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Benjamin Lingnau

Nonlinear and Nonequilibrium Dynamics of Quantum-Dot Optoelectronic Devices

Doctoral Thesis accepted by
the TU Berlin, Germany

 Springer

Author

Dr. Benjamin Lingnau
Institut für Theoretische Physik
Technische Universität Berlin
Berlin
Germany

Supervisor

Prof. Eckehard Schöll
Institut für Theoretische Physik
Technische Universität Berlin
Berlin
Germany

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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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Contents

1	Introduction	1
1.1	Light-Matter Interaction in Semiconductors	1
1.2	Semiconductor Lasers	4
1.3	Semiconductor Lasers as Dynamical Systems	6
1.4	Semiconductor Quantum-Dots	7
1.5	Outline of the Thesis	9
	References	10
2	Theory of Quantum-Dot Optical Devices	13
2.1	Introduction	13
2.2	Charge-Carrier Scattering in Quantum-Dot Structures	14
2.2.1	Coulomb-Scattering of Charge Carriers	16
2.2.2	Electron-Hole Picture	20
2.2.3	Detailed Balance	21
2.2.4	Carrier-Phonon Scattering	23
2.3	Light-Matter Interaction	25
2.3.1	Electric Field Dynamics	26
2.3.2	Maxwell–Bloch Equations	29
2.4	Quantum-Dot Laser Rate Equations	32
2.4.1	Maxwell–Bloch Laser Rate Equations	32
2.4.2	Adiabatically Eliminated Polarization	37
2.4.3	Modeling of Spontaneous Emission	39
2.4.4	Carrier-Induced Gain and Refractive Index Changes	41
2.5	Quantum-Dot Laser Carrier-Heating Model	43
2.5.1	Charge-Carrier Energy and Temperature	43
2.5.2	Carrier Heating by Auger-Scattering Processes	45
2.5.3	Energy Balance Equations	46
	References	47

3	Quantum-Dot Laser Dynamics	53
3.1	Introduction	53
3.2	Laser Dynamics—Relaxation Oscillations	54
3.2.1	Relaxation Oscillations in Two-Variable Laser Equations	55
3.2.2	Turn-On Dynamics of Quantum-Dot Lasers	58
3.2.3	Influence of Charge-Carrier Scattering	63
3.3	Minimal Model for Quantum-Dot Laser Dynamics	66
3.3.1	Linearization and Eigenvalue Problem	68
3.3.2	Asymptotic Analysis—Relaxation Oscillations	71
3.4	Modulation Response of Quantum-Dot Lasers	76
3.4.1	Small-Signal Response	76
3.5	Amplitude-Phase Coupling in Quantum-Dot Lasers	82
3.5.1	The Linewidth-Enhancement Factor α	83
3.5.2	Charge-Carrier-Induced Susceptibility in Quantum-Dot Lasers	84
3.6	Dynamics Under Optical Injection	89
3.6.1	Quantum-Dot Laser Model with Optical Injection	90
3.6.2	Injection Locking of Quantum-Dot Lasers	92
3.6.3	Dependence on the Quantum-Dot Structure and Pump-Current	97
3.6.4	Evaluation of the α -Factor from Optical Injection	101
3.6.5	Comparison with α -Factor-Based Models	104
3.7	Optical Injection—Numerical Path Continuation	111
3.7.1	Quantum-Dot Laser Model Simplification	112
3.7.2	Path Continuation Results	117
3.7.3	Dependencies on Scattering and Reservoir Loss Rates	120
3.7.4	Summary	122
3.8	Dynamics Under Optical Feedback	123
3.8.1	Quantum-Dot Laser Model with Optical Feedback	123
3.8.2	Quantum-Dot Laser Dynamics Under Optical Feedback	125
3.9	Small-Signal Frequency Response of Quantum-Dot Lasers	131
3.9.1	Evaluation of the Frequency and Amplitude Modulation Indices	131
3.9.2	Numerical Evaluation of FM/AM Measurements	132
3.9.3	Influence of Scattering Rates and Reservoir Losses	135
3.10	Conclusion	137
	References	139

- 4 Quantum-Dot Optical Amplifiers** 147
 - 4.1 Introduction 147
 - 4.2 Quantum-Dot Semiconductor Optical Amplifier Model 148
 - 4.2.1 Electric Field Propagation 149
 - 4.2.2 Quantum-Dot Material Equations 150
 - 4.2.3 Modeling of Spontaneous Emission 152
 - 4.3 Large-Signal Amplification in Quantum-Dot Amplifiers 154
 - 4.3.1 Calculation of Amplified Spontaneous Emission Spectra 155
 - 4.3.2 Gain Saturation 159
 - 4.3.3 Amplification of Optical Data Streams 161
 - 4.4 Multi-State Operation of Quantum-Dot Amplifiers 164
 - 4.5 Coherent Transients in Quantum-Dot Amplifiers 169
 - 4.5.1 Rabi-Oscillations in Quantum-Dot Semiconductor Amplifiers 171
 - 4.5.2 Comparison with Experimental Measurements 175
 - 4.6 Conclusion 180
 - References 182
- 5 Summary and Outlook** 187
- Appendix A** 191