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Lina Jaurigue

Passively Mode-Locked Semiconductor Lasers

Dynamics and Stochastic Properties in the Presence of Optical Feedback

Doctoral Thesis accepted by
Technical University, Berlin, Germany

Springer
Supervisors’ Foreword

Nowadays, many innovations are related to advances in photonics and optical data communication. Also, in medicine, the implementation of optical technologies for microscopical data recording is emerging and devices are required that can be used as optical clocks. For many of these applications, regular optical pulse trains with short pulses and high repetition frequencies are needed. One way to produce this pulsating laser light is to use the technique of mode-locking. Here, a saturable absorber element is introduced to synchronize the longitudinal modes within the laser resonator. This phase synchronization leads to pulsations of the total emitted light output.

In this thesis, mode-locked semiconductor lasers with optical self-feedback are investigated. Those integrated multisection devices can be epitaxially grown on a chip; they are very small, relatively cheap, easy to fabricate and thus highly demanded by the industry. They can be operated by using electric contacts and emit regular pulse trains with repetition frequencies in the GHz regime and sub-ps pulse widths. To capture the dynamics of these devices, a complex modeling approach is required. It has to describe the internal gain dynamics as well as perturbation effects of reflected light while still allowing for reasonable computational times. Here, a delay differential equation approach for the evolution of the electric field within the device is used which balances between the more complex traveling wave approaches and simple rate equation models.

The focus of the thesis is on the analytic understanding of the different complex dynamics emerging within the mode-locked laser output. It resolves one major drawback of semiconductor-based devices: the relatively large timing jitter. Due to significant spontaneous emission, the pulses emitted by these integrated lasers show a large irregularity of the pulse positions, called timing jitter. Different ways to reduce the timing jitter are discussed, and analytic results with predictive power for other devices are presented. The first chapters give an overview on the dynamic regimes obtained by direct integration and path continuation. Strong attention is paid to multistability, which plays a crucial role for the timing jitter. Later, the focus is on the stochastic properties, and extensive simulations are compared to experimental data. The very good agreement proves the validity of the approach.
Moreover, a new theoretical method to efficiently calculate the timing jitter via a semi-analytic approach is developed. Using this method, the characterization of different devices can be done more efficiently than using the time-consuming process of averaging different noise realizations. This allows one to access experimentally relevant delay times within reasonable computational time. Finally, the thesis extends the analysis to a wide class of delay systems including basically all oscillating devices and derives a simple and easy-to-use equation to predict optimal operation conditions for regular pulse trains.

Various theoretical methods are used within the work, i.e., numeric integration of stochastic differential equations to characterize the dynamics, bifurcation analysis with path continuation to predict parameter regions for specific dynamic solutions, as well as semi-analytic calculations to derive analytic dependencies between the system parameters and the emission properties. The thesis presents new and relevant results that are outstanding in their breadth and depth. They are of great importance for the people working in photonics research as a guideline for optimizing existing devices as well as for the nonlinear dynamics community because the results also apply for oscillating systems with delay in general.

Berlin, Germany
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Eckehard Schöll
Kathy Lüdge
Passively mode-locked semiconductor lasers produce short optical pulses at very high repetition rates. In this thesis, we investigate the influence of time-delayed optical feedback on the dynamics and timing jitter of such a laser.

Using a delay differential equation model, we investigate the dynamics and bifurcations of a passively mode-locked laser. When the laser is operated in the fundamental mode-locking regime, it produces a pulsed output with a repetition rate which is determined by the length of the laser cavity. Adding optical feedback to the laser in this regime, the dynamics depend on resonances between the period and the feedback delay times. Feedback conditions can be selected to tune the repetition rate of the mode-locked pulse train, to induce harmonic mode-locking or to destabilize the periodic mode-locked dynamics, resulting in quasiperiodic or chaotic dynamics. Surrounding each resonantly chosen delay time there is a locking range in which fundamental mode-locking is exhibited. This locking region becomes wider as the delay times are increased, which can lead to a large degree of multistability between solutions locked to different resonances. With feedback from two external cavities, the same dynamics can be exhibited as with single cavity feedback, but the multistability of the fundamentally mode-locked solutions can be lifted if the two external cavities are of different lengths.

In the presence of noise, the regularity of the mode-locked dynamics is significantly reduced, since due to the absence of a restoring force the pulse positions can drift over time. By adding resonant optical feedback, correlations between temporal pulse positions are introduced, which can lead to a significant reduction in the timing jitter. We derive an expression for the timing jitter that shows that this reduction increases with the feedback delay time. However, for long feedback cavities noise-induced modulations of the dynamics also play a role, leading to fluctuations in the pulse positions on timescales of the feedback delay time.

The noise-induced modulations that arise for long feedback delay times can be suppressed by adding a second feedback cavity. We show that a linear stability analysis of the mode-locked laser system allows predictions to be made for the optimal feedback conditions for this effect. This is done by first studying the suppression of noise-induced modulations in a simple oscillatory system, the Stuart-Landau
oscillator, and relating the results for this system to the mode-locked laser system. For the Stuart-Landau oscillator, a simple characteristic equation, which provides the dominant Floquet exponents, can be analytically derived. By comparison with numerical results, we show that the dominant Floquet exponents of the mode-locked laser system can be described by a simple characteristic equation of the same form as that derived for the Stuart-Landau oscillator.

Using this characteristic equation, feedback delay times are found which effectively suppress the noise-induced modulations of the mode-locked pulse train. We show that this leads to a significant improvement in the regularity of the mode-locked laser output, as the suppression of noise-induced modulations reduces fluctuations in the pulse positions on timescales of the feedback delay times, as well as decreasing the variance of the temporal pulse positions on much longer timescales.
Parts of this work have been previously published in


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Contents

1 Introduction .............................................. 1
  1.1 Semiconductor Lasers ................................... 2
  1.2 Mode-Locking ........................................ 6
    1.2.1 Passive Mode-Locking .............................. 7
    1.2.2 Timing Jitter .................................. 8
  1.3 Time-Delayed Feedback ................................ 9
  1.4 Outline .......................................... 10
References ................................................ 10

2 Mode-Locked Laser Model. ................................. 15
  2.1 Introduction ......................................... 15
  2.2 Derivation of the DDE Model ............................ 16
    2.2.1 Dimensionless Formulation of the DDE System ....... 25
    2.2.2 Parameter Values ................................. 26
  2.3 Discussion of the DDE Model ............................ 27
References ................................................ 29

3 Mode-Locked Laser Dynamics ............................. 33
  3.1 Introduction ......................................... 33
    3.1.1 Bifurcations .................................... 33
  3.2 Solitary Mode-Locked Laser Dynamics .................... 37
    3.2.1 Lasing Threshold ................................ 38
    3.2.2 Continuous Wave Solutions ....................... 39
    3.2.3 Mode-Locked Solutions ........................... 42
  3.3 Dynamics Induced by Feedback from a Single
     External Cavity ..................................... 53
    3.3.1 Short Delay ..................................... 54
    3.3.2 Intermediate Delay ............................... 81
    3.3.3 Long Delay ..................................... 85
    3.3.4 Frequency Pulling and Delay-Induced Multistability . 89
6 Summary and Outlook .................................................. 187
Appendix A: Floquet Theory ........................................... 191
Appendix B: Linearised Mode-Locked Laser System ............. 193
Appendix C: Suppression of Noise-Induced Modulations .......... 195