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Editorial

Special Issue "Semiconductor Laser Dynamics: Fundamentals and Applications"

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Abstract: With the advent of integrated photonics, a crucial role is played by semiconductor diode lasers (SDLs) as coherent light sources. Old paradigms of semiconductor laser dynamics, like optical injection, external feedback and the coupling of lasers, regained relevance when SDLs were integrated on photonic chips. This Special Issue presents a collection of seven invited feature papers and 11 contributed papers reporting on recent advances in semiconductor laser dynamics.

Keywords: semiconductor laser; dynamics and stability; laser coupling; integrated lasers

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1. Introduction

As one of the most widely used coherent light sources today, the semiconductor laser is an essential component of many optical systems, notably for communication, storage, sensing and metrological applications but nowadays mainly as parts of photonic integrated systems. They can be linear Fabry–Pérot or ring-type lasers, operating in narrow linewidth, single frequency or pulsed. Their numerous applications are ever increasing due to the unprecedented fabrication accuracy and reproducibility offered by photonic integration technology, allowing total control of the phase and intensity of the generated laser light. Many of these applications involve the nonlinear dynamics of the coupled photon inversion system in one way or another. We mention lasers for the generation of micro-waves or short mode-locked pulses and lasers for the generation of chaotic light in encrypted communication, as well as linewidth narrowing and frequency stabilization by external optical feedback and increased modulation bandwidth by optical injection.

In the well-defined embedded setting of integrated lasers, the issues of reproducibility and long-term dynamical stability are becoming ever more important and should be considered in the design and fabrication of such laser systems. Since precise control of quantities like optical distance, group velocity, wave-guide loss, gain and many other relevant parameters is very feasible, knowledge of the dynamical behaviour of semiconductor lasers in their dependence on parameter values can be successfully incorporated into the optimal design of these lasers and laser systems.

This Special Issue presents a collection of original state-of-the-art research articles dealing with the dynamics and stability of semiconductor lasers in a broad sense, sometimes with special emphasis on their operation in a photonic chip. Specifically, this issue comprises 18 papers dealing with semiconductor lasers coupled to various kinds of optical perturbations, such as delayed feedback, delayed coupling and optical injection, etc. Among these papers, seven are invited "feature" papers on the highly topical subjects of coupled lasers, reservoir computing, injection locking, external optical feedback and very narrow linewidth lasers. The feature papers are reviewed in Section 2 and the contributed papers in Section 3.

2. Feature Papers

A long-standing and central problem in semiconductor laser dynamics (SLD) is the influence of external delayed optical feedback [1]. This is the situation in which part of the output laser light is reflected from an external reflector and coupled back into the laser. The paper by A. Locquet [2] reviews various aspects of the routes to chaos that can occur under these circumstances. One important application of delayed optical feedback is found in reservoir computing [3], and the task-independent computational abilities are the subject of the paper by Harkhoe and Van der Sande [4]. The review paper by Boller et al. [5] presents an overview of their record-breaking results on linewidth narrowing in hybrid-integrated diode lasers with feedback from low-loss silicon nitride circuits.

Another equally important and often encountered problem in SLD concerns the semiconductor laser with optical injection, usually from another laser. The slave laser may exhibit a large variety of dynamical features; for example, frequency locking to the injected signal, micro-wave oscillations, chaos and excitability [6]. The invited paper by Torre and Masoller [7] explores the combined effects of excitability and the emission of extreme pulses with promising applications to sensing. A problem which is intimately related to laser injection is laser coupling, that is, where each laser injects light into the other at the same time. The feature article by Perrott et al. [8] compares the cases of true injection and pure mutual coupling between semiconductor diode lasers in one photonic integrated circuit. The observed additional types of dynamics in the case of mutual coupling are general features of coupled lasers, which are studied in the invited paper by Erneux and Lenstra [9]. In the latter article, the synchronization of mutually delay-coupled quantum-cascade lasers with different pump strengths is theoretically analyzed. In all the above-mentioned cases of coupled lasers, the coupling was typically face-to-face. A different type of coupling is treated in the feature paper of Vaughan et al. [10], in which the dynamical behavior of two laterally coupled semiconductor lasers is theoretically analyzed.

3. Contributed Papers

The contributed papers reflect the importance of optical injection and feedback as the generic fundamental processes in semiconductor laser systems. The paper by Sortiss et al. [11] describes the use of injection locking for side-mode suppression with the application to optical communication in general and optical demultiplexing in particular. Jiang et al. [12] numerically investigate the dynamical properties of excited-state emitting quantum-dot lasers with optical injection.

In the numerical study by Ebisawa and Komatsu [13], an ingenious combination of three diode lasers with optical injection and feedback is investigated in order to quantify the orbital instability of the produced chaotic dynamics in terms of Lyapunov exponents. Jayaprasath et al. [14] numerically investigate the properties of the chaotic output light that is produced by a semiconductor laser with delayed external optical feedback, with consequences for the security of chaotic communication. The security theme is also addressed in the numerical study by Wang et al. [15], who consider the risk of the bias current as a key for secure communication.

Using the technology described in the invited paper by Ref. [5], the generation of tunable microwave oscillations by optical sideband injection is described in a paper by Khan and Hoque [16]. Microwave generation is also the theme of the paper by Qi et al. [17], in which a monolithically integrated laser-photodetector chip was designed and fabricated.

An interesting problem is external feedback in a ring laser since the feedback light from a clockwise mode will couple into the counterclockwise mode. The optical-feedback sensitivity of such a laser is studied, experimentally and numerically, by Verschaffelt et al. [18] by applying on-chip filtered optical feedback. The article by Zhang et al. [19] presents the design and performance of a compact, highly stable, external-cavity diode laser for use in an optical clock in space.

Vertical-cavity surface-emitting lasers (VCSELs) are well-suited for high-speed data communication. In the paper by Sanayeh et al. [20], an equivalent circuit model is presented that accurately describes the dynamic behavior of high-performance VCSELs and applies this to a simulation of their intrinsic modulation response. The article by Wilkey et al. [21] addresses the fundamental problem of whether a pair of coupled semiconductor lasers could possess Parity-Time (PT) symmetry. Based on a rate-equation model, they predict intensity dynamics like those in a PT-symmetric system.

4. Outlook and Prospective Further Developments

The collection of papers in this Special Issue on semiconductor dynamics offers only a small window with a view on the present interests and developments. The field is very much alive and forms a fertile ground for innovative ideas, of which we have seen a few examples only. Promising novel developments are to be expected for applications in the sensing of PT-symmetric photonic systems with exceptional points of operation [22], in photonic neural networks [23] and excitable laser systems [24], in the metrology of super-stable mode-locked pulse lasers and frequency combs [25] and in the search for feedback-resistant lasers [26] and integrated non-reciprocal devices [27].

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