WIAS Online-Workshop “Nonlinear Dynamics in Semiconductor Lasers”

Weierstrass Institute for Applied Analysis and Stochastics

June 16–18, 2021

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Some thoughts on length scale selection and dissipation in cavity solitons

Ackemann, Thorsten
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Dissipative (spatial) solitons are usually described by a double balance of nonlinearity and diffraction and dissipation and driving leading to the collapse of the continuous family of solutions of conservative solitons to a single attractor with defined amplitude and width [1]. Optical cavity solitons based mainly on dispersive characteristics allow also to construct a connection between propagating conservative solitons and dissipative solitons via a "soliton-in-a-box" model [2]. However, to my knowledge, the details of this transition and how dissipation enters into the length scale selection, are not well investigated. It should be noted that contrary to the conservative case, the transverse size of cavity solitons is influenced by the longitudinal boundary conditions, i.e. cavity detuning. The talk will present arguments how to construct the size of cavity solitons from self-consistency arguments involving diffraction within a cavity with a self-induced lens and how dissipation enters to determine the size of the nonlinearity. The considerations are illustrated by looking at semiconductor laser solitons.

References:

[1] e.g. N. Akhmediev, A. Ankiewicz, Dissipative solitons, Lecture Notes in Physics 661, Springer, Berlin (2005).

[2] W. J. Firth, G. K. Harkness, Cavity solitons, Asian J. Phys. 7, 665 (1998).

Self-induced transparency mode-locking as a novel way to generate few-cycle pulses in lasers

Arkhipov, Rostislav
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Passive mode-locking is a commonly used method to generate ultra-short pulses in lasers. Generation of short pulses arises due to the incoherent absorption/gain saturation. In this case, pulse duration is limited by the inverse bandwidth of intracavity media. It is possible to overcome this limit using self-induced transparency mode-locking (SIT ML) or coherent mode-locking (CML) technique. It was actively studied theoretically [1] and observed experimentally only recently [2]. This ML is based on SIT soliton (2π pulse) formation in absorber media. In this talk, we present our recent theoretical and experimental results illustrating arising of SIT ML in Ti: Sapphire laser with a coherent absorber cell (Rb vapors) [2]. It is demonstrated experimentally the emergence of the extreme events in the system of SIT dissipative solitons in such system. Furthermore, we present recently derived scaling rules [3]. Using these rules makes it possible to generalize the results of numerical calculations of a mode-locked laser for the case of obtaining pulses with extremely short few-cycle durations. It shows that in order to reduce the pulse duration to few oscillation cycles, it is necessary to reduce the laser cavity length rather than increase the pump power. Possibility of single-cycle pulse generation in two-section laser with ultra-short cavity is also studied theoretically [4].

References:

[1] R.M. Arkhipov, M.V. Arkhipov, I. Babushkin, N.N. Rosanov, Optics Letters, 41(4), 737-740, (2016).

[2] M.V. Arkhipov, A.A. Shimko, N.N. Rosanov, I. Babushkin, R.M. Arkhipov, Physical Review A 101 (1), 013803 (2020).

[3] R. Arkhipov, A. Pakhomov, M. Arkhipov, I. Babushkin, N. Rosanov, Scientific Reports 11, Article number: 1147 (2021).

[4] R.M. Arkhipov, M.V. Arkhipov, A.A. Shimko, A.V. Pakhomov, N.N. Rosanov, JETP Letters 110 (1), 15-24 (2019).

High pulsed power, asymmetric waveguide laser diodes with a short cavity and bulk active layer

Avrutin, Eugene
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We present theoretical analysis of a high pulsed power semiconductor laser design combining a double-asymmetric waveguide with strongly doped n-waveguide layer for suppressing carrier accumulation at high injection levels, a short (0.5-2 mm) cavity to increase the output efficiency, and a bulk active layer to prevent excessive threshold compromise. The remaining limitations to pulsed optical power are identified and discussed, and high output power and brightness predicted. Experimental output and spectral dependences are also presented and compared to the theoretical predictions.

Thermodynamic effects in nonlinear optical systems

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Multimode optical systems are commonplace in science and engineering. For instance, they form the basis of frequency combs, fiber lasers, mode-multiplexed communication systems, etc. One advantage offered by such systems is their capability to operate at rather high power levels where nonlinear effects become important. Specifically, these nonlinear effects induce interactions between the (linearly non-interacting) modes and lead to a plethora of interesting phenomena such as solitons, spatio-temporal mode-locking, supercontinuum generation, parametric instabilities, and the so-called beam self-cleaning effect. This latter effect is universal in multimode optical systems with weak nonlinearities and originates in the power migration, caused by the nonlinear mode interactions, towards a particular group of modes. Recently, it has been recognized that the resulting mode distribution is analytically described by the Rayleigh-Jeans distribution [1]. In other words, for multimode optical systems endowed with weak nonlinearities, every input mode distribution evolves towards a steady state in which the mode occupancies are described by a thermal distribution. Moreover, these effects occur even though the systems are closed, i.e. the internal energy and the total power remain constant.

Thus, any mode distribution becomes thermal due to the nonlinearity. The question is why?

To answer this question, we have carried out extensive numerical experiments for different multimode optical systems (1D and 2D waveguide arrays, and optical fibers) and in all cases we found that the nonlinearity induces chaotic fluctuations in the refractive index as a function of the propagation coordinate. Our results suggest that these chaotic fluctuations arise via two competing processes: The first is diagonal in the energy basis (reversible linear Hamiltonian evolution), the second is irreversible and diagonal in a complementary basis (e.g., localized perturbations in the sites/modes).

References:

[1] Wu, F. O., Hassan, A. U. and Christodoulides, D. N., Nat. Photonics 13, 776–782 (2019)

Frequency-domain description of semiconductor mode lock lasers

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Mode lock semiconductor lasers have the potential to radically change the next generation of time and wavelength division multiplexing systems used in telecommunications. The phenomenon is typically investigated with time-domain (traveling-wave) approaches, because they have the advantage of giving a physical picture of pulse train formation [1]. This paper discusses a complimentary frequency-domain approach based on multimode semiclassical laser theory [2]. The motivation is direct connection of optical nonlinearities to electronic structure. The locking mechanism, gain saturation, mode competition and carrier-induced refractive index are treated on equal footing via the quantum mechanical electron-hole polarization [3]. Equally important, the frequency-based approach allows a precise and physically intuitive description of the mode locking process from the Adler equation perspective [4]. To illustrate the frequency-domain approach, this paper discusses two examples of insight gained from applying the theory to analyze experiments. One application involves single-section InAs quantum-dot lasers, where the experimentally observed spontaneous mode locking is traced to combination tones created by nondegenerate four-wave mixing in an inhomogeneously-broadened quantum-dot active medium. The second application involves the use of the theory to extract quantum-dot and quantum-well four-wave mixing susceptibilities from nondegenerate pump-probe measurements. Combining theory and experiment to link device performance to electronic structure provides physical understanding that will help translate laboratory discoveries to manufacturing reproducibility.

This work was performed, in part, at the Center for Integrated Nanotechnologies, an Office of Science User Facility operated for the U.S. Department of Energy (DOE) Office of Science.

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[2] M. Sargent III, M. O. Scully and W. E. Lamb, Jr, Laser Physics. Reading: Addison-Wesley, 1974.

[3] W. W. Chow, S. Liu, Z. Zhang, J. E. Bowers and M. Sargent III, Optics Express 28, 5317, 2020

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Spatiotemporal chaos induces extreme events in an extended microcavity laser and liquid crystal light valve

Clerc, Marcel
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Extreme events such as rogue waves in optics and fluids are often associated with the merging dynamics of coherent structures. We present experimental and numerical results on the physics of extreme event appearance in a spatially extended semiconductor microcavity laser with an intracavity saturable absorber and liquid crystal light valve with optical feedback. We have identified parameter regions where extreme events are encountered and established the origin of this dynamics in the emergence of deterministic spatiotemporal chaos, through the correspondence between the proportion of extreme events and the dimension of the strange attractor.

Coherently injected ring quantum cascade lasers: Cavity solitons and optical frequency combs

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We generalized the well-known LugiatoLefever Equation to unify the description of the spatio-temporal dynamics in nonlinear passive and active ring resonators with cubic nonlinearity in terms of spontaneous generation of Optical Frequency Combs (OFCs) and temporal solitons. This approach makes it possible to connect from a formal viewpoint Kerr micro-resonators and unipolar semiconductor lasers, i.e. Quantum Cascade Lasers (QCLs). A step in this direction has been already made by a recent work dealing with free running QCLs in a unidirectional ring configuration [M. Piccardo et al., Nature 582, 360 (2020)] where OFCs emerging from phase turbulence were experimentally observed and theoretically predicted. Our model also describes the physics of a device never explored before in terms of OFCs generation: an unidirectional ring QCL driven by a coherent holding beam. The numerical simulations, guided by the results of the linear stability analysis of the spatially homogenous stationary solutions (or continuous wave solutions), show that for realistic sets of physical parameters this system realizes a wealth of spatio-temporal dynamics ranging from turbulence to the self-generation of highly correlated patterns (Turing rolls) and high contrast, temporally localized structures known as Cavity Solitons (CSs). Analogously to what happens for the Kerr combs in micro-resonators, CSs are associated with frequency combs spectra characterized by a sech-type envelope. Very appealing for applications to the deterministic control of the OFCs properties such as their repetition rate, is the possibility to externally switch-on one or more CSs by superimposing to the holding beam suitable addressing pulses. In this regard some preliminary results on CSs interactions and manipulation will be presented. Although we focused mainly on CSs properties and existence regions, we observed also the formation of other types of dissipative localized structures in the form of phase solitons, i.e. chiral structures excited by phase jumps in the cavity.

Spontaneous symmetry breaking in lasers with periodically modulated gain and refractive index

Dolinina, Daria
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The dynamics of light in active optical systems with periodic complex potentials is considered using coupled modes approach where the field is approximated by two counter-propagating waves. It is demonstrated that by shifting the position of the imaginary part of the potential (periodic effective gain) with respect to the real part of the potential (periodic variation of the refractive index)one can control the effective gain/losses seen by the upper and the lower modes. This effect can be used to control the radiation from the laser. The effects of the Kerr and dissipative nonlinearities are also considered and it is shown that this can result in spontaneous symmetry breaking leading to the formation of the dynamically stable hybrid nonlinear states characterized by nonzero energy flux. Such spontaneous symmetry breaking bifurcation can be used to obtain highly directed laser radiation. Besides, the formation of the dynamically stable spatially periodic patterns and localized states on such asymmetric backgrounds is demonstrated.

Nonlinear dynamics and polarization properties of VCSEL subject to polarized optical frequency comb injection

Doumbia, Yaya
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We propose experimentally and theoretically a new approach of broad frequency comb generation that offers the possibbility to adapt the comb properties to applications ranging from optical communications to gas spectroscopy by exploiting the nonlinear polarization dynamics in VCSEL from an optical frequency comb injection. When the polarization of the injected comb is tuned to be orthogonal to that of the VCSEL, several bifurcations scenario lead to a significantly extended output comb with number of lines up to 15 times that of the injected comb. When varying the injection parameters, we analyze the possibility to control the comb spacing through harmonic frequency comb generation. Harmonic frequency combs with repetition rates of hundreds of MHz are indeed demonstrated. Such combs have been recently used for dual-comb spectroscopy. Most importantly, for some injection parameters, the VCSEL shows two frequency combs with orthogonal polarization from a single device which may be very useful for polarization division multiplexing through the suppression of several optical devices. We also show that the power of the individual output comb lines above the noise pedestal (Carrier to Noise Ratio (CNR)) can be increased to as high as 60 dB which is 3 times higher than the one used for recent dual spectroscopy measurement [1,2,3]. Finally, we unveil several interesting varieties of nonlinear polarization dynamics of VCSEL when varying both the injection parameters and the comb properties, which extends our work beyond the particular applicability of the reported frequency combs. We observed that the power required to switch increase with the injected comb spacing and there is no linear dependence between the comb spacing and switching power.

References:

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[3] B. Jerez et al. Opt. letters 41, 4293–4296 (2016).

Quantum optics in room temperature QD gain media

Eisenstein, Gadi
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Using short pulse excitation and ultra fast characterization, various quantum optics phenomena were demonstrated: Rabi oscillations,Ramsey fringes, quantum control of the two and photon echoes. Recently, this work took a major step forward when the hallmark quantum optics effect of quantum coherence revival was demonstrated together with the effect of coherent time prolongation. These open the way for potential quantum technology using room temperature semiconductors. The talk will survey experiments and modeling as well as predictions for future applications.

Temporally localized fourier patterns

Giudici, Massimo
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In this contribution, we show that a self-imaging VECSEL hosts Fourier patterns when the pumped area is large enough. These complex patterns are temporally localized, i.e. they are localized pulses of PML solutions. This result shows that self-imaging VECSEL configurations present unique opportunities for studying complex spatio-temporal phenomena and it paves the way to the generation of spatially-organized individually-adressable pulses which can be used as information bits, arbitrary streams of pulses, frequency combs with tunable spectral density and light bullets.

High performance semiconductor lasers made with a harmonic photonic potential

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This presentation will review the recent results on a new distributed feedback (DFB) laser heterogeneously integrated onto silicon. The geometry is optimized in such a way that the mode is buried into a silicon waveguide with a shallow grating. The width of the grating is tapered longitudinally to create an effective confining potential which allows a single, bell-shaped longitudinal mode within the stopband of the DFB. This mode has a large Q factor leading to a cavity photon lifetime of 100 ps. An additional weakly confined mode with a much lower Q also exists at a lower optical frequency. First, I will show that this DFB laser operates with much reduced spectral linewidth < 20 kHz along with a constant relative intensity noise <150 dB/Hz over 20 GHz. Second, I will show that this device offers a great immunity against back-reflections with a high suppression of coherence collapse which is of paramount importance for isolator-free communications. Finally, I will discuss the two-state lasing operation between the fundamental mode and the weakly confined mode. When the pumping current is increased, a 4-wave mixing regime takes place with stokes and anti-stokes peaks. The coherent interaction leads to a radio-frequency beatnote of 80 GHz. Altogether these features unveil the strong potential of this new DFB laser structure for all-optical microwave generation and future optical communications.

Dynamics of temporal localized states in time-delayed optically injected Kerr Gires-Tournois Interferometers

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We study theoretically the formation and dynamics of phase-locked temporal localized states (TLSs) and frequency combs that can be generated from a high finesse Fabry-Perot microcavity containing a Kerr medium that is coupled to a external cavity in the presence of optical injection. These TLSs possess a strongly asymmetrical oscillating tail which results from third order dispersion induced by the cavity. Using a first principle model based on delay algebraic equations and applying a combination of direct numerical simulations and path continuation methods, we disclose sets of multistable dark and bright TLSs coexisting on their respective bistable homogeneous backgrounds. In particular, we show that the detuning of the injection with respect to the microcavity resonance controls the region of existence of TLSs and its change can lead to a period-doubling route to chaos. Further we discuss a transformation of the original delay model to a normal form given by a partial differential equation using a rigorous multiple time scale analysis and a functional mapping approach.

Wiggling instabilities of temporal localized states in passively mode-locked vertical external-cavity surface-emitting lasers

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We analyze the emergence of wiggling temporal localized states in a passively mode-locked vertical external-cavity surface-emitting laser composed by a gain chip and a resonant saturable absorber mirror. We show that the wiggling instability stems from the interplay between the third-order dispersion induced by the micro-cavities and their frequency mismatch. The latter is identified as an experimentally crucial parameter defining the range of existence of stable emission. We reveal the homoclinic scenario underlying the wiggling phenomenon, and we show how it allows us to control the oscillation.

Dynamics of vertical cavity swept sources with optical injection or optical feedback

Huyet, Guillaume
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Abstract not available.

Non-classical light emission in semiconductor nanolasers and ultrafast carrier dynamics in tunnel-injection quantum-dot lasers

Jahnke, Frank
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Quantum effects of the light-matter interaction in nanolasers can lead to highly unusual effects not known in conventional lasers, such as a strongly reduced laser threshold and non-classical light emission. These properties can be characterized using the second-order photon correlation function $g^{(2)}$. Lasers usually exhibit a change from $g^{(2)} = 2$ for thermal light to $g^{(2)} = 1$ for coherent emission. For a nanolaser with a small number of atom-like quantum-dot emitters in an optical cavity we demonstrate that radiative coupling of the emitters via the cavity field can establish a superradiant state of the active material, which can reveal itself as giant photon bunching with $g^{(2)} \gg 2$ in the emitted radiation. Another examples for unusual photon correlation effects is the delayed formation of coherence in the emission dynamics of high-Q nanolasers. The second part of the talk addresses increased modulation speed in quantum-dot lasers by means of a tunnel-injection design. The concept was introduced to improve the dynamical properties of semiconductor lasers by avoiding the problem of hot carrier injection which increase the gain nonlinearity and hence limit the modulation capabilities. Cold carriers are efficiently provided via an injector quantum well that is tunnel coupled to excited QD states. We study the ultrafast carrier population dynamics in tunnel-injection lasers by comparing LO-phonon-assisted tunneling processes and Coulomb-scattering-assisted processes.

Emergence of dispersive dynamics in passively mode-locked lasers

Javaloyes, Julien
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We will review our recent theoretical and experimental results regarding the emergence of dispersive temporal localized structures in the output of semiconductor mode-locked lasers. We will disclose new instabilities that occur in vertical external-cavity surface-emitting lasers that stem from the influence of third order dispersion. The latter induces the appearance of asymmetrical pulse satellites that destabilize the mode-locking regime, which leads to complex excitable dynamics and pulse explosions. Our work is set within the framework of time delayed dynamical systems. While time delayed systems are usually considered devoid of the essential dispersive effects for pattern formation,we will show how dispersion may appear naturally in singular delayed equations, and make the link via a normal form description with the physical properties of Gires-Tournois interferometers.

Chaos bandwidth: How should it be defined and how can it be optimised?

Kane, Deb
Department of Physics and Astronomy Macquarie University, Australia

A plethora of nonlinear dynamical semiconductor laser systems are reported in the literature, almost too numerous to recount, that generate chaotic output. They use different types of semiconductor laser (Fabry Perot lasers, distributed feedback lasers, vertical cavity surface emitting lasers (VCSELs), quantum dot lasers, quantum cascade lasers, semiconductor optical amplifiers in ring configurations), and, one or more of the standard approaches to destabilising the laser. The rf bandwidth of the chaos, typically several GHz, has been a key characteristic of the system output that researchers have sought to define, maximise and optimise. In this presentation the ways of defining chaos bandwidth that have appeared in the literature will be critically reviewed. Results of the chaos bandwidth from more recent numerical simulations of a free-space Fabry-Perot semiconductor laser with delayed optical feedback system, as key parameters are varied systematically, will be presented. These results are used to give new insights into the world of chaos bandwidth.

Emergence of coherence and condensation signatures in light emission of exciton gases

Manuel Katzer, Andreas Knorr, Malte Selig
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Bose Einstein condensation of excitons was predicted already in the 1960s and is intriguing due to the expected comparatively high condensation temperatures. On top, the formation of the condensed phase emitting coherent light might establish a completely new form of lasing. We discuss a theory for lasing from a excitonic Boson gas in atomically thin semiconductors using a Heisenberg equation of motion approach that gives insight in the microscopic dynamics of exciton-phonon scattering processes which lead to a dynamic stabilization or even emergence of exciton coherence.

Information processing using dual state quantum dot lasers

Kelleher, Bryan
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InAs based quantum dot lasers can lase from multiple different energy states. In combination with the high relaxation oscillation damping of the material this endows optically injected dual state quantum dot lasers with many unique dynamical properties. Several neuromorphic phenomena are observed, including dual state excitability and several optothermally induced dynamics. There is also a marked absence of chaos. I will present recent experimental and theoretical results for this system, including a novel photonic image reconstruction technique. I will also address some recent work regarding coupled devices on photonic integrated circuits and some prospects for integration of coupled dual state quantum dot lasers.

Vectorial dark dissipative solitons in Kerr resonators

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Extreme events such as rogue waves in optics and fluids are often associated with the merging dynamics of coherent structures. We present experimental and numerical results on the physics of extreme event appearance in a spatially extended semiconductor microcavity laser with an intracavity saturable absorber and liquid crystal light valve with optical feedback. We have identified parameter regions where extreme events are encountered and established the origin of this dynamics in the emergence of deterministic spatiotemporal chaos, through the correspondence between the proportion of extreme events and the dimension of the strange attractor.

Quantum-optical modelling of photon-correlation measurements in high-beta semiconductor nanolasers

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Nanolasers with metallic cavities achieve light confinement below the diffraction limit, resulting in devices with ultra-low thresholds and very small footprints. Strongly enhanced light-matter interaction in these lasers' cavities leads to (near-) linear input-output characteristics. This fact necessitates studying second-order photon correlations $g^{(2)}(0)$ in order to detect the transition from thermal to coherent photon statistics at the onset of stimulated emission. We report on quantum optical modeling of metal-clad coaxial nanolasers with semiconducting multi-quantum-well gain media and near-unity beta factor. Our cluster-expansion approach gives access to a range of device characteristics, including first- and second-order correlation functions with excellent agreement with experimental data. In the talk, we will discuss the role and suitability of the Siegert relation $g^{(2)}(\tau) = 1 + |g^{(1)}(\tau)|^2$ to relate first- and second-order coherence properties in such nanolaser devices. The Siegert relation is frequently used to deal with the finite time resolution of detectors used in the correlation measurement that inhibits the full resolution of photon bunching in the thermal-emission regime below threshold. The validity of the used approaches and extensions of the Siegert relation to the partially coherent regime will be discussed.

Stability of delay coupled nano-lasers

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Coupled nanophotonic semiconductor lasers are a prototypical model for on-chip laser networks. Due to their small footprint and low power consumption they are promising light sources for a wide range of nanophotonic applications such as neuromorphic computing or secure optical communication. One crucial precondition for a successful photonic implementation is the knowledge about the borders of stability. Although a lot is known about the dynamics of delay-coupled macroscopic lasers, the question about how the small size of nano-lasers and thus the small photon lifetime influences the stability under optical perturbations is still unanswered, especially because the dynamic degree of freedom of the microscopic polarization and thus the full Maxwell Bloch equation system (class-C laser model), has to be considered. We present an in-depth analysis of the dynamics for two non-identical class-C lasers with delayed coupling. Interestingly, a value of the polarization lifetime T_2 can be found where the relative stability is optimal despite the fact that a second laser threshold to chaotic emission exists. Thus, coupled nano-lasers are more stable than macroscopic lasers and can be tuned to show quite extensive locking ranges. The optimal T_2-value depends on the photon lifetime within the cavity. We can predict that nano-lasers show best synchronization properties for the case where the photon lifetime is equal to the polarization lifetime. For the case of strong optical coupling we find that a ratio of two-thirds between photon and polarization lifetime yields extensive parameter regions with stable and locked operation.

Single frequency electrically injected semiconductor laser exploiting the concept of parity-time symmetry

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The progress of nanotechnologies has triggered the emergence of many photonic artificial structures: photonic crystals, metamaterials, plasmonic resonators. Recently the intriguing class of PT-symmetric devices referring to Parity-Time symmetry has attracted much attention. Their distinctive feature is that the refractive index profile of the structures is complex-valued due to the gain and/or loss, which are spatially separated in the system. One characteristic for PT-symmetry in optics functionality is the ßpatial non reciprocityör ünidirectionality"distinctly different from that based on the Faraday magneto-optical effect. In the case of a PT-symmetric Bragg grating waveguide the reflectivity can be extremely low in a broadband wavelength range for light incident from one side, and extremely high in a narrow band when light is incident from the opposite side. Due to the narrow-band ünidirectional"reflection of PT-symmetric Bragg grating introducing an additional gain discrimination mechanism, it is expected that the coherence of such a laser would be highly tolerant with respect to the optical feedback i.e. reflections along the optical path. In this work we report on the implementation of single frequency electrically injected DFB lasers based on Parity-Time symmetric dual gratings in a standard ridge waveguide configuration. We demonstrate enhanced modal discrimination for these devices as compared with index or gain coupled ones, fabricated in the same technology run. Optical transmission probing experiments further show asymmetric amplification in the light propagation confirming the Parity-Time symmetry signature of unidirectional light behavior. Another asset of these complex coupled devices is further highlighted in terms of robustness to optical feedback.

Observation of highly regular oscillations in the intensity of a semiconductor laser near threshold with optical feedback and small-amplitude direct current modulation

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In periodically driven disordered systems time-crystal states manifest as regular subharmonic oscillations that are stable over long time intervals and that rigidly persist under parameter changes. Since the dynamics of a time-delayed system (TDS) has many similarities to that of a 1D spatially extended system, we analyze whether oscillations with time-crystal fingerprints can occur when a stochastic TDS is modulated with a small-amplitude periodic signal. We consider an experimental TDS consisting of a semiconductor laser with time-delayed optical feedback, operating near threshold, where the laser intensity exhibits sudden spikes (known as low frequency fluctuations), which occur at irregular times. By modulating the laser injection current with a small-amplitude signal, we found that some modulation frequencies induce very long-range temporal correlations in the timing of the spikes, which become either extremely regular over thousands of modulation cycles, or become bursts of spikes with fractal characteristics. With a pulsed modulation waveform, both, rigid harmonic and subharmonic locked spikes were found, while with sinusoidal waveform, only subharmonic rigidly locked spikes were found, a fact that is interpreted as a fingerprint of time-crystal behavior. Simulations of the Lang-Kobayashi model with small-amplitude sinusoidal injection current modulation were found to be in reasonable agreement with the experimental observations: by varying the modulation frequency we found plateaus were the spikes are sub-harmonically locked, and we did not find a plateau where the spikes are 1:1 locked. However, unlike the experiments, in the simulations we did not find long-range spike timing regularity.

Nanolasers based on extreme confinement of light

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Recently, new nanocavity structures have emerged that confine light to length scales far below the diffraction limit and significantly enhance the light-matter interaction strength. Notably, these structures do not involve metals, and thereby avoid the losses associated with plasmonic excitations. The application of such extreme nanocavities in nanolasers will be analyzed, including the possibility of realizing intensity noise squeezing at very low power levels and with high bandwidth.

Injection locking and coupling large VCSEL arrays via diffraction in an external cavity

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Coupled semiconductor lasers are of interest from a fundamental complex systems perspective, as well as for various applications, including brain-inspired computing [1-4]. Coupling or feedback can be realized using different approaches, via integrated photonic circuits [5], optical fiber networks [6], or free-space optical setups [7,8]. We present how 25 vertical-cavity surface-emitting lasers (VCSELs), configured in a square array [9], can be coupled and locked to an external drive laser via an optical diffraction scheme in an external cavity. Such a system might constitute the basis for a laser network based implementation of reservoir computing. In our scheme, the external cavity includes a diffractive optical element that allows for scalable coupling [10] between next and second-to-next neighboring VCSELs, and to simultaneously injection lock the VCSELs to an external injection laser. Crucially, every VCSEL in the custom-manufactured arrays can be electrically pumped independently [9], which allows to essentially remove inhomogeneous broadening of the array's lasing wavelengths. In our experiments, we analyze the emission spectra and the dynamical behavior of the VCSELs for different scenarios of feedback, coupling and injection. We observe locking between VCSELs and achieve simultaneous locking of nearly all 25 VCSELs to the external injection laser. We discuss our experimental findings and put them into context for reservoir computing applications.

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Rectified polarization coupling: A means to scale up power density of semiconductor lasers

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Generally, a superposition of laser beams of orthogonal polarization is possible only once. Here we present a concept to cascade the coupling multiple times. This becomes possible by spreading phase space along the wavelength and force different lasers onto slightly shifted emission lines. The concept will be explained, its experimental results and prospects presented and its limitations discussed.

Quantum dot micropillar lasers for applications in neuromorphic computing and ultra-fast spin-lasing

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Micro- and nanolasers featuring high quality factors and low mode volumes are very interesting objects to explore the physical limits of semiconductor lasers in the quantum regime and to study new dynamical effects. For instance, the allow one to achieve thresholdless lasing associated with a spontaneous emission coupling factor (beta-factor) of 1. In this talk, I present the development and in-depth optical study of high-beta quantum dot micropillar lasers for applications in neuromorphic computing and as ultra-fast spin-lasers. Neuromorphic reservoir computing is enabled by patterning large arrays of spectrally highly homogeneous micropillars which form a network of nonlinear nodes via diffractive coupling. Beyond that, bimodal micropillar lasers with an elliptical cross-section provide a very attractive opportunity to realize and study spin-lasing effects with a polarization-oscillation frequency predetermined by the spectral splitting of the fundamental emission mode. As such the talk give insight into the latest developments of quantum dot micropillar lasers and it provides an outlook to exciting future applications of these nanophotonic devices.

Multimode dynamics in a hybrid semiconductor laser in a silicon photonic platform

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Silicon photonic (SiPh) technologies, which provide integration of photonic devices in silicon-based circuits, are attracting surging interest in the field of optical communications as candidates for the realization of the next-generation of compact, low-cost, mass-producible optical transceivers. In this context, hybrid integrated lasers, where a semiconductor laser source is edge-coupled to a SiPh frequency selective mirror, potentially offer single-mode and narrow optical linewidths (typically >100kHz and sometimes down to the sub-kHz range). Therefore, the dynamics of this new class of semiconductor lasers needs to be properly characterized to provide the best parametric region for CW lasing stability. In this work, we present a theoretical and numerical model based on delayed discrete-time equations for the description of a hybrid semiconductor laser. The device consists of a commercial III-V Multiple Quantum Well HR/AR RSOA that is edge-coupled to a SiPh integrated circuit, forming the front mirror of the laser cavity. The SiPh circuit is based on a Mach-Zehnder interferometric Si_3N_4 mirror, loaded by two high-Q microring resonators. This configuration provides, through Vernier effect, a narrow effective reflectivity, which extends the photon lifetime of the hybrid laser and lowers its intrinsic linewidth. We have recently shown that this also has an effect in increasing the laser tolerance to spurious back-reflections from the passive parts of the photonic circuit. Simulations of the system evolution equations highlight a rich dynamical scenario, encompassing stable CW emission and multimode regular and chaotic regimes, obtained by acting on a phase control section integrated in the SiPh circuit. Tools for the linear stability analysis of the CW solutions have been also considered. The versatility of the proposed theoretical approach will allow the model to be used in the study of a variety of hybrid laser configurations suitable also for applications in the innovative fields of integrated sensing and spectroscopy.

Towards unipolar radiation pulses

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Since the laser invention, the development of laser physics and technology is largely aimed at achieving ever shorter laser pulses. Now attosecond optical pulses have been obtained experimentally. Pulses of such duration allow reaching record peak electric field strengths (superstrong fields), diagnosing the kinetics of ultrafast processes (attosecond chronoscopy), etc. A further step in shortening the pulses would be generation of subcycle unipolar or quasi-unipolar pulses, in which the direction of the electric field strength vector E would basically not change with time. More precisely, a pulse can be characterized by its electrical area S – the integral of the field strength E over time. For standard bipolar pulses $S = 0$. Apparently, Bessonov (1981) was the first to pay attention to pulses with a nonzero electric area. To date, unipolar radiation pulses have been experimentally demonstrated in GHz and THz domains. However, the subject of unipolar pulses in the literature remains controversial. The transition to subcycle and unipolar pulses requires a departure from many familiar concepts of optics and laser physics. This talk reports on the important for such pulses, strictly following from Maxwell's electrodynamic equations, but counterintuitive rule of conservation of the pulse electric area, as well as the possibility of generating such pulses with a controlled shape and their transporting in waveguides of a special type. The importance of the conservation rule is underlined by the discussion of the Aharonov-Bohm effect. It is revealed that it is the electric area, and not the energy of extremely short pulses, that determines the effectiveness of their action on micro-objects (acceleration of charged particles, change in the direction of their spins, excitation of atoms and molecules). A number of other potential applications of quasi-unipolar pulses are discussed, including holography of fast-moving objects.

Tubular vortex solitons in lasers with saturable absorption

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Stable two-dimensional (2D-) vortex solitons and their complexes in wide-aperture lasers with saturable absorption are known for various values of their topological charge m. In this talk, we present a type of topological solitons generated by “elongation” of 2D- vortex solitons in the third, longitudinal direction the type intermediate between 2D- and 3D-laser solitons. The laser medium model is a matrix in which centers with nonlinear (saturable) gain and absorption are embedded. The matrix is characterized by linear absorption and frequency dispersion. The centers are described by effectively two-level scheme of energy levels with fast response to the field. The medium can be placed into a ring cavity or have formally infinite length. Radiation propagation is described in the paraxial approximation by the generalized complex Ginzburg-Landau equation for a slowly varying envelope, which is scalar in the case of fixed radiation polarization and two-component vector when polarization variations are taken into account. For scalar structures, the 3D-field is constructed by multiplication of the 2D (transverse) field distribution for a 2D-vortex laser soliton by an exponential multiplier describing phase variation in the longitudinal and transverse dimensions. Then point-wise vortices (zeros of the complex envelope) of 2D-soliton form one or several vortex lines of the 3D-field distribution, which acquires tubular shape. These 3D-distributions, if stable, form a family of solitons with continuous spectrum of spectral parameter. The linear stability analysis shows the instability of such tubular structures in a medium with infinite size. For cavities with finite length L such symmetric structures with discrete spectrum are stable for short lengths L. For larger L, tubular solitons acquire shape that is more complicated. For vector case, we discuss additional polarization singularities appearing in the tubular laser solitons.

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Laser fields with optimal properties

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In my talk I will present recent theoretical and experimental work on the design and creation of laser fields with properties that are optimal for focusing on a target [1], for optical micro-manipulation [2] and for information retrieval [3]. The underlying design principle of these light fields is based on a generalisation of the Wigner–Smith time-delay operator.

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Manipulation of temporal localized structures in a VECSEL with optical feedback

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We analyze both theoretically and experimentally the impact of optical feedback on the dynamics of external-cavity mode-locked semiconductor lasers (VECSELs) operated in the long cavity regime. In particular, by choosing certain ratios between the cavity round-trip time and the feedback delay, we show that feedback acts as a solution discriminator that either reinforces or hinders the appearance of one of the multiple harmonic arrangements of temporal localized structures. For the theoretical modeling, the delayed differential equation model of A. Vladimirov and D. Turaev (Phys. Rev. A 72, 033808 (2005)) is extended by a term describing the optical feedback. For the experimental realization, the gain medium consisting in 6 quantum wells embedded between a bottom totally reflective Bragg mirror and a top partially reflective Bragg mirror (1/2 VCSEL) was considered; the 1/2 VCSEL was then placed in an external cavity that was closed by a fast semiconductor saturable absorber mirror (SESAM) to operate the laser in the passive mode-locked regime. In the absence of the optical feedback such a laser can generate so-called harmonic mode-locked solutions. The optical feedback induces that each pulse is followed by a train of small copies of itself. The size and position of this echo can be controlled via the feedback rate and the delay time, respectively. When an echo is placed close to the leading edge of another pulse, the pulse experiences less amplification by the gain medium as it is already depleted by the echo. This interaction can lead to the destruction of the main pulse. In consequence, the system settles on a solution where pulses and echos are well-separated and thus, do not interact. In the further steps, a detailed bifurcation analysis is conducted where the influence of the position of the echo is investigated.

Frequency combs in $\chi^{(2)}$-microresonators

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I will discuss the multi-sideband second harmonic generation in a high-Q ring microresonator. This will include the development of the easy-to-take-home photon-energy conservation picture of the comb build up and engage few analogies with the textbook quantum mechanics allowing to calculate the threshold conditions for parametric frequency conversion into an arbitrary sideband order. I will connect $\chi^{(2)}$-photonics to the Roman God two-faced Janus, and demonstrate how $\chi^{(2)}$-nonlinearity in microresonators can act differently across the broad-band spectrum and manifest itself as either Kerr or Pockels effects. I will be reporting diverse families of combs, including the ones featuring the optimal power conversion. The talk will be build bottom up to make it accessible to colleagues with a basic background in physics and optics.

Nonlinear dynamical regimes in long cavity semiconductor lasers

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We will speak about dynamics of long ring cavity semiconductor lasers which can be used as swept sources. We identify key factors behind the reach dynamical behaviour of such lasers using state-of-the-art experimental and analytical methods. In particular, we study the turn on transient regime of the laser and investigate the formation of coherent structures.

Optical turbulence control by non-Hermitian potentials

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We propose a new method for a smart control of turbulence, in particular of optical turbulence, by modifying the energy flow cascade of turbulence. The method is based on the asymmetric coupling between the spatial excitation modes due to non-Hermitian background potentials. The non-Hermitian potentials are known, since recently, to introduce unidirectional coupling between the waves. A particular case of non-Hermitian potentials are the PT-symmetric potentials. The unidirectional coupling in wavenumber domain is on the root of recently proposed exotic effects as unidirectional invisibility, unidirectional lasing, and others. We consider the unidirectional coupling in an extended wavevector-frequency domain. We demonstrate that such an unidirectional coupling towards larger (smaller) wavenumbers-frequencies can increase (reduce) the energy flow to turbulent states, and therefore influence the strength and the character of the turbulence [1]. The study is based on the Complex Ginzburg-Landau Equation which is an universal model for the pattern formation and turbulence in a wide range of systems, and in particular in active nonlinear optical systems, like spatially extended lasers. We show that enhancement or reduction of the turbulence is indeed governed by the introduced direction of the energy flow, controlled by the phase shift between the real and imaginary parts of the temporal oscillation of the non-Hermitian potential. The proposed turbulence control mechanism can be applied to efficiently control the radiation in micro-lasers, in particular in Broad Area Edge Emitting lasers.

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Bifurcations and instabilities of temporal dissipative solitons in systems with time-delayed feedback and large delay

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We study different bifurcation scenarios and instabilities of Temporal Dissipative Solitons in systems with time-delayed feedback and large delay. As these solitons can be described as homoclinic orbits in the profile equation under the reappearance map, we use homoclinic bifurcation theory for our comprehension of their bifurcations and instabilities. We demonstrate our results with the examples of the FitzHugh-Nagumo system and Morris-Lecar model with time-delayed feedback.

Moving localized structures induced by a Raman nonlocal response in Kerr resonators

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We investigate the non-local delayed Raman response in optical resonators subject to optical injection. The time-delayed non-local response appears in many areas of nonlinear science, such as magnetism, optics, and population dynamics. This phenomenon is a rule rather than an exception. We show that a time-delayed non-local response can generate traveling localized structures. We enlighten this mechanism on the generic bistable model through analytical and numerical investigations. This simple model with a nonlocal Raman effect is obtained from the generalized Lugiato–Lefever equation [1,2] . This reduction is valid close to the nascent bistability regime, where the system undergoes a second-order critical point marking the onset of a hysteresis loop. The interaction between fronts allows for the stabilization of temporal localized structures. Without the Raman effect, moving temporal localized structures do not exist. Numerical results show a reasonably good agreement with the analytical predictions. Characterization of the bifurcation structure of traveling localized structures is provided. Furthermore, we propose an experimentally relevant optical device to demonstrate the feasibility of this mechanism that may lead to proper new research in Kerr-comb-based devices. The Raman scattering breaks the reflection symmetry of the system, and modifies the dynamics, stability, and locking of domain walls. This modification leads to the formation of, not only dark but also bright moving localized states, which otherwise are absent. We perform a detailed bifurcation analysis of these localized states and classify their dynamics and stability as a function of the injected field intensity [3].

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Dynamical properties and feedback sensitivity of detuned DBR semiconductor lasers

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We report results of numerical simulations of the dynamic properties of single longitudinal mode Distributed Bragg Reflector (DBR) laser subject to an external optical feedback provided by a long distant mirror. We also present a so far missing theoretical study how its reflection tolerance depends on the detuning between lasing wavelength and maximum of the DBR reflectivity. We use the Lang–Kobayashi model extended to include the detuning parameter on base of the round-trip condition for stationary states. We consider the detuning as a bifurcation parameter to control the feedback effects and stability of stationary states.

InP based semiconductor laser components for perspective application in high speed datacom, sensing and neuronal networks

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InP based semiconductor laser devices of Fraunhofer HHI covering the spectral range from 1200 nm to 1700 nm have been developed for various applications. In the focus are advanced designs enabling compact and cost effective transmitter chips for high-speed fiber based optical connections. Moreover, versatile layouts of lasers, gain chips and semiconductor optical amplifiers (SOAs) are under investigation to realize customized light sources for different hybrid integration platforms. These designs target high yield and optimum performance of single and arrayed chips and may serve as smart optical solutions in multi-chip approaches. The semiconductor components are realized within the in-house InP fabrication line. The talk presents performance and applications of recent approaches of HHI's laser components. It includes arrays of electro-absorption modulated lasers (EMLs) for up to 1.6 Tb/s, DFB Lasers with integrated SOA, vertically emitting DFB lasers, tunable lasers and optical comb sources.

Rate-equation based simulation of lateral-longitudinal mode dynamics in blue broad-area InGaN laser diodes

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Broad-area laser diodes offer high optical output powers of several watt, while preserving most other advantages of laser diodes, such as compactness and the ability for fast modulation. Especially in the blue spectral range, this enables new promising application fields, from industrial metal processing to lighting. But the inhomogeneous, complex lateral (slow-axis) intensity pattern is still a major challenge, impairing the beam quality and coherence. For high power emission, the ridge waveguide is made tens of μm broad to prevent catastrophic optical damage, but this also brings rise to lateral multi-mode operation. In order to further understand the extensive time-dependent mode dynamics, we developed a simulation model on the foundation of rate equations. There we consider the lateral distribution of charge carrier density and the combined longitudinal-lateral optical modes with their respective photon densities. The model involves the calculation of lateral mode shapes from the complex refractive index with various contributions, at each point in time. The behavior of carrier- and photon densities is described with several gain terms, including the influence of the spatial carrier distribution on the optical modes and vice versa, as well as coupling between longitudinal modes and modal cross-saturation. The system is solved using the Dormand-Prince method with adaptive step size based on a Runge-Kutta algorithm. The simulation results show combined onset dynamics in the first nanoseconds: the lateral modes build up sequentially from lower to higher orders during the relaxation oscillations, while the wavelength spectrum narrows and shows a fast red-shift. Afterwards, a longitudinal-lateral mode correlation emerges, where lateral modes of lower order are mainly found in the longer wavelength side of the spectrum and vice versa. Also, longitudinal mode rolling is simulated and this phenomenon now interacts with lateral dynamics, so that also the lateral modes are switching in a periodical way.

Using the nonlinear dynamics of a laser-driven opto-electronic oscillator with feedback to build a low-cost coherent ising machine

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Optimization problems are frequently encountered in society and are often computationally difficult to solve. Such tasks are for example encountered in airline crew scheduling, traffic flow optimization, and search engine optimization. These problems are challenging to solve on conventional digital computers as they are typically NP-hard. Therefore, there is considerable interest in developing new, unconventional computing schemes that can aid in these tasks. Ising machines are a promising candidate for this purpose. These machines are physical implementations of the Ising Hamiltonian and finding the optimal solution to various optimization problems becomes equivalent to a ground state search of the corresponding Ising problem. The natural tendency of physical systems to evolve towards the lowest energy state allows these Ising machines to automatically find optimal solutions, which promises to be significantly faster and more efficient than current digital computers. Ising machines have been fabricated using various physical systems. Optical systems in particular have shown to be an attractive choice due to their ability to operate at room temperature and their low energy dissipation. In this contribution we discuss how nonlinear opto-electronic oscillators can be used to implement low-cost Ising machines in a time-multiplexed feedback scheme. The oscillator consists of a laser-driven Mach-Zehnder modulator with feedback and the Ising Hamiltonian is implemented through the (electronic) feedback circuit. This design can be constructed from just a few off-the-shelf components, is inexpensive to build and fits within a small footprint. We compare the performance of our scheme with state-of-the art systems on various benchmark tasks, showing not only fast conver

Spatially modeless laser cavity based on III-V semiconductor technology and sub-lambda metasurface: Non-linear localized light

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Degenerate laser cavities have been used for second-harmonic generation and spatially incoherent laser emission using solid-state gain medium and monolithic VCSEL. In this work we investigate cw spatial coherent states of a degenerate laser cavity using 1/2-VCSEL and high numerical aperture optical system for spatio-temporal localization of light. The 1/2-VCSEL has been designed based on GaAs materials at 1060nm with a high reflectivity GaAs/AlAs Bragg mirror and multi-quantum-well strained-balanced InGaAs/GaAsP active region. A sub-lambda chromium mask was also design as a meta-surface to better control the transverse light emission. The external cavity implemented is made up two lenses in 4-f self-imaging configurations. A Zeemax and optical physics study was carried out to optimized the system and ensure high numerical aperture with minimal aberrations. In the self-imaging condition, two strong different regimes of spatial structures have been observed and studied. The first one being an on axis emission at normal incidence with respect to the gain mirror allowing for small localization of light. The second one is a Tilted Wave emission akin to a ring laser cavity where the stable fundamental Gaussian mode emitted with an angle circulates inside the cavity. This kind of emission can arise only close to the self-imaging geometry condition of the cavity. Unlike in monolithical VCSEL where this is attributed to non-linearity and micro-cavity effect, we believe here to be stabilized by the 3-D degeneracy of the optical cavity. Next step is to insert a saturable absorber and design a large cavity round-trip time compare to the gain recovery time (nanosecond scale), in order to exploit this type of spatially modeless laser cavity to support 3D localized light structures – in time and in space –, also known as Light Bullets.

Monolithically integrated extended cavity diode laser

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The semiconductor (SC) laser is the light source of choice for miniaturized contemporary photonic integrated devices. Many applications, such as optical atomic clocks, atom interferometry, gravitational wave detection, space-based metrology and optical quantum sensing impose strict demands on the coherence of the light source. While semiconductor lasers excel in terms of small weight, footprint and high electro-optical conversion efficiency, further reduction of their spectral linewidths remains challenging [1].

Realization of longitudinal single-mode SC lasers with ultra-narrow linewidth relies on improving the optical cavity while minimizing the generation of spontaneous photons by the gain medium. This paradigm dictates to store as much light as possible in a lossless part of the cavity without significantly increasing the threshold carrier density [2,3]. A frequently used approach to decrease the linewidth of the SC laser is to increase the resonator length and therefore the photon round trip time. For GaAs-based SC Lasers, this has been demonstrated by means of hybrid micro-integrated extended cavity diode lasers (ECDLs) [4]. In such an extended cavity diode laser the narrow linewidth is achieved by means of resonant optical feedback, while the optical mode propagates mostly through a lossless medium, e.g. air. However, the ECDL concept has several disadvantages in terms of thermal control and mechanical stability. Moreover, micro-integration assembly of the components is a costly process and it significantly increases the footprint of the laser.

Here, we present a novel approach for transferring the hybrid ECDL concept onto a single chip to realize a monolithically integrated ECDL (mECDL). We use two-step epitaxy to realize an mECDL emitting at the wavelength of 1064 nm on an AlGaAs/GaAs platform. The epitaxial layer structure exhibits a strained InGaAs double quantum well. Lateral optical confinement of the weakly index-guided mode is provided by a dry-etched ridge. Longitudinal single-mode operation is established by a distributed Bragg-reflector. The manufactured chips have a total length of 8 mm.

We present experimental results, including measured frequency noise spectrum and electro-optical characteristics such as threshold current, optical power and mode-hop behavior. We also discuss the geometry, manufacturing process and structural aspects of the laser design. The mECDL exhibits a significantly reduced frequency noise as compared to a conventional DBR laser. Our measurements show a 3 dB linewidth as small as 25 kHz @ 1 ms [5] and an intrinsic linewidth of 2 kHz which is, to the best of our knowledge, the smallest linewidth to date for monolithically-integrated diode lasers. The inherent flexibility of our mECDL concept allows for future improvements in SC laser characteristics, including the change of the emission wavelength by transferring this concept to different material platforms.

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Diode lasers for quantum technology applications

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Diode lasers play a key role in many quantum technology (QT) 2.0 applications like optical atomic clocks, sensors for inertial navigation or atom-based quantum computers. This presentation aims at explaining why. First, a typical atom-based QT application will be described as an example and the corresponding requirements envelope for the lasers will be derived. Based on this analysis it will be explained why diode laser technology, among all other laser technologies, is best suited to meet the QT laser requirements. The application example will further motivate why laser performance parameters like spectral purity, laser power and frequency/phase noise as well as modulation response are critical for QT applications. We will show how they can be accessed experimentally and also discuss experimental difficulties and limitations.

Folding a deep neural network in time using a single neuron with modulated delay loops

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Deep neural networks are among the most widely applied machine learning tools showing outstanding performance in a broad range of tasks. We present a method for folding a deep neural network of arbitrary size into a single neuron with multiple time-delayed feedback loops. This single-neuron deep neural network comprises only a single nonlinearity and appropriately adjusted modulations of the feedback signals. The network states emerge in time as a temporal unfolding of the neuron's dynamics. By adjusting the feedback-modulation within the loops, we adapt the network's connection weights. These connection weights are determined via a modified back-propagation algorithm that we designed for such types of networks. Our approach fully recovers standard Deep Neural Networks (DNN), encompasses sparse DNNs, and extends the DNN concept toward dynamical systems implementations. The new method, which we call Folded-in-time DNN (Fit-DNN), exhibits promising performance in a set of benchmark tasks.

This is joint work with Florian Stelzer, Andre Röhm, Raul Vicente, and Ingo Fischer.

Lumped-cavity simulation of an integrated excitable two-section laser neuron in a generic InP PIC platform for neuromorphic applications

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Photonic components have gained renewed interest recently in use for neuromorphic applications. Solutions to various tasks such as image feature extraction or channel equalization in optical communications have been proposed, relying on optical neural networks. Spiking neural networks are regarded as promising architectures for energy efficient, event-based applications as they allow for spatio-temporal coding schemes and an increase in network sparsity. A well-known isomorphism between the behavior of spiking neurons and that of excitable semiconductor lasers has led to intensive research work on utilizing various laser designs for spike processing. VCSELs have been shown to be able to perform image processing tasks in experiments but are not easily suitable for scaling towards larger network sizes. Integrated lasers in InP photonic integrated circuits, however, can be readily made and interconnected with each other to scaled-up networks. We propose a two-section integrated laser design based on gain and saturable absorber sections that is compatible with generic InP foundry technology and use the lumped-cavity Yamada model to analyze its excitability behavior under optical pulse injection. The model parameters are based on prior extraction work performed for the InP PIC platform, which enables us to study the effect of design parameters on the excitability of the proposed laser. Our numerical results indicate a clear range of reasonable operating conditions for the injected current, the absorber control and optical stimulus where the laser is excitable. In that region, it reacts like a spiking neuron whereas outside that region, the laser can exhibit CW or self-pulsating behavior. The model can be used to synthesize concrete laser designs that are suitable for manufacturing in InP foundries.

Phase transition of spinor polariton condensates in magnetic field

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The effect of spin-orbit interaction and magnetic field on the formation of vortices in incoherently pumped polariton condensates is considered theoretically. The condensate is characterized by two polarizations described by Ginzburg-Landau equations coupled to the equations for the densities of the incoherent excitons. In wide range of parameters the system is multi-stable allowing for the formation of vortex states with different topological charges in each of the polarizations. However the probability of the formation of these vortex states from a weak noise can be very different and depends on the applied magnetic field strongly. By numerical simulations we demonstrate that a phase transition from a state with zero total topological charge to a state with non-zero total charge occurs if the magnetic field exceeds a threshold value. It is shown that the phase transition can be explained in terms of modes competition.

Lateral mode dynamics and non-linear filamentation in broad-area semiconductor lasers

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To generate high output powers and prevent catastrophic optical (mirror) damage, broad-area lasers have a large lateral aperture of some tens to hundreds of micrometers. As a result, they show a structured optical field and a reduced lateral beam quality compared to ridge-waveguide lasers with narrower apertures [1]. The structures of the optical field have sometimes been termed “filaments” [2] in analogy to the laser beam break-up resulting from propagation through a medium with a strong focusing Kerr nonlinearity. In semiconductor lasers this effect is small. However, an indirect dependence of the refractive index on the intensity results from the carrier density dependence of the refractive index in combination with spatial depletion of carriers in regions of high intensity [3]. To analyze the origin of the intensity modulation the software kit BALaser [4] is used. It bases on a traveling-wave model which properly describes the lateral-longitudinal complex spatio-temporal electro-optical characteristics of broad area lasers. Using this model, no ad-hoc assumptions of modes or stationarity are made and filamentation effects are automatically accounted for. Due to the highly dynamic optical field no indication of filamentation is found for realistic device structures. Instead, the optical field is structured by the transverse modes of the cavity [5,6].

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