Complex states of laser solitons: anti-vortices and mode-locking

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We present advances on the complex dynamics of spatial laser solitons in boroad-area vertical-cavity surface-emitting lasers with frequency-selective feedback. Fundamental solitons and high-order solitons acquire non-trivial polarization properties at high initial detuning between VCSEL and feedback resonance leading to a high threshold gain. A particular intriguing structure is a spontaneously forming vector vortex beam with an approximately doughnut-shaped intensity structure and a hyperbolic polarization structure (so-called “anti-vortex”). Vector vortex beams have interesting properties like classical entanglement and found considerable interest for applications in sensing, trapping and material processing. Another interesting feature is the demonstration of spatio-temporal solitonic structures: Three external cavity modes are locked to produce pronounced self-pulsing of fundamental spatial solitons. This creates temporal structures shorter than the external cavity round-trip time which share some properties with light bullets and thus provide a promising path to achieve 3D self-localization of light.

Rogue waves and related patterns

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Higher-order rogue-wave solutions of the nonlinear Schrödinger equation are the nonlinear superposition of first-order breathers. This hierarchy is subdivided into structures that exhibit varying degrees of radial symmetry, all arising from independent degrees of freedom associated with physical translations of component breathers. There are certain general rules required to produce these fundamental patterns. The patterns are complicated and include atomic-like structures, triangular cascades etc.

Bifurcations in closely coupled lasers

Amann, Andreas
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The field of photonics currently experiences a drive towards Photonic Integrated Circuits (PICs), where many interacting lasers and optical components are assembled on a single chip. In order to build a theoretical framework for the modelling of such devices, we consider two paradigmatic example systems: (i) closely coupled single mode lasers and (ii) injected two-mode lasers. In both cases we theoretically find nontrivial complex dynamical phenomena, including bursting and spontaneous symmetry breaking. In the case of injected two-mode lasers the phenomena are also reproduced experimentally with high accuracy.

Solitons on a background, Rogue waves, and Classical Soliton Solutions of extended Nonlinear Schrödinger Equations

Bandelow, Uwe
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For short pulses with wide spectrum, the Nonlinear Schrödinger Equation (NLS) has to be supplemented with additional terms that describe higher-order effects. If the coefficients are related in a special way, analytic solutions can be found, as, e.g., for the Hirota Equation and the Sasa-Satsuma equation (SSE). Recently, for the SSE, soliton solutions, and, more recently, heteroclinic connections have been presented. For SSE it will be considered the most general case of a soliton on a background solution and several limiting cases demonstrated. Among these limits are rogue waves and classical solitons with zero background.

Spiking dynamics in a micropillar laser

Barbay, Sylvain
(CNRS - UPR20, Laboratoire de Photonique et de Nanostructures, France)

Particle-like behavior of propagative dissipative optical solitons

Barland, Stéphane
(CNRS, Institut Non Linéaire de Nice, France)

Pulse train patterns of passively mode-locked semiconductor lasers: timing stability improvement and radio-frequency side-band suppression

Breuer, Stefan
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Pulse trains of ultra-short optical pulses with multi-gigahertz repetition rates generated by semiconductor lasers are affected by timing instabilities. To improve their timing stability, different experimental concepts exist, besides the laser design, and the control by optical self-feedback has proven as an effective technique. Recent investigations of the pulse train properties of a quantum dot semiconductor laser subject to an extended optical feedback configuration indicate a promising potential towards timing stability improvement and repetition rate control

Patterns in passively mode locked fibre laser

Broderick, Neil
(University of Auckland, Science Centre - Mathphysic, Auckland, New Zealand)

From stationary patterns to spatiotemporal chaotic textures in a liquid crystal light valve with optical feedback

Clerc, Marcel G.
(Universidad de Chile, Departamento de Física, Blanco Encalada 2008, Chile, Chile)

Macroscopic systems subjected to injection and dissipation of energy can exhibit complex spatiotemporal behaviors as result of dissipative self-organization. Despite the substantive theoretical and numerical progress to characterize these behaviors, its experimental implementation has been almost sterile. Here, we will present a two-dimensional pattern forming set up, which exhibits a transition from stationary patterns to spatiotemporal chaotic textures, based on a nematic liquid crystal layer with spatially modulated input beam and optical feedback. Using an adequate projection of spatiotemporal diagrams, we determine the largest Lyapunov exponent. Lyapunov exponents allow us to characterize the transition to chaos. This exponent and Fourier transform lead to a reconciliation of experimental observations and theoretical developments in spatiotemporal complexity. In particular, we can distinguish between spatiotemporal chaos and amplitude turbulence concepts; which are usually merged.

Nonlinear light propagation and solitonic localization in aperiodic and random photonic lattices

Denz, Cornelia
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Nonlinear photonics is one of the most forthcoming fields of modern photonics in the last decade due to its intriguing combination of nonlinear science with applications in information processing. An important cornerstone is the use of light itself to create nonlinear photonic structures. While in early years light was used in a simple way to create periodic refractive index material changes, by now the fascinating class of complex beams allows on the one hand creating novel structured nonlinear materials, and on the other hand exhibits surprising propagation features itself. Among these complex beams classes are nondiffracting beam families including Penrose to Weber beams that create novel aperiodic lattices, accelerating Airy beams and random beams. Transferring these beams into photonic lattices requires complete control of amplitude and phase in the transverse light field.

Light propagation in turn in these lattices is governed by nonlinear light-matter interacting and feedback effects and shows a series of nonlinear phenomena ranging from localization, soliton formation up to coherent backscattering and Anderson localization. Novel soliton dynamics and complex soliton formation have been demonstrated in these lattices.

In this contribution, we will present the fundamentals of formation and light propagation in these complex lattices and demonstrate new localization phenomena as soliton types as Weber of Airy solitons or coherent backscattering arising from the mutual interaction of photonic lattices with complex light.

Temporal and spectral dynamics in nonlinear microresonators

Erkintalo, Miro
(The University of Auckland, Department of Physics, Department of Physics, Auckland, New Zealand)

In this talk, I will review the nonlinear dynamics of continuously-driven optical microresonators. I will describe the physics and dynamics that underpin the generation of broadband optical frequency combs in Kerr nonlinear microcavities, as well as sketch future research directions that involve radically new classes of nonlinear resonators and correspondingly new types of nonlinear dynamics.

Photonic Information Processing using Semiconductor Lasers

Fischer, Ingo
(Consejo Superior de Investigaciones Científicas, IFISC, Nonlinear Photonics Lab, Palma de Mallorca, Spain)

Photonic transport in disordered random media and quasi-crystals

Frank, Regine
(Rutgers, The State University of New Jersey, Department of Physics and Astronomy, Piscataway, USA)

The Anderson transition was originally proposed for electrons, however it has been soon searched for all kinds of waves in disordered media. This physics became extremely interesting with the application of high amplitude excitations, where the medium is supposed to respond with non-linear effects. In theory it is ever since a challenge to treat large random ensembles numerically, even if the medium is completely non-resonant or passive. We discuss in this talk transport of light with respect to a quantum field theoretical approach and we explain through comparison to other existing theories, what the advantages of state of the art theory in that field is, especially with aperiodic and quasi-crystalline structures.

Progress in measuring rogue waves in linear and nonlinear optical systems

Genty, Goëry
(Tampere University of Technology, Optics Laboratory, Physics Department, Tampere, Finland)

We will provide a summary and overview of recent experiments in optics that show that rogue waves can be readily observed in both linear and nonlinear systems. In particular, we report rogue wave statistics of an optical field generated from purely linear propagation of random-phase induced speckle, and we also report experiments were we have measured in real time both the statistics and intensity profiles of nonlinear rogue waves emerging from spontaneous modulation instability.

Spontaneous mirror-symmetry breaking in two coupled photonic crystal nanolasers

Giacomotti, Alejandro
(CNRS UPR20, Laboratoire de Photonique et de Nanostructures, Marcoussis, France)

The interplay between photon tunneling and light-matter interactions in multi-well optical potentials is at the heart of many recent developments in quantum and nonlinear optics [1-3].
A key phenomenon taking place in double well potentials is the spontaneous breaking of the inversion symmetry: a bifurcation from delocalized to localized states in the wells, which are mirror images of each other. Although few theoretical studies have addressed mirror-symmetry breaking in micro and

nanophotonic systems, we provide here the first experimental evidence, using two evanescently coupled photonic crystal nanolasers [4]. We reveal a transition to spontaneously broken parity states in the form of a pitchfork bifurcation as long as the nonlinear interaction –the nonlinear nanolaser frequency shift– overcomes photon tunneling. Coexistence of these states is shown by switching them through short pulse perturbations in the cavities.
Our (spatially) bistable switchable nanolaser opens exciting prospects for the realization of scalable optical flip-flop memories based on symmetry breaking without any resonant driving beam. In addition, since the tunneling rate can be finely adjusted [5], we can predict such transitions with few intracavity photons for future nanolaser devices with strong quantum correlations.

[1] M. Abbarchi, et al., Nat Phys 9, 275 (2013).
[2] A. Dousse, et al., Nature 466, 217 (2010).
[3] T. C. H. Liew and V. Savona, Physical Review Letters 104, 183601 (2010).
[4] Ph. Hamel et al., Nature Photonics 9, 311 (2015)
[5] S. Haddadi et al., Optics Express 22, 12359 (2014)

Delayed feedback control of spatiotemporal patterns in a broad area vertical cavity surface emitting laser with saturable absorber

Gurevich, Svetlana
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We are interested in spatiotemporal dynamics of cavity solitons (CSs) in a transverse section of a broad area vertical cavity surface emitting laser (VCSEL) with saturable absorbtion subject to time-delayed optical feedback. In the absence of delayed feedback, a single branch of localized solutions appears in the parameter space. However, in the presence of the delayed feedback, multistability of CS solutions emerges; The branches of CSs fill the surface of the "solution tube" in the parameter space, which is filled densely with increasing delay time. Further, our study reveals that the multistability of stationary solutions is caused by a delayed-induced phase bifurcation of CSs. Furthermore, it was shown that stability properties of CSs strongly depend on the delayed feedback parameters. In particular, the thresholds of the drift and phase bifurcations as well as corresponding bifurcation diagrams are obtained by a combination of analytical and numerical continuation methods. In addition, we demonstrate that the presence of the delayed optical feedback can induce the drift bifurcation as well as the Hopf bifurcation and a period doubling route to chaos. Moreover, a coupling between this bifurcation scenario with delay-induced multistability leads to a complex spatiotemporal behavior of the system in question.

Feedback induced dynamics of passively mode-locked semiconductor lasers

Jaurigue, Lina
(Technische Universität Berlin , Institut für Theoretische Physik, Germany)

Semiconductor passively mode-locked lasers are promising candidates as sources of high-repetition rate, ultra-short light pulses for on-chip optical data communication and all-optical computing. However, for the use of these lasers to become viable the issue of their relatively large timing jitter must be overcome. One method to improve the pulse train regularity is to apply optical feedback. With correctly chosen feedback parameters very regular mode-locked dynamics can be achieved, however when feedback delay times are not integer multiples of the fundamental mode-locking repetition period a wide range of complex dynamics can be exhibited. Here we present a bifurcation analysis of the dynamics of a passively mode-locked laser subject to optical feedback and an investigation of the feedback induced multistability of mode-locked solutions.

Cavity Light Bullets in Passively Mode-Locked Semiconductor Lasers

Javaloyes, Julien
(Universitat de les Illes Balears, Non Linear Waves Group, Fisica: Non Linear Wave Group, Palma de Mallorca, Spain)

I demonstrate the existence of stable three dimensional dissipative localized structures in the output of a laser coupled to a distant saturable absorber. These phase invariant cavity light bullets are individually addressable and can be envisioned for three dimensional optical information storage. An effective theory provides for an intuitive picture and allows to relate their formation to the morphogenesis of static spatial auto-solitons and temporal cellular patterns.

Direction dependent dynamics in swept source lasers

Kelleher, Bryan
(University College Cork, Physics, Cork, Ireland)

Oscillator network emulated by photonic delay dynamics

Larger, Laurent
(University Bourgogne Franche-Comte, femto-st, Optics, Besancon, France)

Delay dynamics are well known for their infinite dimensional phase space. An analogy with space-time dynamics was proposed 20 years ago from a theoretical perspective. In this talk, we will develop such an analogy from two particular point of views recently explored through experimental investigations in photonic, with optoelectronic nonlinear delay oscillators.
Emerging and self-sustained spatio-temporal patterns, known as chimera states in network of oscillators, will be first reported and analyzed in such purely temporal, but high-dimensional enough, dynamics. The conditions for their occurrence will be described and analyzed with respect to the characteristic operating parameters of the delay dynamics, and a highly multistable organisation of the parameter space will be reported.
Second, a novel application of delay dynamics in photonic will be reported, consisting in a brain-inspired information processing system. Again, space-time properties will be emphasized, showing how a delay dynamics can efficiently emulate a network of neurons. An experimental speech recognition test will be reported with unprecedented processing speed, up to 1 million words/second classification rate, moreover with very low word error rate.

Big data approach to dynamical optical complexity

Masoller, Cristina
(Universitat Politecnica de Catalunya, Departament de Fisica, Terrassa, Spain)

In this talk I will discuss how nonlinear analysis tools, applied to the observed output signals of various optical systems, can provide new insights into their underlying dynamics. First, I will consider the spiking output of semiconductor lasers induced by optical feedback. I will show how symbolic ordinal analysis allows inferring relevant information about temporal correlations in the sequence of optical spikes [1]. Then, I will consider an example of a sudden transition: polarization switching in a vertical-cavity surface-emitting laser (VCSEL). By analyzing empirical data recorded from the polarization-resolved VCSEL output intensity, I will show that symbolic analysis tools provide early warning measures able to anticipate the abrupt switching [2]. Finally, I will analyze the transition from the laminar to the optical turbulent regime in a Raman fiber laser. By applying to experimental data symbolic analysis tools, we are able to uncover the presence of long temporal correlations in the laser intensity during transition, with well-defined intrinsic time-scales [3].
[1] A. Aragoneses et al, Sci. Rep. 4, 4696 (2014).
[2] C. Masoller et al, New Journal of Physics 17, 023068 (2015).
[3] A. Aragoneses et al, http://arxiv.org/abs/1505.07365, to appear in Phys. Rev. Lett. (2016).

Characterizing how Complex Optical Signals Emerge from Noisy Intensity Fluctuations

Quintero-Quiroz, Carlos Alberto
(Universidad Politécnica de Cataluña , Universidad Politécnica de Cataluña , Departamento de Física, Terrassa, Spain)

Identifying transitions to complex dynamical regimes is a fundamental open problem with many practical applications. Semiconductor lasers with optical feedback are excellent test-beds for studying such transitions, as they can generate a rich variety of output signals. Here we apply three analysis tools to quantify various aspects of the dynamical transitions that occur as the laser pump current increases. These tools allow to quantitatively detect the onset of different regimes and can be used for identifying the operating conditions that result in specific dynamical properties of the laser output. They can also be valuable for analyzing regime transitions in other complex systems.

Nonlinear Dynamics in Quantum Dot Micropillar Lasers

Reitzenstein, Stephan
(Technische Universität Berlin , Institut für Festkörperphysik, Germany)

Quantum dot microcavities are highly interesting systems to realize and study cavity quantum electrodynamics effects in the solid state. We take advantage of the underlying opportunities and combine this active field of nanophotonics with the field of nonlinear dynamics by external feedback coupling and optical injection of light into quantum dot microlasers. This opens up new perspectives and opportunities at the crossroads between classical and quantum physics in the few photon regime. For instance, we observe cavity enhanced emission of thermal light at the solitary frequency of a slave microlaser under external drive by tunable master laser.

Vortex Emission Accompanies the Advection of Optical Localized Structures

Rojas, René
(Pontificia Universidad Catolica de Valparaiso, Instituto de Fisica, Valparaíso, Chile)

We show that the advection of optical localized structures is accompanied by the emission of vortices, with phase singularities appearing in the wake of the drifting structure. Localized structures are obtained in a light-valve experiment and made to drift by a mirror tilt in the feedback loop. Pairs of oppositely charged vortices are detected for small drifts, whereas for large drifts a vortex array develops. Observations are supported by numerical simulations and linear stability analysis of the system equations and are expected to be generic for a large class of translated optical patterns.

Chimera States in Complex Networks

Schöll, Eckehard
(Technische Universität Berlin, Institut für Theoretische Physik, AG Nichtlineare Dynamik und Kontrolle, Berlin, Germany)

Chimera states are intriguing examples of spontaneous symmetry breaking and pattern formation in dynamical networks.
They consist of coexisting incongruous domains of spatially coherent (synchronized) and incoherent (desynchronized) dynamics in systems of nonlocally coupled oscillators, and they have recently been discussed
in diverse classical and quantum systems, including neuronal networks, nonlinear chemical and optical systems,
and coupled lasers [1]. We show that a plethora of novel chimera patterns
arise if one goes beyond the Kuramoto phase oscillator model and considers coupled amplitude and phase dynamics.
For the FitzHugh-Nagumo system [2,3], the Van der Pol oscillator [4,5], and the Stuart-Landau oscillator with S^1 symmetry-breaking coupling [6,7] various chimera patterns have been found.

Of particular current interest is the influence of complex network connectivities other than simple ring topologies.
To test the robustness of chimera patterns, we study small-world and fractal (hierarchical) topologies [3,5].
This is of relevance in neuroscience since there exists evidence that the connectivity in the brain has a

fractal structure.
We also address the emergence of coherence-resonance chimeras in excitable systems in the presence of noise [8].

A second focus of recent research are chimeras in small networks. Chimeras are generally difficult to observe in small
networks due to their short lifetime and erratic drifting of the spatial position of the incoherent domain. We propose a control scheme which can stabilize and fix the position of chimera states in small networks by symmetric and asymmetric
self-adaptive feedback control [9]. Like a tweezer, which helps to hold tiny objects, our control has two levers:
the first one prevents the chimera collapse, whereas the second one stabilizes its lateral position. The control scheme
might be useful in experiments, where usually only small networks can be realized.

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[1] E.~Schöll, S.~H.~L. Klapp, and P.~Hövel (Eds.): {\em Control of self-organizing nonlinear systems\/} (Springer, Berlin, 2016); M.~J. Panaggio and D.~M. Abrams, Nonlinearity {\bf 28}, R67 (2015).
[2] I. Omelchenko, O. E. Omel'chenko, P. Hövel, and E. Schöll, Phys. Rev. Lett. 110, 224101 (2013).
[3] I. Omelchenko, A. Provata, J. Hizanidis, E. Schöll, and P. Hövel, Phys. Rev. E 91, 022917 (2015).
[4] I. Omelchenko, A. Zakharova, P. Hövel, J. Siebert, and E. Schöll, Chaos 25, 083104 (2015).
[5] S.~Ulonska, I.~Omelchenko, A.~Zakharova, and E.~Schöll: {\em Chimera states in hierarchical networks of {Van der Pol} oscillators\/}, arXiv:1603.00171 (2016).
[6] A. Zakharova, M. Kapeller, and E. Schöll, Phys. Rev. Lett. 112, 154101 (2014).
[7] S.~Loos, J.~C. Claussen, E.~Schöll, and A.~Zakharova, Phys. Rev. E {\bf 93}, 012209 (2016).
[8] N. Semenova, A. Zakharova, V. Anishchenko, and E. Schöll (2016), arXiv:1512.07036.
[9] I.~Omelchenko, O.~Omel'chenko, A.~Zakharova, M.~Wolfrum, and E.~Schöll, Phys. Rev. Lett. {\bf 116}, 114101 (2016).

Light complexity in time and space and the underlying physics of analogies

Sciamanna, Marc
(CentraleSupélec, Campus de Metz, LMOPS , METZ, France)

This talk will cover several recent contributions to the emergence of nonlinear dynamics from laser diodes and other nonlinear beam interactions in optical cavities. It will focus in particular on the physics of analogies with concepts such as rogue waves and gravitational effects.

Interaction of temporal cavity solitons in driven fiber resonators and mode-locked lasers

Vladimirov, Andrei G.
(Weierstrass Institute for Applied Analysis and Stochastics,)

We investigate interaction of well-separated localized light pulses in the presence of periodic perturbations caused by periodic modulations or self-pulsing instability. We show that oscillating pulses emit weakly decaying dispersive waves leading to a strong enhancement of the interaction and formation of new types of bound states. We discuss the applicability of our analytical results to the interpretation of experimental and numerical data reported earlier.

Effects of Active-Medium Polarisation on Nonlinear Laser Dynamics

Wieczorek, Sebastian
(University College Cork, Department of Applied Mathematics, Cork, Ireland)

This paper examines laser stability during transition between class B and class C conditions, when the active-medium polarisation changes from a fast dynamical variable that can be adiabatically eliminated (class B lasers) to a regular dynamical variable that evolves on a similar timescale as the population inversion and laser intensity (class C lasers).
Firstly, we introduce geometrical concept of shear in the laser phase space and explain why class-B (semiconductor) lasers exhibit such a wealth of instabilities and chaos.
Secondly, we introduce relative stability difference and show, using the Maxwell-Bloch equations, that class C conditions can either stabilise or destabilise a laser. The stabilising effect is counter-intuitive and is demonstrated using examples of optical injection and time-delayed feedback, where, rather surprisingly, externally induced instabilities and chaos found for class B conditions disappear for class C conditions.
Thirdly, we perform systematic parametric study and identify combinations of laser parameters, i.e. the excitation rate, cavity detuning and ratio of laser-field to population-inversion decay rates, giving rise to the two opposite effects of transitioning from class B to class C operation. In particular, we show that the new stabilizing effect is robust, meaning that it can be found for a wide range of laser parameters.
The results give insight into stability of new generation of semiconductor emitters, such as quantum-dot lasers, quantum-cascade lasers, polariton lasers and nanolasers, being developed for applications in optical interconnects and quantum information.

Spatiotemporal Dynamics of Optical Pulse Propagation in Multimode Fibers

Wise, Frank
(Cornell University, School of Applied and Engineering Physics, Ithaca, USA)

Optical fibers designed to support multiple transverse modes offer opportunities to study wave propagation in a setting that is intermediate between single-mode fiber and free-space propagation. However, there are very few experimental studies of nonlinear pulse propagation in multimode fiber. As in single-mode fiber, solitons may be particularly important. Theoretical and experimental studies of the basic properties and spatiotemporal behavior of solitons in multimode fiber will be presented. Multimode solitons consist of synchronized, non-dispersing pulses in multiple spatial modes, which interact via the Kerr nonlinearity of the fiber.

At higher powers, self-focusing and multiple filamentation are observed at a fraction of the critical power. By varying the launched spatial modes, it is possible to generate megawatt ultrashort pulses tunable between 1550 and 2200 nm, dispersive waves over one octave in frequency, intense combs of visible light, or continua that span multiple octaves.

Possible directions for studies of new nonlinear wave physics in multimode fibers will be discussed along with potential applications.