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Benjamin Lingnau

Nonlinear and Nonequilibrium Dynamics of Quantum-Dot Optoelectronic Devices

Doctoral Thesis accepted by
the TU Berlin, Germany

Springer

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Supervisors' Foreword

Anticipating the rapidly increasing need for telecommunication and data-streaming applications within our society, a deeper understanding of the physical processes behind this emerging technology is crucial for further innovations. A central element here is the optical data transmission via fibers that needs to become more efficient regarding speed, bandwidth, and energy consumption. By concentrating on active optical elements like lasers and optical amplifiers, the work presented in this book explores new device concepts by exploiting nonlinear as well as nonequilibrium dynamics in nanostructured semiconductor devices. Thus, it focuses on the charge-carrier dynamics within very small epitaxial structures (quantum-dots) that can be included into standard quantum-well laser designs as the final step in miniaturizing the active zone, and herewith also in miniaturizing the energetic footprint of optical devices. The advantages of using nanostructured quantum-dot devices are twofold. At first, these semiconductor structures can be electrically driven and thus easily modulated as needed for input–output devices. Secondly, due to their confined energy states, quantum-dots have sharp energetic transitions similar to gas lasers which results in a smaller linewidth and better temperature stability. Nevertheless, the complex scattering processes involved in filling the optically active quantum-dot states are identified as sources for distinct dynamical behavior as discussed here. Also, the presence of charge-carrier nonequilibrium conditions during operation gives rise to new dynamics that first needs to be understood before it can find its way into novel applications.

Starting from complex kinetic equations, this thesis derives and presents comprehensive theoretical models, which allow for an accurate description of optically active quantum-dot devices. Comparisons with recent experimental observations validate the modeling approach and predict routes for optimization. The thesis further shows that most well-established models describing the dynamics of the electric field in semiconductor bulk and quantum-well lasers do not correctly model the dynamics of quantum-dot lasers, and it gives detailed suggestions on how to circumvent this problem. The low sensitivity of quantum-dot lasers to optical perturbations is directly attributed to their unique charge-carrier dynamics and amplitude-phase-coupling, which was so far ignored by the scientific community.

The potential of quantum-dot semiconductor optical amplifiers for novel applications such as simultaneous multi-state amplification, ultrawide wavelength conversion, and coherent pulse shaping is investigated. The scattering mechanisms and the unique electronic structure of semiconductor quantum-dots are found to make such devices prime candidates for the implementation of next-generation optoelectronic applications, which could significantly simplify optical telecommunication networks and open up novel high-speed data transmission schemes.

The methods used within this work range from numerical integration of stochastic partial differential equations, needed to understand pulse shaping effects in the optical amplifiers, to asymptotic perturbation analysis of effective rate equations to explore limits in parameter space. The thesis is outstanding in its breadth and depth and achieves a comprehensive introduction to the topic of laser modeling as well as a guide for optimization of nanostructured devices.

Berlin
June 2015

Kathy Lüdge
Eckehard Schöll

Abstract

In this thesis the dynamics and performance of optoelectronic devices based on semiconductor quantum-dots are investigated.

In the first part, the dynamics of quantum-dot lasers under external perturbations is discussed. Using a microscopically based balance equation model that incorporates detailed charge-carrier scattering dynamics and the possibility to describe nonequilibrium between intraband electronic states, the relaxation oscillations of the quantum-dot laser are investigated. Three qualitatively different dynamic regimes are identified in dependence of the scattering rates—the "constant-reservoir" regime for slow scattering, the "overdamped" regime, and the "synchronized" regime for high scattering—characterized by a varying degree of nonequilibrium between the quantum-dot and reservoir states.

Important differences to conventional lasers are found in the modulation response and the dynamics in optical injection and feedback setups. Common theoretical models and approaches used to describe these applications are shown to yield inaccurate predictions, especially in the "constant-reservoir" and "overdamped" dynamic regimes. An important consequence is that the amplitude-phase coupling in quantum-dot lasers, commonly described by the α-factor, differs from conventional descriptions due to the desynchronization of gain and refractive index. While the α-factor describes bifurcations of fixed points accurately, it fails in describing dynamic solutions and overestimates the extent of complex dynamics. The observed low sensitivity to optical perturbations in quantum-dot lasers can therefore be attributed partly to the charge-carrier nonequilibrium. Three quantum-dot laser models on different levels of sophistication are presented that can accurately describe the quantum-dot nonequilibrium dynamics.

In the second part of the thesis, the performance of quantum-dot semiconductor optical amplifiers is investigated, and two types of applications unique to quantum-dots as active medium are discussed. The ground and excited states of the quantum-dots allow an ultra-broadband amplification of optical data streams. Amplified signals on the ground-state frequencies are shown to generally exhibit higher quality than on the excited state, due to a lower sensitivity of the ground-state to carrier-density variations. Nevertheless, the quantum-dot amplifier is found to allow effective amplification on both frequency ranges. Furthermore, a parameter range is identified that allows for a simultaneous amplification of data signals on the ground and excited state in a counter-propagating setup.

The long microscopically polarization dephasing times in quantum-dots are found to enable quantum-coherent interactions on a macroscopic scale at room temperature. By comparison with experiments, the occurrence of Rabi oscillations by amplification of ultrashort pulses is demonstrated. Quantum-dot-based devices could therefore be used for future applications based on quantum-coherent effects.

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