unfiltered) with the cavity highlighted as the white dashed line.

In conclusion, we proposed and experimentally validated the use of slow light dispersion engineering in active PhC cavities for the miniaturization of frequency comb chip-based sources that could sustain the emission of short optical pulses. Our practical design involves a robust hybrid InP/silica geometry, which offers the potential for integration with silicon photonic devices, while enabling the integration of a saturable absorber for achieving mode-locked laser operation in very compact structures.

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