

Microcavity photonic crystal lasers and quantum dot lasers epitaxially grown on silicon: theory and numerical modelling

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Summary

In this thesis, we deal with theoretical and numerical modelling of semiconductor lasers targeted at on-chip optical communications. Specifically, we focus on photonic crystal lasers, where the optical cavity is carved out of a semiconductor slab by strong, periodic modulation of the slab refractive index. These lasers are promising sources for optical interconnects, as they are microscopic and have low threshold current, as well as reduced energy cost. We also cover quantum dot (QD) lasers epitaxially grown on silicon. In addition to other well-known advantages, QDs offer enhanced tolerance against threading dislocations (TDs) in the crystalline structure. These dislocations are caused by the mismatch in the lattice constant and thermal expansion coefficients between the silicon substrate and III-V semiconductor materials grown above. Therefore, QDs are a highly attractive active material for on-chip applications. In Chapter 1, we briefly draw up this overarching research context.

In Chapter 2, we investigate the modal properties of passive photonic crystal cavities. We model a photonic crystal cavity as an effective Fabry-Perot resonator. The travelling modes are the Bloch modes of the waveguide on which the cavity is based. By this approach, we derive compact and transparent expressions for the resonance condition and field distribution, which agree with previous predictions based on fitting of finite-difference time-domain (FDTD) simulations. By our approach, we also analyze the scaling of radiation loss with the size of the cavity and offer new insights.

In Chapter 3, we analyze the optical propagation in active photonic crystal waveguides, with a special interest in slow-light effects associated with material gain. In fact, photonic crystal waveguides may support significant slow-light, meaning that the group velocity may be much smaller than the vacuum light speed. In this propagation regime, the modal gain per unit length is enhanced as compared to conventional waveguides under the same pumping conditions, with possible applications to compact optical amplifiers and lasers. We view the presence of material gain as a weak perturbation to a reference photonic crystal waveguide with purely real refractive index. Thus, we expand the field in the basis of the counter-propagating Bloch modes of this reference waveguide. Owing to the presence of gain, a distributed feedback sets in between these Bloch modes, which would be otherwise uncoupled. By this coupled-Bloch-mode approach, we derive a scattering matrix formulation which efficiently describes the optical propagation in active photonic crystal waveguides in the presence of slow-light.

Our model confirms previous results that a fundamental limitation to the slow-light gain enhancement is posed by the gain itself. Furthermore, we offer new insights on the impact of a generally complex refractive index perturbation. In particular, we show that slow-light semiconductor optical amplifiers may benefit from a smaller linewidth enhancement factor.

In Chapter 4, we leverage the scattering matrix formulation of the previous chapter to investigate the impact of slow-light on the oscillation condition of various types of photonic crystal lasers. These include lasers with photonic bandgap mirrors, photonic heterostructure mirrors and a new kind of photonic crystal laser, known as the Fano laser. Our approach goes beyond the conventional picture of slow-light simply reducing the mirror loss and offers new insights. Furthermore, it is flexible and adaptable to the laser configuration of interest. In fact, the laser cavity may generally consist of various sections, either passive or active, with each section modelled by a scattering matrix.

By expanding the oscillation condition around the lasing point, in Chapter 5 we derive a rate equation model which self-consistently accounts for slow-light, including the gain-induced distributed feedback. This approach is potentially applicable to various kinds of lasers, including the Fano laser. We focus on lasers with photonic bandgap mirrors and presents preliminary results on the stationary and small-signal characteristics.

Finally, in Chapter 6 we deal with the continuous wave operation of Fabry-Perot, QD lasers epitaxially grown on silicon. As compared to previous approaches, we employ a drift-diffusion transport model, augmented with conventional rate equations for photons and carriers in the dot-in-a-well (DWELL) layers. Our analysis reveals that TDs in the DWELL layers are those responsible for the degradation of the laser performance. We demonstrate that the asymmetric transport of electrons and holes explains the quenching of the power emitted on the ground state above the excited state lasing threshold under dual state emission. Furthermore, we show that electrostatic effects lead to an optimum p-type modulation doping minimizing the ground state threshold current, an effect evidenced by recent experiments.

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