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Simulative study of QD lasers on Si and PhC lasers

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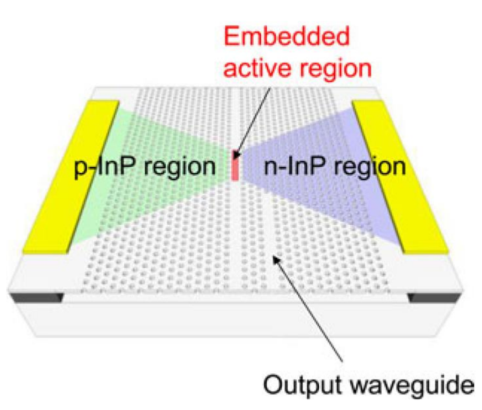
Research context and motivation

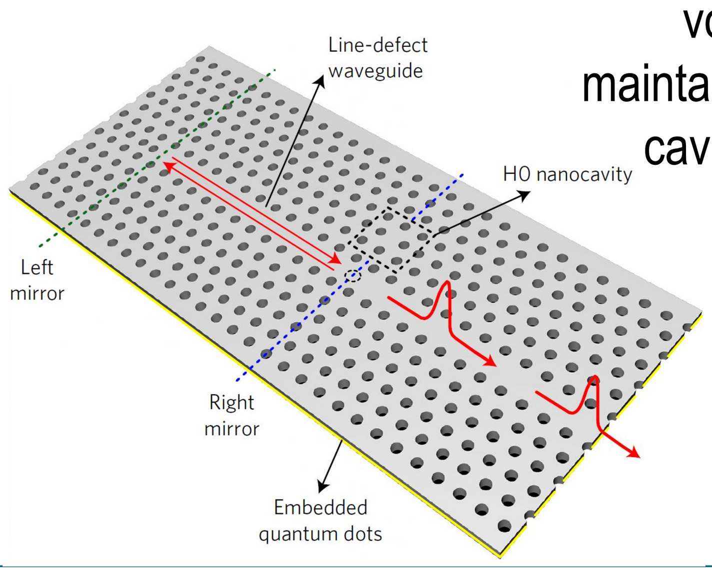
Photonic-crystal (PhC) lasers

The ever increasing traffic volumes in datacentres and supercomputers pose a continuing demand of low-power and high-speed data links. With this regard, optical links have great advantages as compared to their electrical counterpart.



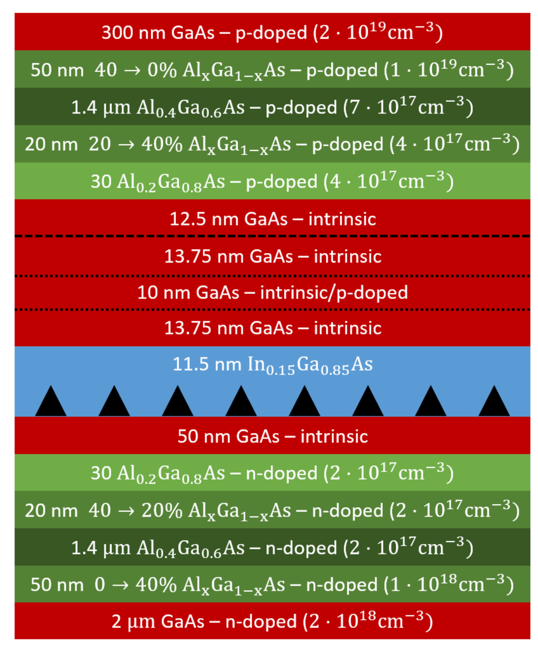
To extend the application of optical communications to chip-to-chip and chip-scale distances, it is essential to develop semiconductor lasers with a smaller energy cost as compared to conventional ones.

For this purpose, **PhC lasers** represent ideal candidates, as they allow to scale the active volume while maintaining a high cavity Q-factor.



QD lasers on Si

The use of mature Si-based complementary metal-oxide semiconductor (CMOS) processes, traditionally targeted at electronic devices, to realize **QD lasers epitaxially grown on Si**, would pave the way to low-cost and high-density PICs.



Active material potential candidate

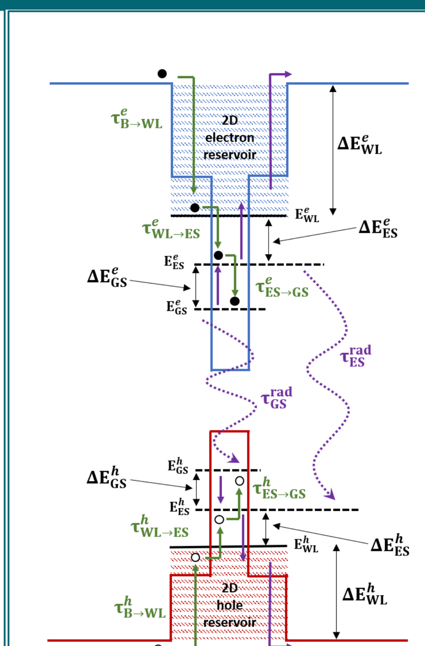
As compared to QWs, QDs benefit of a reduced sensitivity to crystalline defects and surface recombination. QDs also have a lower linewidth enhancement factor, which translates into a higher immunity to optical feedback.

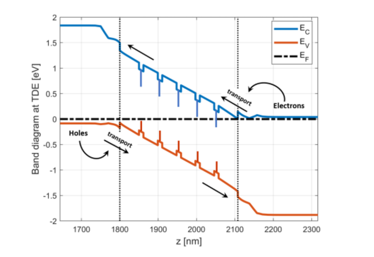
Adopted methodologies

Photonic-crystal (PhC) lasers

PhC lasers consisting of various sections are analyzed, which are perturbed in either refractive index (passive mirrors) or gain (active section) as compared to a reference, passive waveguide. The weak perturbation of the refractive index and/or gain induces a strong coupling between the otherwise independent counter-propagating Bloch modes. The scattering matrix resulting from this distributed feedback is computed for each section and the threshold characteristics of a PhC laser are investigated by computing the cavity complex loop-gain. This also allows to incorporate the fundamental limitation to the SL gain enhancement imposed by the gain itself.

QD lasers on Si





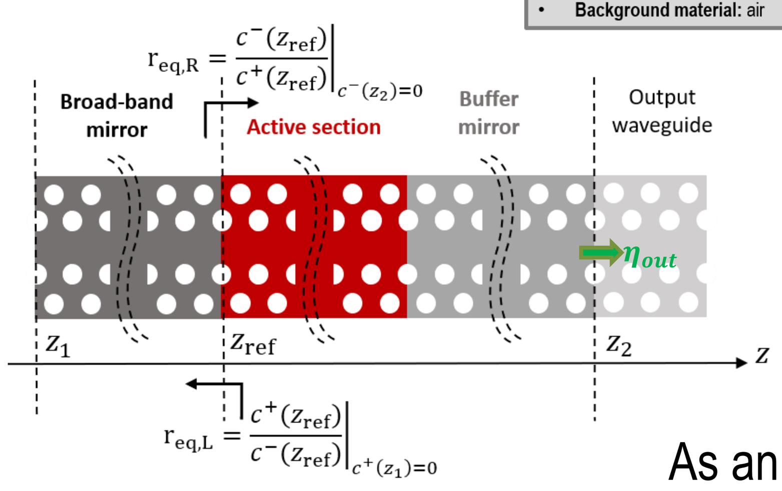
1.3 um QD lasers grown on silicon are studied by employing a **drift-diffusion** model for the transport of carriers across the separate confinement heterostructure (SCH) region.

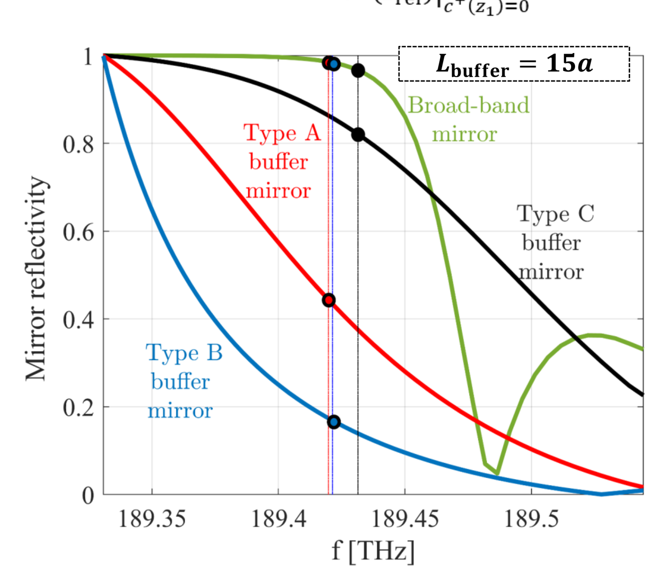
Photonic-crystal (PhC) lasers

Refractive index perturbation Δn_r

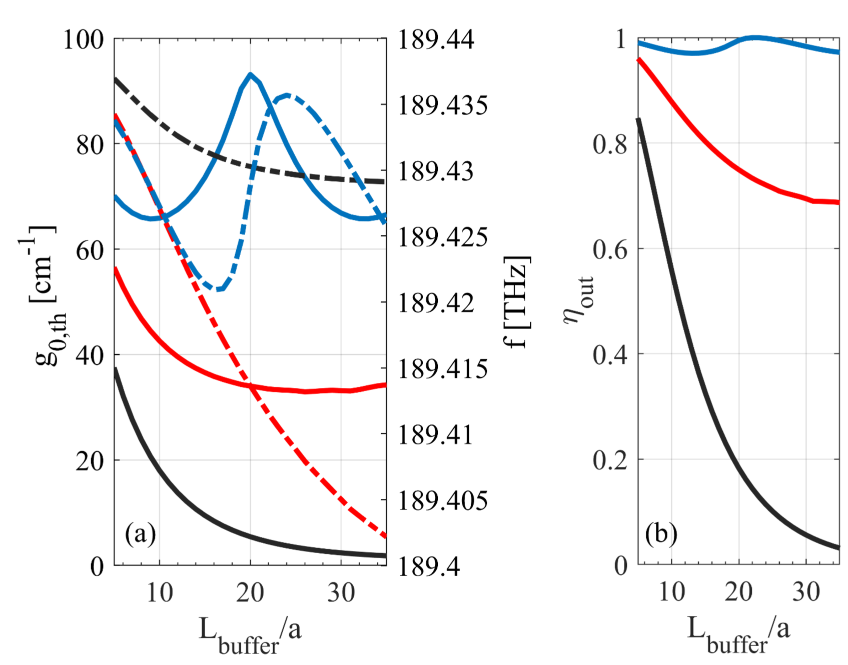
Broad-band mirror	Active section	Buffer mirror
−0.002	−0.001	−0.002 (Type C) −0.001 (Type A) −0.0005 (Type B)

Reference waveguide parameters
- Lattice constant: $a = 438$ nm
- Hole radius: $r = 0.25\,a$
- Slab thickness: $h = 250$ nm
- Slab refractive index: $n_r = 3.17$
- Background material: air





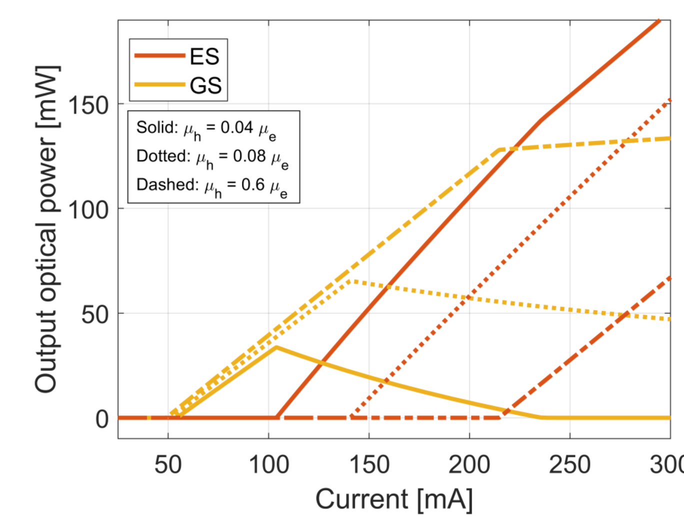
As an example, threshold gain and output coupling efficiency of a multi-section PhC cavity are optimized.



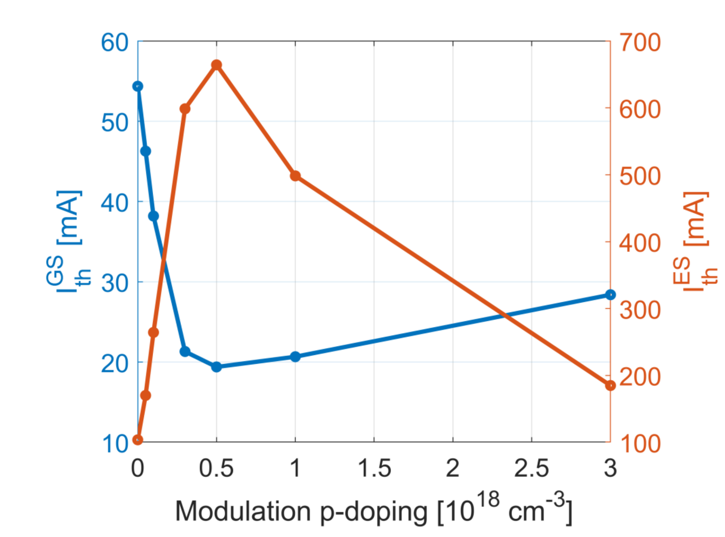
Novel contributions

QD lasers on Si

The role of the electron and hole mobility unbalance on the GS power quenching is emphasized.



An optimum modulation p-doping level is shown to exist, minimizing (maximizing) the GS (ES) threshold current, consistently with experimental findings. This optimum is attributed to electrostatic effects induced by the doping.



Addressed research questions/problems

Photonic-crystal (PhC) lasers

- **Need for an intuitive model**. Rigorous approaches to analyze PhC lasers, such as FDTD or RCWA, are either time- and memory-consuming or not always useful to provide an intuitive understanding of the physical phenomena into play.
- **Slow-light gain enhancement**. The modal gain coefficient of a Bloch mode is enhanced in the slow-light (SL) region of a PhC laser. However, a fundamental limitation to the SL gain enhancement is imposed by the gain itself.

QD lasers on Si

- **GS power quenching.** Several experiments on QD lasers grown on GaAs and on Si have revealed the quenching of the GS optical power as the current overcomes the ES lasing threshold.
- **Modulation p-doping.** A common technique to enhance the GS gain and mitigate this quenching is the modulation p-doping. However, experimental results have demonstrated that an excessive p-doping level results in a deterioration of the GS optical power and threshold current, an effect which is still to be fully understood.

Future work

Photonic-crystal (PhC) lasers

The analysis of a novel type of PhC laser, the so called **PhC Fano laser**, will be carried out during my external stay at the Technical University of Denmark. This laser has resulted in the first observation of passive short-pulse generation in micro-cavity lasers.

QD lasers on Si

- Carry on a more systematic comparison with experimental results provided by the University of Padova
- Investigate on the reduced sensitivity of QD lasers to crystalline defects

Submitted and published works

- Saldutti, M. , Mørk, J., Bardella, P., Montrosset, I., and Gioannini, M., "*Coupled Bloch-Wave Analysis of PhC lasers*", presented at ESLW 2018, 20-21 September 2018, Bari, Italy.
- Saldutti, M. , Mørk, J., Bardella, P., Montrosset, I., and Gioannini, M., "*Coupled Bloch-Wave Analysis of Active PhC Waveguides and Cavities*", presented at NUSOD 2018, 5-9 November 2018, Hong Kong, China.
- Saldutti, M., Mørk, J., and Gioannini, M, "A simple approach, based on coupled mode theory, to study PhC lasers", presented at CLEO/Europe 2019, 23-27 June 2019, Munich, Germany.
- Saldutti, M., Bardella, P., Mørk, J., and Gioannini, M., "*A Simple Coupled-Bloch-Mode Approach To Study Active Photonic Crystal Waveguides and Cavities*", Journal of Selected Topics in Quantum Electronics, vol. 25, no. 6, 2019.
- Saldutti, M., Tibaldi, Cappelluti, F., Bertazzi, F., and Gioannini, M., "*Study of CW performance of QD lasers on Silicon including carrier transport in the SCH barrier*", submitted to SPIE Photonic West 2020, 1-6 February 2020, San Francisco, USA.
- Saldutti, M., Mørk, J., and Gioannini, M., "*Analysis, by a Simple Coupled-Bloch-Mode Approach, of various PhC Laser Cavities*", submitted to SPIE Photonic West 2020, 1-6 February 2020, San Francisco, USA.

List of attended classes

- 01SFURV – Programmazione scientifica avanzata in Matlab (13/04/2018, 4 CFU)
- External Activity – La gestione dello stress (5/05/2018, 15 hours)
- 01SIKRV – Optical components for Telecom (17/05/2018, 4 CFU)
- External Activity – Soft-Skill Course on International Project Management in CFRP Development Programs (21/06/2018, 6 hours)
- 01QORRV – Writing scientific papers in English (27/06/2018, 3 CFU)
- 01QWLBG – Signal processing and transmission laboratory (6/07/2018, 6 CFU)
- 02MXBOQ – Passive optical components (27/02/2019, 6 CFU)
- 05BVCOQ – Optoelettronica (27/02/2019, 6 CFU)
- 01TEXRO - Waves in Periodic Structures and Elastic Metamaterials (23/05/2019, 3 CFU)

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