NDSL 2023: Nonlinear Dynamics in Semiconductor Lasers 2023

Weierstrass Institute for Applied Analysis and Stochastics

Berlin, July 3-5, 2023

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This workshop is supported by:

Weierstraß-Institut für
Angewandte Analysis und Stochastik

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Berlin Mathematics Research Center
MATH+

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Contents

1 Scope

The aim of the workshop is to bring together applied mathematicians and scientists from photonics and semiconductor physics and to give them the opportunity to exchange experience in the field of nonlinear phenomena in optoelectronic devices.
The workshop will focus on, but not be limited to, all types of semiconductor lasers. See below for a list of topics.

- AM, FM and self mode-locking in lasers
- Bifurcation theory, analytical and numerical methods in optoelectronics
- Coupled laser systems
- Experimental aspects of optoelectronic and photonic device dynamics
- Frequency combs
- Lasers with delayed feedback
- Machine learning with photonic devices
- Model reduction using dynamical systems theory
- Nonlinear and stochastic dynamics in semiconductor lasers
- Narrow-linewidth lasers
- Noise in semiconductor lasers
- Numerical methods for simulation of semiconductor lasers
- Polarization dynamics in VCSELs
- Single-photon sources and quantum light emitting devices
- Spatial and temporal localized structures of light
- Superradiance
- Synchronization of laser arrays

2 General Information

Dear Participant,

Welcome to the Weierstrass Institute for Applied Analysis and Stochastic in Berlin. We wish you a pleasant stay at the Institute and in Berlin. For your convenience, you can find more information below:

Entrance to the building will be provided showing your participants badge. Please make sure to wear it anytime you want to enter the building.

Lectures are given in the Erhard-Schmidt lecture room on the ground floor.

Poster session will be on **Monday, July 3 from 5:45 pm**. We provide sandwiches and drinks.

Get-together will be in front of the Erhard Schmidt lecture room on the ground floor. We provide snacks and drinks.

Smoking in the building, also electronic cigarettes, is not allowed. As your coffee breaks take place on the ground floor, please use this opportunity to smoke outside of the building.

To use a **WiFi connection** with your own laptop kindly use the personal card that you received at the registration. Eduroam will of course work too.

Computer facilities are provided for your use in the graphics room on the ground floor to the right-hand side coming from the doorkeeper′s. Any workstation in this room may be used. For login please enter the following:

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For logout, you can use the logout-selection on the K-menu (left down corner). Please be aware that this account is used by all workshops participants. Therefore do not leave any confidential data in its home directory. All remaining files will be deleted after the workshop.

Lunch can be taken in a number of restaurants and snack bars near the institute, see the extra sheet “Places to have lunch".

Workshop dinner will be held in the restaurant Maximilians, Friedrichstr. 185-190, 10117 Berlin on

Thursday, July 4 at 6:00 pm.

Assistance will be given by anybody of the WIAS staff participating in the workshop (wearing blue badges).

Yours sincerely,

Organizers.

3 Program

Monday, 03.07.2023	
08:00 - 08:50	REGISTRATION
08:50 - 09:00	OPENING BY UWE BANDELOW
Machine learning, reservoir computing. Chair: Serhiy Yanchuk	
09:00	**Sergei Turitsyn (Birmingham)** Machine learning in photonic systems (see page 51)
09:25	**Kathy Lüdge (Ilmenau)** How to combine laser modulation-response and delay-induced bifurcations for optimizing reservoir computing (see page 31)
09:50	**Christopher Gies (Bremen)** Quantum reservoir computing with semiconductor-based quantum-photonic hardware (see page 16)
10:15	**Omar Kebiri (Cottbus)** Deep learning for solving initial path optimization of mean-field systems with memory (see page 24)
10:30 - 11:00	COFFEE BREAK
Frequency combs and mode-locking. Chair: Mustapha Tlidi	
11:00	**Dmitry Skryabin (Bath)** Real-field theory of modelocking (see page 45)
11:25	**Svetlana Gurevich (Münster)** Super mode-locking in passively mode-locked vertical external-cavity surface-emitting lasers: The role of dispersion (see page 20)
11:50	**Thomas Seidel (Münster)** Impact of time-delayed feedback on pulse interaction in mode-locked laser (see page 44)
12:05 - 14:00	LUNCH

Fano lasers and hybrid integration. Chair: Sergei K. Turitsyn	
14:00	**Kestutis Staliunas (Terrassa/Barcelona)** Fano Resonances at the Edge of a Continuum: Fundamentals and Applications in Microlasers (see page 47)
14:25	**Yu Yi (Kongens Lyngby)** Dynamics and quantum noise in Fano lasers (see page 55)
14:50	**Mariangela Gioannini (Turin)** CW emission with ultra-damped relaxation oscillations and formation of optical combs in III-V/Si external cavity hybrid lasers (see page 17)
15:15	**Lina Grineviciute (Vilnius)** Nanostructured coatings for anisotropy and Fano-like resonances: fabrication and applications for microlasers (see page 19)
15:30 - 16:00	COFFEE BREAK
Frequency combs + QCLs. Chair: Julien Javaloyes	
16:00	**Frederic Grillot (Palaiseau)** Nonlinear photonics of mid infrared interband quantum cascade lasers (see page 18)
16:25	**Benedikt Schwarz (Vienna)** Solitons in quantum cascade laser based Kerr combs (see page 41)
16:50	**Aleksandr Razumov (Kogens Lyngby)** Phase noise source separation for frequency combs (see page 38)
17:15	**Georgia Himona (Athens)** Time crystals, phase response and complex synchronization dynamics of externally modulated optically injected semiconductor lasers (see page 21)
17:45 - 20:00	POSTER

Tuesday, 04.07.2023	
Towards quantum technologies. Chair: Christopher Gies	
09:00	**Stephan Reitzenstein (Berlin)** Development and deterministic nanofabrication of single quantum dot devices for applications in photonic quantum technologies (see page 39)
09:25	**Dmitri Boiko (Neuchâtel)** Two faces of superradiance in tandem-cavity ridge waveguide heterostructures (see page 13)
09:50	**Christian Nölleke (Gräfelfing)** Highly coherent diode lasers for quantum technologies (see page 37)
10:15	**Lutz Mertensktter (Berlin)** Bayesian estimation of laser linewidth from delayed self-heterodyne measurements (see page 36)
10:30 - 11:00	Coffee Break
Data-Transmission, VCSELs Chair: Thorsten Ackemann	
11:00	**Richard Schatz (Stockholm)** Modal stability and noise of cavity enhanced DMLs (see page 40)
11:25	**Markus Lindemann (Bochum)** Spin-VCSELs for ultrafast and low power optical data transmission (see page 30)
11:50	**Kamel Merghem (Palaiseau)** Self-injected mode locked lasers for frequency comb generation and application to multi-Terabit/s data transmission (see page 35)
12:15	**Kristian Seegert (Kogens Lyngby)** Complex dynamics of lasers with passive dispersive reflectors (see page 43)
12:30 - 14:00	Lunch

Many-Body Effects	
14:00	**Angela Thränhardt (Chemnitz)** Many body effects in semiconductor laser dynamics (see page 49)
14:25	**Martin Virte (Brussel)** Dynamics of multi-wavelength lasers for wavelength conversion (see page 52)
14:50	**Thorsten Ackemann (Glasgow)** Photon thermalization in broad-area vertical-cavity surface-emitting lasers (see page 10)
15:15	**Eduard Kuhn (Berlin)** Simulation of the mode dynamics in broad-ridge (Al,In)GaN laser diodes (see page 28)
15:30 - 16:00	COFFEE BREAK
Patterns and solitons	
16:00	**Marcel Clerc (Santiago de Chile)** Turbulent labyrinthine patterns in optical valve with feedback: Theory and experiment (see page 14)
16:25	**Mustapha Tlidi (Brussels)** Light-bullets in three-dimensional Kerr resonators (see page 50)
16:50	**Majid Taki (Villeneuve d'Ascq)** Transverse drift of Faraday patterns under inhomogeneous external driving (see page 48)
17:15	**Ihar Babushkin (Hannover)** Trapping photons inside a soliton (see page 11)
18:00 - 20:00	DINNER

Wednesday, 05.07.2023	
Nonlinear Dynamics	
09:00	**Serhiy Yanchuk (Potsdam)** Canard cascading in lasers with slow-fast coupling (see page 54)
09:25	**Deb Kane (Canberra)** Which laser parameters are the top influencers in chaotic SL-based systems? (see page 23)
09:50	**Mathias Marconi (Nice)** Direct measurement of critical slowing down in a low-dissipation optical system at a tipping point (see page 34)
10:15	**Elias Koch (Münster)** Dynamics and bifurcation analysis of active mode-locked semiconductor lasers (see page 25)
10:30 - 11:00	Coffee Break
Mode-Locking. Chair: Svetlana Gurevich	
11:00	**Julien Javaloyes (Palma)** Coherence and multiplicity of frequency combs in Harmonic mode-locked lasers (see page 22)
11:25	**Tushar Malica (Metz)** Passive modelocking using VCSELs and without SESAMs: A theoretical approach (see page 32)
11:50	**Shulin Wohlfeil (Berlin)** Picosecond pulses with 40 W peak power from a mode-locked tapered laser diode emitting at 830 nm (see page 53)
12:15 - 12:30	Closing

4 Abstracts

Photon thermalization in broad-area vertical-cavity surface-emitting lasers

Ackemann, Thorsten
University of Strathclyde, UK

Co-authors: S. Eisendorfer, J. Fletcher

The intriguing concept of photon condensation was originally proposed and demonstrated in microcavities filled with dyes [1] but more recent work yielded evidence for the same phenomenon in semiconductor microcavities [2]. We are investigating electrically pumped broad-area vertical-cavity surface-emitting lasers (VCSELs) very similar to the one investigated in [2] and vary injection current and ambient temperature. Ref. [2] reported a lower than expected fitted temperature for a moderate injection current (256 K for a substrate hold at 293 K) but did not provide a systematic investigation of the photon temperatures. We find consistently an exponential decay of the strength of the photoluminescence vs modal energy confirming thermalization of modes. For low injection currents the fits to the Boltzmann tail yields temperatures close to or slightly above room temperature as expected. However, for increasing injection currents the fitted temperatures drop significantly with increasing current and reach values below 200 K at the highest currents accessible. The scaling region becomes smaller and is confined to high energy modes. This indicates some non-equilibrium dynamics which is currently not understood.

References

1 J. Klaers et al., Nature 468, 545 (2010)
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Trapping photons inside a soliton

Babushkin, Ihar
Leibniz Universität Hannover, Germany

A soliton, propagating in a waveguide or in a laser cavity, modifies the refractive index, creating thereby a potential well for a weaker probe light. This well can, under certain conditions, trap light. Such trapping can be better described as “trapping in time”, rather than “trapping in space”. It is rather unusual, demonstrating, among others, nonreciprocical coupling of the trapped state to the outer world. The trapping provides a novel tool to control weak light, even single photons, including zero-noise frequency conversion, waveshape shaping and others, and even universal quantum gates.

Stable periodic solutions in fractional dissipative systems with non-Hermitian modulation

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Universitat Politecnica Catalunya, Spain

In this study, we explore new periodic solutions in non-linear dissipative systems, focusing on the Complex Ginzburg Landau Equation (GCLE), its fractional counterpart, and Class B lasers. We demonstrate how the addition of a non-Hermitian potential can effectively stabilize these solutions across a wide range of parameters. Turbulence and instability in such systems is a complex problem, with significant practical implications, including limitations on laser output power. Our approach involves stabilizing these specific stationary solutions by introducing a complex spatial modulation, corresponding to a harmonic modulation of the gain and refractive index of the system for the optical case. Our results demonstrate that this stabilizing effect holds across different parameters, even for small modulation amplitudes of up to 5% We also demonstrate that this approach is effective in Ginzburg-like models for physical systems, including Class B lasers, where it can stabilize highly unstable parameter ranges and create a large attractor basin. Our findings provide valuable insights into the dynamics of non-linear dissipative systems and have practical implications for controlling turbulence and improving laser performance.

Two faces of superradiance in tandem-cavity ridge waveguide heterostructures

Boiko, Dmitri
Centre Suisse d'Electronique et de Microtechnique, Switzerland

Cooperative emission due to spontaneous build-up and rapid decay of macroscopic polarization dipole in a strongly inverted gain medium is drastically different from the lasing dynamics. Suddenly, the medium polarization and not the cavity field begins to drive the system in the Maxwell–Bloch picture. Yet as pioneered by Dicke, the decay of the highest-energy state in a quantum ensemble of two-level systems proceeds through a ladder of the highest-symmetry partially deexcited states, each of which is formalistically an entangled state in mathematical sense. In this talk, on example of multi-section tandem cavity laser heterostructures I will attempt to address two important questions from both theoretical and experimental view-points: (i) How can the superradiance be reached in semiconductor quantum wells albeit the ultrafast dephasing of individual microscopic e-h dipoles? (ii) Could the ensemble non-classicality be transferred to the emitted optical field and what could be the photon state?

Turbulent labyrinthine patterns in optical valve with feedback: Theory and experiment

Clerc, Marcel
Universidad de Chile, Chile

Systems with energy injection and dissipation self-organize by forming stationary two-dimensional patterns at the onset of spatial instabilities. Increasing the imbalance between injection and dissipation of energy causes disordered patterns with complex spatiotemporal behaviors to form. In a liquid crystal light-valve with optical feedback, we examine the turbulent dynamics of labyrinthine patterns experimentally and theoretically. By determining the phase and amplitude of the complex patterns, we show that the system exhibits phase and defects turbulence characterized by power spectrum exponents 2 and 3, respectively. Additionally, we reveal an exponent 2 in the power spectrum of the orientational field associated to the labyrinthine patterns. The structure functions associated with light intensity allow us to establish that the observed dynamical behaviors are also of intermittent nature. We determine experimentally the largest Lyapunov exponent, which shows the chaotic character of the dynamics. Further, to theoretically capture the experimental observations, we provide a phenomenological model.

Neutral delay differential equation for modeling a Kerr cavity dynamics

Dolinina, Daria
WIAS Berlin, Germany

The generation of optical frequency combs using nonlinear microresonator devices is currently a hot topic that is attracting a significant amount of research. One of the most commonly used methods to model Kerr optical cavities is based on the application of the Lugiato-Lefever equation (LLE), which is known to exhibit bistability of continuous wave (CW) solutions as well as dissipative solitons preserving their shape in the course of propagation along the cavity and sitting on a homogeneous background. However, LLE assuming the mean-field approximation when intracavity power is relatively low describes a bistable behavior and soliton formation only in the vicinity of a single cavity resonance. To overcome this limitation of the LLE model the Ikeda map approaches and generalized LLE with localized injection and losses were proposed in the literature. Here we develop an alternative approach to model nonlinear dynamics of an injected Kerr cavity based on a neutral delay differential equation (NDDE). We show that in a certain limit the NDDE model can be reduced to the LLE model. We perform the linear stability analysis of the NDDE model in the practically important large delay limit and present numerical evidence of the existence of stationary and oscillating dissipative optical solitons in it both within and beyond the LLE limit.

Quantum reservoir computing with semiconductor-based quantum-photonic hardware

Gies, Christopher
Universität Bremen, Germany

Semiconductor-based nanolasers have been thoroughly researched over the past decades. From an application perspective, they are not only a promising platform for green photonics, but they may also be an enabling technology for noisy intermediate scale quantum (NISQ) hardware. While fully-fledged quantum computing requires near-error free qubit- and gate operations, alternative approaches are being developed for the NISQ-era that deserve attention. Quantum reservoir computing (QRC) is such a paradigm: It relies on the complex dynamics that can be found in open quantum systems and aims at exploiting the exponentially large internal degrees of freedom. In my talk, I will explain the interest in this novel field that combines machine learning, quantum mechanics, and complex systems theory. I will introduce measures for quantifying performance and quantum advantage, as well as discussing possible implementations. Interconnected nanolasers forming a quantum-photonic artificial neural network may turn out as a suitable platform to realize such a quantum-machine learning devices in the foreseeable future.

CW emission with ultra-damped relaxation oscillations and formation of optical combs in III-V/Si external cavity hybrid lasers

Gioannini, Mariangela
Politecnico di Torino, Italy

In recent years, laser sources based on hybrid integration of RSOA and silicon photonic mirrors have been attracting surging interest for their compatibility with silicon photonic platforms making them the key components for applications in optical communication and sensing. These hybrid external cavity lasers have been studied for their very narrow linewidth and wide tunability. In this contribution we present the results of our theoretical and numerical investigations focusing on other relevant characteristics of these lasers. Thanks to the flexibility in the design of the silicon photonics mirror, we can get very narrow band reflectors with bandwidth of a few GHz. We demonstrate that this can bring to ultra-dumped relaxation oscillation, very high tolerance to the external optical feedback and in some cases to generation of optical frequency combs.

Nonlinear photonics of mid infrared interband quantum cascade lasers

Grillot, Frederic
Institut Polytechnique de Paris, France

Interband cascade lasers (ICLs) constitutes a new class of semiconductor lasers allowing lasing emission in the 3-10 micrometer wavelength region. Their structure presents similarities and differences with respect to both standard bipolar semiconductor lasers and quantum cascade lasers (QCLs). In contrast to QCLs, the stimulated emission of ICLs relies on the interband transition of type-II quantum wells while the carrier to photon lifetime ratio is similar to conventional bipolar lasers. Therefore, ICLs can be classified into Class-B laser systems like common quantum well lasers, and hence are more prone for generating complex dynamic like fully-developed chaos. Moreover, ICLs take advantage of a cascading mechanism over repeated active regions, which allows us to boost the quantum efficiency and, thus, the emitted optical power. Consequently, the power consumption of ICLs is one or two orders of magnitude lower than their QCL counterparts whereas high-power of few hundreds of milliWatts can be achieved. Here, we report some recent results on dynamic and nonlinear properties of ICLs. In particular, we demonstrate the generation of fully-developed chaos of ICLs with a perturbation of external optical feedback. We show that ICLs exhibit some peculiar intensity noise features with a clear relaxation oscillation frequency. Together, these properties are of paramount importance for developing long-reach secure free-space communications, random bite generator, and remote chaotic Lidar systems. Lastly, we predict that ICLs are preferable devices for the amplitude-noise squeezing because large amplitude noise reduction is attainable through inherent high quantum efficiency and short photon and electron lifetimes.

Nanostructured coatings for anisotropy and Fano-like resonances: fabrication and applications for microlasers

Grineviciute, Lina
Center for Physical Sciences and Technology, Lithuania

During the presentation, the evolution of optical coatings from one-dimensional to tree-dimensional periodic structures will be presented. The focus will be on two topics: i) anisotropic coatings for polarization control [1,2] and ii) the possibility to form the dielectric structures with periodic modulation of optical constants together with the application of angular filtering of light [3,4]. We propose and demonstrate a conceptually novel mechanism of spatial filtering in the near-field domain, by a nanostructured multilayer coating - a 2D photonic crystal structure with a periodic index modulation along the longitudinal and transverse directions to the beam propagation. The structure is built on a nano-modulated substrate (grating), which provides the transverse periodicity. The physical vapor deposition of materials with different refractive indexes is used for the self-repeating modulation in the longitudinal direction. We experimentally demonstrate a // 5 micrometer thick photonic multilayer structure composed of nanostructured layers of alternating high- and low-index materials (Nb_2O_5 and HfO_2, respectively) providing angular selectivity in the near-infrared frequencies with 2 degree low angle passband. The proposed 2D photonic structure can be considered as a promising component for intracavity spatial filtering even in high power microlasers systems. Moreover, the possibility to form all-silica waveplates and polarizers for 0 angle of incidence will be presented.

References

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2 L. Grineviciute, et. al. “Highly resistant all-silica polarizing coatings for normal incidence applicationsÖptics letters, Vol. 46, No. 4, 2021

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4 L. Grineviciute, et. al.,“Fano-like Resonances in Nanostructured Thin Films for Spatial Filtering", Applied Physics Letters 118, 131114, 2021

Super mode-locking in passively mode-locked vertical external-cavity surface-emitting lasers: The role of dispersion Gurevich, Svetlana

Universität Münster, Germany

We analyze the dynamics of passive mode-locking in Vertical External-Cavity Surface-Emitting Lasers using a first-principles dynamical model based on delay algebraic equations that intrinsically contain the group velocity dispersion incurred by the micro-cavities. We show that apart from the conventional fundamental mode-locked state, another mode-locked solution with higher amplitude exists that we termed as “super mode-locking”. We show that this regime exists for a specific detuning between the gain and the saturable absorber micro-cavities. Using a combination of multi-scale analysis, path-continuation and direct numerical simulations, we disclose the mechanisms responsible for the emergence and stability of the super mode-locked state. In particular, we find that due to the relative detuning between the maximum of gain and the peak of absorption, our theoretical approach reproduces naturally the presence of either positive or a negative second order group velocity dispersion. This result allows us to explain why super mode-locking appears only for the anomalous second order dispersion regime. Further, we derive a normal form partial differential equation close to the onset of lasing using a multiple time scale analysis. We show that our model differs in several aspects with the generic Haus master equation and that it shows a good agreement with direct numerical simulations of the original delay algebraic model.

Time crystals, phase response and complex synchronization dynamics of externally modulated optically injected semiconductor lasers

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National Technical University of Athens, Greece

Optically Injected Semiconductor Lasers (OISLs) are well-known for their ability to produce robust self-sustained oscillations (limit cycles) with multi-harmonic spectral content as well as a rich set of complex dynamical features making them suitable for use in a variety of cutting-edge applications. The timing properties of limit cycles can be captured by the concepts of isochrons, phase response and time crystal, originally introduced in the context of mathematical biology. By using these notions, an efficient reduction of the original system can be achieved, and the effect of periodic external stimulations can be studied through the resulting one-dimensional circle map. The effect of periodic stimulations in the form of a time (and frequency) comb, corresponding to either Dirac delta impulses or finite-time pulse stimulations, on both the current of the slave laser and the amplitude of the injected wave field is investigated. The overall phase response of the system under these modulations can be described by the associated time crystal, whose form dictated by the isochrons structure suggests a parametric modification of the input frequency comb to achieve desirable output ranging from continuous to discrete frequency spectra. Thus, conditions for resonant synchronization resulting in desirable outputs of the original nonlinear system of ordinary differential equations can be accurately obtained towards potential practical applications related to nonlinear filtering effects and photonic signal-processing units.

Coherence and multiplicity of frequency combs in Harmonic mode-locked lasers

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In this contribution we want to answer a seemingly obvious question: Are the pulses in a harmonic mode-locked state coherent with each other? Similarly, one may ask if the HML solution is unique. The answer to these questions is actually far from trivial if one considers a unidirectional ring laser or a Vertical External-Cavity Surface-Emitting Laser. In these configurations, the pulses never cross each other within the active material: How could they then exchange information regarding their relative phase?
We base our analysis upon the well accepted Haus master equation [1,2,3] as well as the Vladimirov and Turaev model [4] and we demonstrate that, due to residual interaction between the pulses′tails, a phase information may be transferred between the nearest neighbor. However, this extremely weak interaction must be sufficiently large to compensate for the spontaneous emission noise that randomizes the phases. We introduce an order parameter as a measure of the degree of coherence in the HML configuration and we predict the existence of a continuous transition from perfect coherence to total incoherence. In addition, we demonstrate that a HML solution may exist in N different states which, in the frequency spectrum, correspond to shifted frequency combs. We predict multistability between N/2 of these states and that the system may randomly explore. This has a profound implication on the notion of coherence that is a time averaged quantity.

References

1 H. A. Haus, IEEE J. Sel. Top. Quantum Electron. 6, 1173 (2000).
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Which laser parameters are the top influencers in chaotic SL-based systems?

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The semiconductor laser with delayed optical feedback continues to be a workhorse for fundamental studies in nonlinear semiconductor laser dynamics. Numerical simulations of this system using a travelling wave model ([1, 2] and references there-in) provide new insights into the impact of key device parameters affecting the chaos bandwidth and spectrum. These suggest that up to a five-fold increase in spectral spread of the chaos, over that demonstrated experimentally to date, might be achievable if semiconductor lasers designed to optimise the chaotic output are fabricated and used. Additionally, connections with prior experimental results are made [3, 4]. An improved fundamental understanding of the chaotic output from this system is achieved.

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Deep learning for solving initial path optimization of mean-field systems with memory

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We consider the problem of finding the optimal initial investment strategy for a system modelled by a linear McKean–Vlasov (mean-field) stochastic differential equation with delay, driven by a Brownian motion and a pure jump Poisson random measure. The problem is to find the optimal initial values for the system in the period $[\delta, 0]$, where $\delta > 0$ is a delay constant, before the system starts at t $=$ 0. Because of the delay in the dynamics, the system will after startup be influenced by these initial investment values. It is known that linear stochastic delay differential equations are equivalent to stochastic Volterra integral equations. By using this equivalence we can find implicit expression for the optimal investment. Moreover, we propose a deep neural network-based algorithm to solve stochastic control problem with delay. Specifically, we employ multi-layer feed- forward neural network for control modeling in the interval $[\delta, 0]$), and the backpropagation for training the feedforward neural network,where we com- pute the gradient of the loss function using stochastic gradient descent (SGD) with respect to the weights of the network. This method can also apply for delay differential equations for mode-locked semiconductor lasers.
Joint work with B. Oksendal, N. Agram and M. Grid

Dynamics and bifurcation analysis of active mode-locked semiconductor lasers

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Universität Münster, Germany

Active mode-locking (AML) consists in generating pulses via direct modulation of the gain. It allows to directly modify the pulse shape and its repetition rate by changing the parameters of the modulation [1]. Most analysis of AML dynmaics have been based upon the Haus master equation, which accomodate for the regimes of small gain and losses per round-trip [2]. In this work we propose the use of the delay-differential equation model [3] with active modulation of the cavity losses. We perform a bifurcation analysis with parameters typical of semiconductor lasers in which the round-trip gain is not small. In particular, we found out that the solution branches corresponding to higher order Hermite-Gauss modes in a modulated potential can interact leading to a complex scenario. Furthermore, by performing a multiple time-scale analysis close to the lasing threshold, we derive a normal form which shows a good qualitative agreement with the original time-delayed model. Finally, we discuss the limit of slow gain that would correspond to an Erbium-Doped Fiber Amplifier (EDFA) regime.

References

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Ultra-low frequency noise laser-systems based on laser-diodes

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Narrow-linewidth continuous-wave lasers are essential in many quantum applications which exploit ultra-cold atoms. Special tasks like optical trapping or coherent qubit manipulation have high requirements on the laser frequency noise (FN). External-cavity diode lasers (ECDL) are the tool of choice due to their versatility and robustness: A wide range of atomic transitions in the visible and infrared frequency ranges can be addressed. On the other hand, ECDLs typically process a high level of FN due to relatively short cavity length. To push the performance of quantum experiments even further it is important to develop efficient methods of FN reduction for ECDLs. We implement an ultra-low noise laser (ULNL) by applying optical feedback from a fiber-cavity to a grating-based ECDL. The additional fiber-cavity consists of a 1.5 m PM-fiber patchcord. A mirror reflects the light back to the laser-diode. This mirror is placed on a piezo-electric actuator to control the length of the cavity. This technique results in a reduction of FN at high frequencies in the MHz range around the carrier. In this work we experimentally investigate the characteristics of ULNL with different types of laser-diodes (LD) in detail. We focus on two types of LDs: A Fabry-Pérot (FP) LD and an anti-reflection coated (AR) LD. The difference between an FP LD and an AR LD is the reflectivity of the front facet, which affects the modal structure of the laser resonator. Our analysis is in agreement with a theoretical model for ECDL linewidth narrowing. A reduction of facet reflectivities results in increasing the long-term stability of single longitudinal mode operation. This makes the system more robust against environmental fluctuations: They are leading to phase drifts causing lasing on several longitudinal modes or a mode hope.

Raman-induced isolas of localized structures in Kerr microstructured resonators

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In the regime of traveling wave instability, the combined effect of Kerr and stimulated Raman scattering on the formation of localized structures has been shown to induce both the formation of isolas of bright and dark localized structures and a motion of these structures. This phenomenon is first described through a real-order parameter derivation leading a Swift–Hohenberg with nonlocal delayed feedback. This allows to characterize the motion of the traveling wave periodic solutions by estimating their thresholds and speeds. Then, a numerical continuation method allows to construct the bifurcation diagram showing the emergence of these traveling wave period solutions, as well as bright and dark moving localized structures in the form of isola branches. Numerical simulations of the generalized Lugiato-Lefever equation confirm these findings.

Simulation of the mode dynamics in broad-ridge (Al,In)GaN laser diodes

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Broad-ridge laser diodes exhibit rich lateral mode dynamics in addition to longitudinal mode dynamics observed in narrow-ridge laser diodes. To simulate mode dynamics in these diodes, an effective mode interaction term is derived from the bandstructure and carrier scattering in the quantum well. The spatial dependency of pump current densities plays a crucial role in lateral mode dynamics, and thus, a Drift-Diffusion model is employed to calculate the current densities with an additional capturing term.

Formation of disordered patterns by photoisomerization in liquid crystals

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Pattern formation can be observed in various out-of-equilibrium systems in nature. These physical systems, which are in thermodynamic equilibrium, can be characterized by homogeneous equilibria that are invariant in spatial and temporal translation. Processes out of equilibrium often lead to the formation of dissipative structures. Previously, for low powers, the formation of stable concentric patterns has been observed . However, when passing a critical power, these patterns become unstable and generate disordered modulations. The purpose of this work is to describe the structures formed in this process.

Spin-VCSELs for ultrafast and low power optical data transmission

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Fast intensity modulated diode lasers reach their fundamental limits for the modulation bandwidth in the regime below 50 GHz and thus represent a major contribution to the bandwidth bottleneck in optical data centers. Spin-controlled vertical-cavity surface-emitting lasers (Spin-VCSELs), in contrast, have been shown to enable modulation bandwidths exceeding 200 GHz because they operate with a different physical mechanism, based on the interplay of spin polarized electrons and the polarization of the light field in specifically anisotropic VCSEL cavities. Theoretical studies on the basis of a modified spin-flip model have shown that polarization modulation frequencies far above 200 GHz are feasible. So far, no physical limits have been identified, yet, that generally inhibit modulation frequencies approaching the THz range. Furthermore, the extremely high modulation bandwidth can be achieved even close to threshold in contrast to conventional intensity modulation where highest bandwidth is obtained far above threshold. Thus, spin-VCSELs are potentially much more energy efficient than intensity modulated lasers. We discuss the principle and the potential of spin-VCSELs for ultrafast modulation and develop a device architecture for room-temperature electrically pumped spin-VCSELs.

How to combine laser modulation-response and delay-induced bifurcations for optimizing reservoir computing

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The field of reservoir computing is a fast developing subfield of machine learning and various systems are explored with respect to their potential for fast and energy efficient computations. Optical reservoir computing systems, e.g. coupled semiconductor lasers, are promising, as data injection and analysis can be realized on chip in the optical domain. Nevertheless, the internal timescales of the system and the control induced bifurcation structure play a crucial role for the performance on a specific task and can be detrimental for applications. In this presentation, we investigate the impact of the different timescales via evaluating the modulation response for the laser system. Further, we discuss the role of external input and output delay lines for mitigating the task specific hyperparameter optimization usually necessary in reservoir computing systems.

Passive modelocking using VCSELs and without SESAMs: A theoretical approach

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A time-delay-differential equation theoretical model will be presented as a paradigm for multi-sectional and free-space elements with flexible cavity configuration used to analyze the dynamics of mutually-coupled Vertical-cavity surface-emitting lasers (VCSELs). Herein, two single-longitudinal mode VCSELs placed facing each other and optimized for fundamental mode-locking (FML) over a wide range of parameters are simulated. The biased VCSEL chip is made to act as the gain, while the second VCSEL chip is unbiased and hence functions as an absorber. This setup is shown as a promising alternative to the popularly used conventional SESAM mode-locked VECSEL to produce mode-locked pulses. The rate-equation model calculates the carrier density and electric fields using the 4th-order Runge-Kutta method. Parameter space for the work is defined by laser facet reflectivities and bias current and used to show general trends in the exhibited nonlinear dynamics and pulsed solutions. The presented model is argued to be a more global and inclusive model than the current alternatives, which accurately, but in isolation, either solve for nonlinear dynamics for FML regime.

Mode distribution in VCSELs with non-cylindrical symmetry

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Recently, there has been a growing interest in Vertical Cavity Surface Emitting Lasers (VCSELs) due to their increasing use in data transmission, face recognition systems, and LIDAR systems in smartphones. This research focuses specifically on VCSELs with non-cylindrical symmetry apertures and mesas. We performed an analysis of the modes in arsenide 980 nm VCSELs designed for telecommunication applications with non-cylindrical mesas. This is a state-of-the-art VCSEL structure with an active region consisting of 5 InGaAs quantum wells sandwiched between 6 GaAsP barriers placed in a cavity of 0.5-lambda optical length. We utilized semiconductor GaAs/AlGaAs DBR mirrors (37 bottom pairs and 21.5 top pairs) and an oxide aperture for current and optical confinement. Our investigation focused on mode near field distribution variation induced by current in time domain. To investigate the time dependence of the mode distribution, we used Temporally Resolved Imaging by Differential Analysis (TRIDA), a method described in A. Bachraski et al, JQE 39.7, 2003. The method enables observation the mode distribution variations in nanosecond timescale. In our experiment we investigate the time evolution of two orthogonal polarizations. The aim of this poster is to present the mode distributions obtained for VCSELs with different non-cylindrical oxide apertures. Our results bring new perspective for the mode dynamics in VCSELs and contribute to new degree of freedom in designing multi-bit data transmission systems and neuromorphic networks.

Acknowledgment: This work is supported by the Polish National Agency for Academic Exchange within the program Bekker NAWA (BPN/BEK/2021/1/00308/DEC/1). M. Marciniak would also like to acknowledge the support of the Polish National Center of Science within the project Preludium (2018/29/N/ST7/02460).

Direct measurement of critical slowing down in a low-dissipation optical system at a tipping point

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The dynamics of complex systems can exhibit abrupt changes also known as tipping points. These tipping points can lead to catastrophic events and crisis at different scales, that we are currently facing in the context of global climate change for instance. Reliable indicators of the incoming tipping points are therefore needed in order to predict, anticipate and potentially avoid their dramatic consequences. An observable phenomenon occurring close to a bifurcation is known as the critical slowing down (CSD), which corresponds to a divergence of the relaxation time of the system as we approach asymptotically the bifurcation point. However, even if CSD is a well-known phenomenon in dynamical systems, its direct experimental measurement is a challenging task. The observation and analysis of CSD in complex physical systems hashave therefore remained elusive. In this work, we implement an experimental laser platform that allows to provide a direct measurement of the CSD via the application of a perturbation in the variables of the system. We assess for the first time the qualitative change in the CSD when an experimental parameter is swept and when the duration of the perturbation is varied.

Self-injected mode locked lasers for frequency comb generation and application to multi-Terabit/s data transmission

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The enormous growth of internet data traffic imposes new challenges for data centers and metro/access networks requiring the development of new advanced photonics components. Optical frequency combs have emerged as a promising approach towards compact and efficient light sources that provide a multitude of tones for parallel WDM transmission. In this talk, we start by introducing the concept of optical frequency combs and their wide variety of applications. To generate optical frequency combs, monolithic semiconductor passively mode-locked lasers are very attractive components. We will focus our talk on semiconductor based mode-locked lasers, especially quantum dot and quantum-dash based lasers with unique characteristics, such as broad gain bandwidth, low threshold current and enhanced temperature stability. To achieve the desired features for coherent communication systems, we have developed different stabilization schemes to improve both coherence and phase correlation between optical comb lines. We will conclude by demonstrating WDM coherent transmission with net data rates exceeding terabit/s transmission rates thanks to the implementation of resonant optical feedback based stabilization system.

Bayesian estimation of laser linewidth from delayed self-heterodyne measurements

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Self-heterodyne beat note measurements are widely used for the experimental characterisation of the frequency noise power spectral density (FN–PSD) and the spectral linewidth of lasers. The measured data, however, must be corrected for the transfer function of the experimental setup. The standard approach disregards the detector noise and thereby induces reconstruction artefacts in the reconstructed FN–PSD. We present a Bayesian estimation approach, that takes into account the transfer function, as well as the detector noise in a statistical model for the measured PSDs. This model produces the correct distributions of the the PSD at all frequencies and only needs a model for its mean to be parameterised. Our method yields excellent results even in the presence of strong detector noise, where the intrinsic linewidth plateau is obscured by detector noise. The approach is demonstrated for simulated time series from a stochastic laser model including $1/\tau_f$-type noise. Finally we use parametric Wiener filters to generate artefact free reconstructions of the PSDs using the estimated parameters.

Highly coherent diode lasers for quantum technologies

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Quantum technologies exploit the unique features of the atomic world for novel kinds of sensors and ways to process information. Current research and industry activities focus on the transformation of laboratory demonstrators into real-world devices with practical applications. Single-frequency diode lasers with high coherence and stability are key components for matter-based quantum systems, as they enable their precise control. This presentation will discuss current technological challenges and the next generation of diode lasers that will enable the shift of quantum technologies towards real-world applications.

Phase noise source separation for frequency combs

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An understanding of how internal and external phase noise sources affect spectral comb lines is critical for applications involving optical frequency combs. In many practical situations, we may not have an accurate understanding, and a model for, how, and how many, independent phase noise sources contribute to the overall phase noise of each comb line. We propose a measurement method based on subspace tracking, in combination with multi-heterodyne coherent detection, for independent phase noise sources identification, separation and measurement. We experimentally demonstrate that the proposed measurement method is able to identify and measure independent phase noise sources associated with an electro-optic comb and a comb based on a semiconductor frequency modulated mode-locked laser, for which noise sources are less well understood.

Development and deterministic nanofabrication of single quantum dot devices for applications in photonic quantum technologies

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Quantum light sources are key building blocks for the implementation of photonic quantum networks and for the realization of photonic quantum processors. Moreover, they allow one to explore exciting physics in the quantum regime of single emitters and single photons. Of particular interest are devices generating, routing, processing and detecting single photons which act as information carriers in the field of photonic quantum technologies. In this talk, I present recent progress in the development and deterministic fabrication of high-performance single-photon sources (SPSs) and on-chip quantum circuits based on semiconductor quantum dots (QDs) which act as close-to-ideal photon emitters. Using an advanced nanoprocessing technology platform, namely in-situ electron beam lithography, we pre-select suitable QDs and integrate them with nm accuracy into photonic nanostructures such as circular Bragg gratings to enhance the brightness of the sources, and to enable the development of scalable integrated quantum photonic circuits. The talk gives an insight into the physics of such devices and discusses technological challenges, current limitations as well as perspectives of semiconductor QD based quantum devices.

Modal stability and noise of cavity enhanced DMLs

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The directly modulated laser (DML) is a key component in optical datacom due to its simple fabrication, high modulation bandwidth and high output power. The modulation bandwidth of single section DMLs is limited by electrical parasitics, thermal effects and overdamped response at high bias. In multi-section DMLs, the bandwidth can be enhanced by utilizing the wavelength selectivity of the laser cavity. However, this will also affect the noise, linewidth, chirp and side mode suppression of the DML. Three effects will be discussed; detuned loading, photon-photon resonance and chirp to intensity conversion.

Solitons in quantum cascade laser based Kerr combs

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Optical frequency combs (OFCs) stand as the cornerstone of modern optics, with applications ranging from fundamental science to sensing and spectroscopy. Generation of short optical soliton pulses in passive media such as optical fibers and microresonators has been an established technique for stable OFC formation with a broad optical spectrum however these platforms are driven by an external optical signal and often rely on additional bulky elements that increase the complexity of the system. Here, we aim to overcome these difficulties by extending the soliton concept to active media that are electrically-driven and demonstrate a new type of solitons in a free-running semiconductor laser integrated on a chip. We utilize a quantum cascade laser (QCL), embedded in a ring resonator (Fig. 1a). The ring cavity is coupled with a separately-biased waveguide, which allows for the intracavity light to efficiently outcouple and reach output intensities that are comparable with a Fabry-Pérot laser processed from the same material [1].

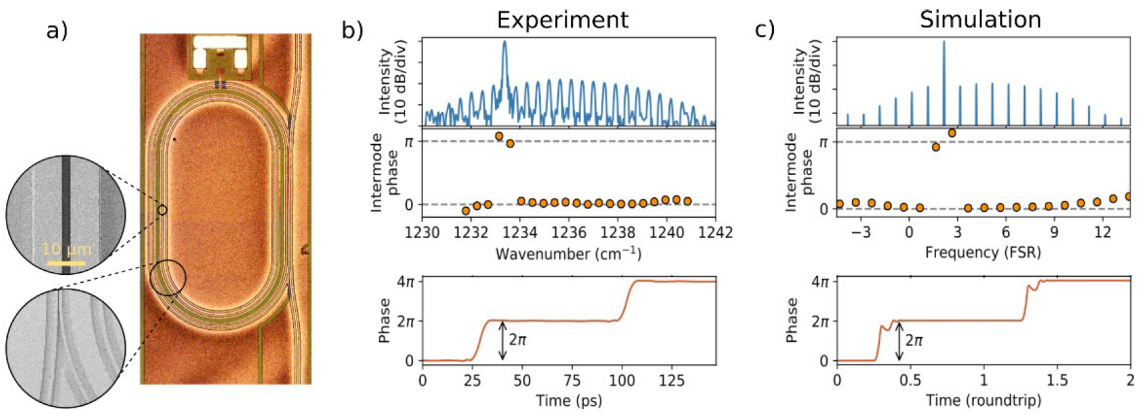

Figure 1 a) Ring laser device with the active coupler waveguide. b) Experimental and simulated c) free-running soliton. The soliton spectrum is displayed in the top, showing a strong mode surrounded by a smooth spectral envelope comprised of weaker sidemodes. The corresponding intermodal phases, given below, indicate a jump between the sidemodes and the strong mode. The temporal phase profile is plotted in the bottom.

In order to explain the multimode laser operation in a ring cavity, which is a prerequisite for OFC emission, we rely on the complex Ginzburg-Landau equation (CGLE) [2]. The main mechanism that allows for the sidemodes to overcome the lasing threshold is the modulational instability (MI), which arises due to the interplay of dispersion and a giant Kerr nonlinearity. In QCLs, the later originates from the optical gain itself and is several orders of magnitude larger than the bulk crystalline nonlinearity, making QCLs the ideal test bed for nonlinear phenomena [3]. Within the CGLE framework, we furthermore predict how appropriate values of the dispersion and the nonlinearity can even lead to soliton generation from the initial MI by forming self-starting localized pulses in the intracavity intensity. We rely on both the experimental measurements (Fig. 1b) and simulations based on the Maxwell-Bloch formalism (Fig. 1c) to corroborate our predictions. The soliton spectrum consists of a strong mode surrounded by weaker equidistant sidemodes with a smooth spectral envelope. Their intermodal phases reveal that all of the weaker modes are synchronized in phase, thus forming a narrow pulse in the time domain, while the strong mode is shifted and forms the continuous wave background around the pulse. The solitonic nature of the comb is furthermore visible from the temporal phase profile, which shows that the narrow localized soliton region, where the phase changes over 2, is surrounded indeed by a constant background containing a single frequency equal to the one of the strong mode in the spectrum. We additionally demonstrate soliton molecules with multiple pulses forming within one roundtrip. These results pave the way for electrically-driven soliton generation on monolithically-integrated platforms.

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Complex dynamics of lasers with passive dispersive reflectors

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Integrating a passive dispersive reflector (PDR) in a semiconductor laser will influence the laser dynamics and properties in several ways. This leads to a variety of possible applications, including linewidth narrowing, enhancement of the modulation response, generation of short pulses dispersive self-Q-switching, and multicolor emission. Examples of lasers with integrated PDRs include lasers based on Fano resonances, multi-section distributed-feedback lasers, lasers coupled to microring resonators, and external feedback lasers. In this work we consider an arbitrary PDR, which is characterized by a frequency dependent effective reflectivity, and study the effects on relaxation oscillations, photon-photon resonances, and more. As a key result, we derive a modified characteristic equation for the linearized system that explicitly takes into account the frequency dependent mirror. Further, we derive approximate expressions for the relaxation oscillation frequency and damping rate that depend on the local shape of the reflectivity. As such, the model can be used as a design guideline for the spectral response of the PDR. Finally, we apply the model to study two particular examples of microscopic Fano lasers. In one example, we observe self-pulsing which is interpreted as dispersive self-Q-switching. In another example, an EIT resonance in a photonic molecule is used to engineer the dispersion to support stable, tunable two-color lasing, which dynamically corresponds to sinusoidal beating-type oscillations. The beating-type oscillations can be associated with the excitation of a photon-photon resonance due to the Bogatov effect.

Impact of time-delayed feedback on pulse interaction in mode-locked laser

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Passively mode-locked lasers can generate multiple pulses per round-trip. In this so-called harmonically mode-locked (HML) regime the pulses can interact with each other via the carriers (in particular, gain repulsion), overlapping tails and time-delayed feedback stemming from e.g. unwanted reflections of lenses. The latter results in small copies of the main pulses in the cavity which amplitude and position are controlled by the feedback rate η and the feedback time τ_f, respectively. The different interactions influence the two degrees of freedom of each pulse: phase and position. From symmetry considerations, we derive fixed points of the system corresponding to equidistant pulses with a phase difference of $2\pi p/n, p = 1, ..., n$. Starting from the Haus equation we derive an effective equation of motion (EOM) for the positions and phases of the n pulses in an HML$_n$ configuration in form of $2n$ ordinary differential equations. We can separate the phase independent force acting via the carriers (as they are only intensity dependent) from the phase dependent force stemming from tail overlap and time-delayed feedback. Comparisons between direct numerical simulations of the full Haus model with the simplified EOM exhibit excellent quantitative agreement. For the case of two coupled pulses we perform a detailed bifurcation analysis of the EOM as a function of the feedback parameters τ_f (feedback position), η (feedback rate) and Ω (feedback phase). The analysis reveals multiple interesting regimes such as stable non-equidistant configurations, multistability between non-equidistant solutions as well as different kinds of periodic orbits. Again, we compare the results with the full Haus model and obtain excellent agreement. We use the knowledge obtained from the two-pulse-case to find corresponding regimes for higher pulse numbers. The resulting higher dimensionality of the phase space allows us to find additional regimes such as aperiodic solutions.

Real-field theory of modelocking

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I will 1) review existing theories of frequency combs, modelocking and solitons in optical resonators and short pulse propagation in waveguides, and 2) propose a real-field carrier-frequency-resolved microresonator model and demonstrate its applications for multi-octave frequency combs.

Turbulent labyrinthine patterns in optical valve with feedback: Theory and experiment

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Systems with energy injection and dissipation self-organise by forming stationary two-dimensional patterns at the onset of spatial instabilities. Increasing the imbalance between injection and dissipation of energy causes disordered patterns with complex spatiotemporal behaviours to form. In a liquid crystal light-valve with optical feedback, we examine the turbulent dynamics of labyrinthine patterns experimentally and theoretically. We first reveal that the observations correspond to the complex temporal evolution of a disordered labyrinth. By means of a two-dimensional conformal Hilbert transform, we are able to determine the phase and amplitude of the observed complex patterns and to show that the system exhibits phase and defects turbulence characterized by power spectrum exponents 2 and 3, respectively. Additionally, we reveal an exponent 2 in the power spectrum of the orientational field associated with the labyrinthine patterns. The structure functions associated with light intensity allow us to establish that the observed dynamical behaviours are also of intermittent nature. Beside these statistical tools, we determine experimentally the largest Lyapunov exponent, which shows the chaotic character of the dynamics. Further, to theoretically capture the experimental observations we provide a phenomenological model, based on a non-variational form of the Swift–Hohenberg equation, which is found to be in good agreements with the latter.

Fano Resonances at the Edge of a Continuum: Fundamentals and Applications in Microlasers

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We recently discovered a new phenomenon in wave dynamics [1]: the Fano resonances, related with the bound states of the wave function in the potential well, deform significantly when the corresponding eigenfrequency approach the edge of the continuum. This deformation is related with the delocalisation of the bound states, i.e. transition from bound states to the extended states (leaky nodes). The resonances at the transition point obtain unusual properties ; their peaks become very sharp. Note that usual Fano resonances have a Lorentzian-like shape asymptotically at its peak, i.e. parabolic $1 - dw^2$. Here, at the edge of the continuum the peak, the resonance has the asymptotics $1 - |dw|$. Such unusual resonances can be realized in the thin, micromodulated films, We will discuss the possible realisation of the effect in passive systems (the thin film on the dielectric substrate) as well as in active (the film on amplifying material).

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Transverse drift of Faraday patterns under inhomogeneous external driving

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In this work, we report the existence of drift instabilities in localised Faraday patterns induced at the surface of a fluid under a nonuniform parametric drive. The counterintuitive effect of inducing a propagating phase in the system, even when the vertical vibration modulation is fixed in space, is an intriguing attribute and differs from other experimental realisations featuring special types of boundary conditions, such as annular channels. We show that such drift is entirely induced by the nonuniform nature of the vertical drive at the bottom of the fluid container and thus cannot be observed under uniform driving. We use the normal form theory to explain the observed drift through an amplitude equation for Faraday patterns under localized driving. We demonstrate that the evolution of the instabilities at the first order of nonlinearity is described by a quintic Complex Ginzburg-Landau equation with Weber-like and self-phase modulation terms in the form of nonlinear gradients. Such nonlinear gradients trigger drift instabilities through a spontaneous nonlinear symmetry breaking above a secondary bifurcation threshold. Such nonlinear gradients trigger drift instabilities through a spontaneous nonlinear symmetry breaking above a secondary bifurcation threshold.

Many body effects in semiconductor laser dynamics

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We give an overview over our calculations in semiconductor lasers, including nonequilibrium and mode rolling effects. The dynamics is discussed in detail and compared to experiment whereever possible. Many body calculations are contrasted with simpler models, and advantages and limitations are discussed.

Light-bullets in three-dimensional Kerr resonators

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We report the existence of stable, dissipative light bullets in diffractive and dispersive Kerr cavities. These three-dimensional (3D) localized structures consist of either isolated, bounded, or clustered structures forming well-defined 3D patterns. They can be considered stationary states in the reference frame, moving with the group velocity of light inside the cavity. The number of LBs and their 3D distribution are determined by the initial conditions, while their maximum power remains constant for a fixed value of the system parameters [1, 2]. Their bifurcation diagram allows us to explain this phenomenon as a manifestation of the homoclinic snaking for dissipative light bullets. However, as the injected beam intensity increases, the LBs lose their stability, and the cavity field exhibits giant 3D pulses of short duration. The statistical characterization of the pulse amplitude reveals a long-tailed probability distribution, indicating the occurrence of extreme events. Extreme events are likely to occur, according to the statistical analysis of the pulse amplitude, which displays a long-tailed probability distribution. However, when the polarization degrees of freedom are taken into account, light bullets exhibit a breathing phenomenon. Stokes parameters and frequency spectra are used to describe the space-time dynamics of breathing light bullets [3].

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Machine learning in photonic systems

Turitsyn, Sergei
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I will discuss our recent works in applications of machine learning in laser systems and photonic elements in machine learning.

Dynamics of multi-wavelength lasers for wavelength conversion

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Multimode emission in a semiconductor laser is typically seen as a negative feature. Although it is sometimes an acceptable drawback for instance when high powers are required, low-linewidth single mode emission remains widely preferred for most applications. From a nonlinear dynamics viewpoint, a multimode laser is a significantly more complex system due to the intrinsic coupling and competition between modes. The underlying mechanisms leading to coupling between laser modes are relatively well-known, but a clear quantification of the process is still missing, and direct measurements are out of reach. Taking the problem in reverse, we explore how the dynamics of multi-wavelength lasers - i.e. multimode lasers with a few modes emitting in a controlled way - could be harnessed for application. We consider here their potential to perform all-optical wavelength conversion. In practice, by taking advantage of the progress of generic photonic integration technology, we can relatively easily design custom devices emitting at different wavelengths and including some modal control mechanisms. Subjecting these devices to modulated optical injection makes an excellent testbed to investigate the nonlinear behavior of multi-wavelength lasers, especially to analyze how well they can convert a given optical signal to another wavelength. We show here that multi-wavelength lasers can very efficiently replicate narrowband optical frequency combs at other wavelengths while preserving phase-locking between comb lines. Moreover, phase-locking between different wavelengths can also be achieved and cascaded, thus opening the way to significant comb expansion. In addition, we show that conversion of data signals is also possible.

Picosecond pulses with 40 W peak power from a mode-locked tapered laser diode emitting at 830 nm

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In this talk, we will present experimental and theoretical results of a monolithically integrated double quantum well laser designed for ultrashort pulse generation. This laser shows promise as a potential alternative to Ti:Sapphire lasers in compact Terahertz time-domain spectroscopy systems. The diode laser, measuring 6 mm in length, incorporates three sections, including a gain-guided tapered (TP) gain section, an index-guided ridge waveguide (RW) gain section and an additional RW section that functions as a saturable absorber. Under passive mode-locking operation, the shortest pulses measure around 3 ps in pulse duration (full width at half maximum). At the same time, the measured pulse peak power can reach as high as 40 W, which is the highest peak power achieved from a monolithically integrated mode-locked quantum well diode laser to the best of our knowledge. The corresponding central emitting wavelength is 830 nm. The pulse repetition rate is 6.3 GHz. The generated pulses are not transform-limited and can therefore be compressed resulting in even shorter pulses with more intense peak power. The experimental results will be compared with numerical simulations to gain a deeper insight into the laser dynamics. For the simulations, we employ BALaser, a software tool developed by the Weierstrass Institute Berlin. BALaser is specifically designed for simulating the nonlinear dynamics in high-power edge-emitting semiconductor lasers. This software integrates the 1+2 dimensional traveling wave model, which describes the dynamics of high-power diode lasers taking into account the lateral and longitudinal dimensions. The simulation model also incorporates thermal effect to provide a comprehensive analysis.

Canard cascading in lasers with slow-fast coupling

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In this presentation I consider a fast-slow system of mean-field coupled semiconductor lasers. The canard cascading is a complex regime that alternates between canards and relaxation oscillations. Using geometric singular perturbation theory, we perform the fast-slow analysis of the system and explain the formation of canards. The heterogeneity of the lasers is identified as the key cause for the occurrence of the phenomenon.

Dynamics and quantum noise in Fano lasers

Yi, Yu
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Conventional lasers are constructed by cavities relying on reflections at interfaces between materials having different refractive indices. In contrast, the Fano laser is constructed by a virtual cavity with one (or both) mirrors realized by Fano interference between a discrete mode and a continuum of modes. This gives rise to a bound state in the continuum trapped by an "invisible" mirror (Fano mirror) that is highly dispersive, equipping the laser with a number of unique properties. In this talk, I will give an overview of the progress of semiconductor Fano lasers, emphasizing laser dynamics and quantum noise. Recent results demonstrating significantly reduced quantum-limited linewidth and the generation of intense optical pulses using the Fano laser in the microscopic regime will be highlighted. These developments open a route for bringing important characteristics of macroscopic lasers to the nanoscale.

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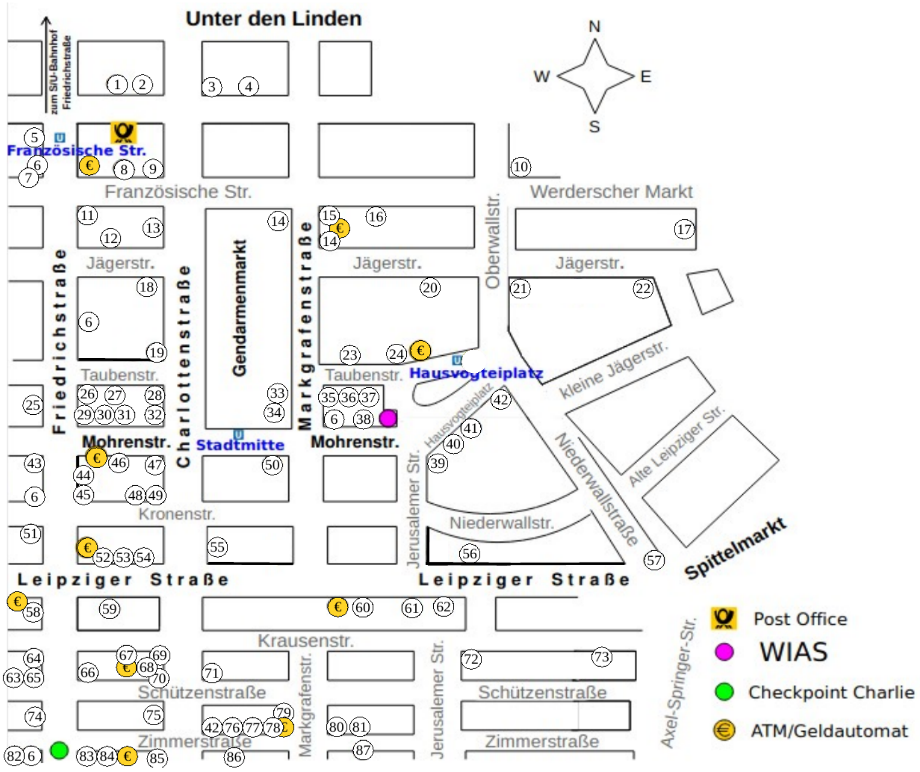
6 Places to have lunch



1 Subway
2 Sagrantino
3 Gendarmerie Restaurant
4 Austernbank
5 Lindner
6 Einstein Kaffee
7 Bocca di Bacco
8 Borchard
9 Charlotte & Fritz
10 Coffee 2 go
11 Galéries Lafayette
12 Bonanza Coffee Roasters
13 Lin
14 Erdinger am Gendarmenmarkt
15 Julian & Elisa
30 dean & david
31 nanoosh
32 Maredo
33 Moët & Chandon
34 Dom Curry
35 Shan Rahimkan Café
36 La Perle
37 THU MY marie
38 Chupenga
39 Bless
40 Steinecke
41 Good Time
42 The coffee shop
43 Kamps
44 auf die Hand
59 Otito Vietnamese Food
60 Schnell
61 Lidl
62 China-City Restaurant
63 Velis
64 Schäfers
65 Ristorante Pizza Pasta
66 The Coffe Shop
67 City Supermarket
68 Zwimpf
69 Lungomare
70 Huong Lua
71 Bistro les amis
72 Alto
73 Hashtag Coffeshop

16	Beef Grill Club	45	nosh nosh	74	Coffee Fellows
17	Town Bar	46	Seaside	75	Small Garden
18	Augustiner am Gendarmenmarkt	47	Rausch	76	ishin
19	Lutter und Wegner	48	sapa	77	Ma'loa
20	Little Green Rabit	49	cadadia	78	Burger, Huong Sen
21	Lunch Time	50	Hilton	79	Mix & Match, Pagashi Luu
22	Noamì	51	Alnatura	80	Soup Kultur
23	Brasserie	52	Monkey Donuts	81	Rustrôt
24	Braufactum	53	La Donna	82	Mc Donalds
25	soul	54	Rewe	83	KFC
26	Caras	55	Planet Wein	84	juice!
27	Rewe, Penny	56	Fontana di Trevi Ristorante	85	Chili Coffee
28	Newton	57	Farmer's Market	86	Caramel
29	Frittenwerk	58	Gregory's Coffee	87	Springer Building