WIAS Workshop
“Optical Solitons and Frequency Comb Generation”

Weierstrass Institute for Applied Analysis and Stochastics

September 18 – 20, 2019

www.wias-berlin.de/workshops/osc19/

WIAS

Weierstraß-Institut für
Angewandte Analysis und Stochastik

www.wias-berlin.de

Halbleiter-Nanophotonik
SFB 787

Edited by
Weierstraß-Institut für Angewandte Analysis und Stochastik (WIAS)
Mohrenstraße 39
10117 Berlin
Germany

Fax: +49 30 20372318
World Wide Web: http://www.wias-berlin.de

Contents

General information

Dear Participant,

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

Entrance to the building will be provided showing your participants badge. Please make sure to wear it anytime you want to enter the building. Otherwise the porter won't let you access the building.

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

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

Smoking in the building is <u>not allowed</u>. As your coffee breaks take place on the ground floor, please use this opportunity to smoke outside of the building.

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

User name	**wiasosc**	OK
Password	**wI&A6FX9**	OK

For logout, you can use the Log out -selection on the K-menu (left down corner).

Please be aware that this account is used by all workshop participants. Therefore, do not leave any confidential data in its home directory. All remaining files will be deleted after the workshop.

Additionally, there is the possibility to use a WiFi connection with your own laptop.
Please ask Laura Wartenberg for your personal WiFi card.

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

Workshop dinner will be held in the restaurant MAXIMILIANS, FRIEDRICHSTR. 185–190, 10117 BERLIN on Thursday, September 19, 2019 at 7:00 p.m. The menu is covered by the conference fee, consisting of starter (salad or soup), main course, dessert and one drink.

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

Yours sincerely,
Organizers

Wednesday, 18.09.2019

08:30 - 09:20	Registration
09:20 - 09:30	Opening
09:30	**Nail Akhmediev** Recent advances in rogue wave theory
10:00	**Giovanna Tissoni** Spatiotemporal extreme events in spatially extended lasers
10:30 - 11:00	Coffee break
11:00	**Sergei Turitsyn** Characterisation of solitons in fibre lasers
11:30	**Goëry Genty** Real-time characterization of nonlinear instabilities in optical fibre systems
12:00	**Maria Chernysheva** Ultrafast dissipative soliton dynamics in isolator-free ring mode-locked laser
12:30 - 14:00	Lunch break
14:00	**Guillaume Huyet** Optical feedback in frequency swept sources
14:30	**Dmitry Skryabin** Parametric frequency comb in microresonators
15:00	**Kestutis Staliunas** Gain-through-filtering enables tuneable frequency comb generation in passive optical resonators
15:30	**Sergey Sergeyev** Vector spatiotemporal structures in mode-locked fibre lasers
16:00 - 16:30	Coffee break
16:30	**Svetlana Slepneva** Dynamics of long cavity lasers
17:00	**Mark Schmidt** On the formation of frequency combs in Fourier domain mode-locked (FDML) lasers
17:20	**Pedro Parra-Rivas** Localized structures and frequency combs in dispersive optical parametric oscillators
17:40	**Sebastian Eydam** Mode-locked solutions in systems of globally-coupled phase oscillators
18:00 - 20:00	Get-together

Thursday, 19.09.2019

09:00	**Ulf Leonhardt** Optical analogue of the event horizon
09:30	**Fabio Biancalana** From black holes to solitons, and viceversa
10:00	**Svetlana Gurevich** Impact of high-order effects on soliton explosions in the complex cubic-quintic Ginzburg–Landau equation
10:20 - 11:00	Coffee break
11:00	**Stefan Rotter** Introducing the random anti-laser: Coherent perfect absorption in disordered media
11:30	**Vladimir Konotop** Nonlinearity controlled by an exceptional point: Solitons in waveguides with absorbing boundary conditions
12:00	**Matthias Heinrich** Nonlinear discrete optics in femtosecond laser-written photonic lattices
12:30 - 14:00	Lunch break
14:00	**Mustapha Tlidi** Nonlocal-delayed Raman effect induces moving localized structures in optical resonators
14:30	**Serhiy Yanchuk** Temporal dissipative solitons in delay feedback systems
15:00	**Yuriy Maistrenko** Dissipative solitons for delayed-feedback systems
15:30 - 16:00	Coffee break
16:00	**Krassimir Panayotov** Polarization dynamics of mode-locked VECSELs
16:30	**Günter Steinmeyer** Pseudo mode-locking
17:00	**Julien Javaloyes** Third order dispersion in mode-locked vertical external-cavity surface-emitting lasers
17:30 - 17:50	**Christian Schelte** Tunable Kerr frequency combs and cavity solitons in a nonlinear time-delayed Gires–Tournois interferometer
19:00 - 22:00	Conference dinner

Friday, 20.09.2019

09:00	**Stephan Reitzenstein** Physics and applications of nano- and microlasers operating close to the thresholdless regime
09:30	**Alexey Yulin** Spontaneous symmetry breaking and the formation of nonlinear optical patterns in the systems with bound states in the continuum
10:00 - 10:30	Coffee break
10:30	**Kathy Lüdge** Localization features in passively mode-locked lasers with V-shaped cavity geometry
11:00	**Massimo Giudici** Temporal localized structures in mode-locked vertical external-cavity surface-emitting lasers
11:30	**Rostislav Arkhipov** Self-induced transparency mode-locking: Towards to single-cycle pulse generation
11:50 - 12:00	Closing

Recent advances in rogue wave theory

Nail Akhmediev

Optical Sciences Group, Research School of Physics and Engineering, Australian National University

New results on the theory of rogue waves will be presented. These are based on infinitely extended nonlinear Schrödinger equation, complex KdV equation and Gardner equation.

Self-induced transparency mode-locking: Towards to single-cycle pulse generation

Rostislav Arkhipov

St. Petersburg State University, ITMO University, Ioffe Institute

Passive mode-locking (PML) is a well-known method to generate ultra-short pulses in lasers. It arises due to the incoherent absorption/gain saturation and pulse duration cannot be shorter than polarization relaxation time T_2 of the gain/absorber media. In contrary, self-induced transparency mode-locking (SIT ML) or coherent mode-locking (CML) technique is based on SIT soliton (2π pulse) formation in absorber media [1-6]. It allows generating optical pulses with duration much shorter than the medium polarization relaxation time T_2. SIT ML is interesting because it allows single-cycle pulse generation with ultra-high repetition rate [1, 6]. Up to now SIT ML was studied only theoretically [1-3]. In this talk, we present our recent experimental results on SIT ML in Ti:Sapphire laser with a coherent absorber cell (Rb vapors) [4-6]. We show that ML arises due to SIT pulse formation in rubidium and not due to Kerr-lens mechanism or absorption saturation. We demonstrate experimentally that pulse duration decreases with the increase of generation power due to SIT phenomenon. In standard PML lasers the situation is vice versa: pulse duration increases with the increase of generation power. Although in the experiment laser pulses have picosecond duration (which is two order of magnitude shorter than T_2 in Rb), these experimental results are the first step towards realization of the PML with pulse durations, which are not limited by the absorber/amplifier line width. In addition, we study theoretically the possibility of few- and single-cycle pulse generation via SIT ML in lasers with linear cavity [6]. Our analysis is based on numerical solution of Maxwell-Bloch equations beyond slow varying and rotating wave approximations. The generation of single-cycle pulses is relevant due to the fact that they allow the generation of unipolar pulses. Unipolar pulses can have a more efficient effect on quantum objects compared to bipolar femtosecond pulses [6-7]. A more detailed analysis of the presented results can be found in review [6]. This work is supported by Russian Science Foundation (project 19-72-00012).

References:

[1] V.V. Kozlov, N.N. Rosanov, and S. Wabnitz, Phys. Rev. A, V.84, p. 053810 (2011).

[2] R.M. Arkhipov, M.V. Arkhipov, I. Babushkin, Optics Communications, V. 361, pp. 73-78, (2016).

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

[4] M. V. Arkhipov, R. M. Arkhipov, A. A. Shimko, I. Babushkin, and N. N. Rosanov, JETP Lett., Vol. 109(10), pp. 634-637 (2019).

[5] M.V. Arkhipov, R.M. Arkhipov, A.A. Shimko, I. Babushkin, N.N. Rosanov, submitted [arXiv preprint arXiv:1906.04587].

[6] R. M. Arkhipov, M. V. Arkhipov, A. A. Shimko, A. V. Pakhomov, N.N. Rosanov, JETP Lett. V. 110(1) (2019), in press [Pis'ma v Zh. Eksp. Teor. Fiz. V.110(1), pp. 9-20 (in Russian)].

[7] R.M. Arkhipov, A.V. Pakhomov, M.V. Arkhipov, I. Babushkin, A. Demircan, U. Morgner, N.N. Rosanov, Optics letters, V. 44 (5), pp. 1202-1205 (2019).

From black holes to solitons, and viceversa

Fabio Biancalana

Heriot-Watt University, Edinburgh

I will give an overview of the recent research in my group on the strict relation between real physical black holes in any dimensions and solitons in 1+1 dimensions. This relation allowed the discovery of previously unknown topological formulas in general relativity.

Ultrafast dissipative soliton dynamics in isolator-free ring mode-locked laser

Maria Chernysheva

Leibniz Institute of Photonic Technology, Jena

The presentation will cover investigation of a hybrid mode-locked Erbium-doped fibre ring laser without optical isolator. Creating different losses in the cavity for counter-propagating pulses via adjustment of net birefringence, the laser can operate in both unidirectional regimes with extinction over 22 dB, as well as can establish stable bidirectional generation. By using newly emerged high precision real-time measurement technologies of spatio-temporal intensity reconstruction and dispersive Fourier transformation, the ultrafast dynamics of solitons, including their formation, has been studied in bidirectional generation regime.

Mode-locked solutions in systems of globally-coupled phase oscillators

Sebastian Eydam

WIAS Berlin

In systems of globally-coupled phase oscillators with equidistant natural frequencies, one can observe an interesting collective phenomenon below the synchronization threshold. The collective behavior is characterized by sharp pulses in the mean-field amplitude and therefore appropriately called mode locked. We discuss the emergence of this particular type of solution as well as the typical bifurcation scenarios at the stability boundaries. In large ensembles, where the natural frequencies are drawn from a multi-modal frequency distribution, mode-locked solutions are observed as a macroscopic phenomenon and the breakdown of the pulsation is explored for increased disorder in the natural frequencies.

Real-time characterization of nonlinear instabilities in optical fibre systems

Goëry Genty

Tampere University

The study of instabilities in optics has attracted significant interest over the past few years. This is partly due to their ubiquitous nature and universal physical character but also to the many dramatic progress in the real-time measurement of ultrafast optical signals. Real-time studies have been performed either in the in the spectral domain with sub-nm resolution using the time-stretch technique, or in the time domain using a time lens approach to obtain sub-picosecond resolution. In nonlinear optical fibres, these real-time techniques have been applied to characterize the propagation of intense fields in the nonlinear regime, allowing e.g. to get insight into the statistical properties modulation instability and supercontinuum generation or into the dynamics of optical turbulences and complex dissipative systems. In this talk, we will review our recent work in this area, including the use of machine learning to obtain time-domain information from real-time spectral intensity measurements as well as the observation of a range of instability processes in dissipative systems such as the soliton-similariton laser.

Temporal localized structures in mode-locked vertical external-cavity surface-emitting lasers

Massimo Giudici

Institut de Physique de Nice, Université Côte d'Azur

In this paper we demonstrate Temporal Localized Structures (TLS) in a self-imaging passive mode-locked system based on an optically-pumped Vertical External Cavity Surface Emitting Laser (VECSEL). Both the gain mirror and the SESAM have been specially grown by MOCVD and engineered to match the parameters requirement for achieving time localization according to a theoretical model based upon Delay Algebraic Equations. Our result paves the way towards the observation of spatio-temporal localized structures, also called dissipative light bullets (LBs).

Impact of high-order effects on soliton explosions in the complex cubic-quintic Ginzburg–Landau equation

Svetlana Gurevich

Institute for Theoretical Physics, University of Münster

We investigate the impact of higher-order nonlinear and dispersive effects (HOEs), namely, third-order dispersion, self-steepening and self-frequency shift determined by the intrapulse Raman scattering on the dynamics of a single soliton solution in the complex cubic-quintic Ginzburg-Landau equation. Using the path following techniques, we reconstruct the branches of a single localized pulse and show that HOEs split the symmetric and asymmetric explosion modes, leading to the formation of left- and right- one-side periodic explosions. Further we show how the interplay of the HOEs results in the controllable selection of right- or left-side periodic explosions. In addition, we demonstrate that HOEs induce a series of pulsating instabilities, significantly reducing the stability region of the single soliton solution.

Nonlinear discrete optics in femtosecond laser-written photonic lattices

Matthias Heinrich

Experimental Solid-State Optics Group, Institute of Physics, University of Rostock

Discrete systems constitute a particularly fruitful playground for nonlinearity to unfold its influence on coherent wave dynamics, as the underlying periodicity may serve as safety net to stave off potentially undesirable runaway effects and instabilities. In the context of optics, femtosecond laser-written waveguide lattices have emerged as versatile platform for the experimental investigation of light propagation in discrete optical systems with Kerr nonlinearity, as well as a host of different physical scenarios ranging from quantum mechanical and solid-state effects to relativistic dynamics, non-Hermitian systems and even supersymmetry. This presentation will provide a brief overview of the technological aspects that enable our research along these lines, and review some of the key results relating to discrete solitons, the all-optical routing of wave packets, and nonlinear spatiotemporal dynamics.

Optical feedback in frequency swept sources

Guillaume Huyet

Université Côte d'Azur, CNRS, INPHYNI

An abstract is not available.

Third order dispersion in mode-locked vertical external-cavity surface-emitting lasers

Julien Javaloyes

Nonlinear Waves Group, Departament de Física & IAC-3, Universitat de les Illes Balears

Time-delayed dynamical systems materialize in situations where distant, point-wise, nonlinear nodes exchange information that propagates at a finite speed. We show how purely dispersive effects appear naturally in some delayed systems and we exemplify our result by studying theoretically and experimentally the influence of third order dispersion in a system composed of coupled optical micro-cavities. Dispersion induced pulse satellites emerge symmetrically and destabilize the mode-locking regime.

Nonlinearity controlled by an exceptional point: Solitons in waveguides with absorbing boundary conditions

Vladimir Konotop

Department of Physics, Faculty of Sciences, University of Lisbon

It is shown that in planar waveguides with weakly nonlinear active core and absorbing boundaries there can exist continuous families of solitons. Stable propagation of TE and TM-polarized solitons is accompanied by attenuation of all other modes. If the linear spectrum of the waveguide possesses an exceptional point an originally focusing (defocusing) material nonlinearity may become effectively defocusing (focusing). This occurs due to the geometric phase of the carried eigenmode when the surface impedance encircles the exceptional point. The existence of an exceptional point can also result in anomalous enhancement of the effective nonlinearity.

Optical analogue of the event horizon

Ulf Leonhardt

Weizmann Institute of Science, Rehovot

The theory of Hawking radiation can be tested in laboratory analogues of black holes. We use light pulses in nonlinear fiber optics to establish artificial event horizons. Each pulse generates a moving perturbation of the refractive index via the Kerr effect. Probe light perceives this as an event horizon when its group velocity, slowed down by the perturbation, matches the speed of the pulse. We have observed in our experiment that the probe stimulates Hawking radiation, which occurs in a regime of extreme nonlinear fiber optics where positive and negative frequencies mix.

Localization features in passively mode-locked lasers with V-shaped cavity geometry

Kathy Lüdge, **Jan Hausen**

Technische Universität Berlin, Institut für Theoretische Physik

Passively mode-locked semiconductor lasers provide an efficient and cost effective opportunity to generate short optical pulses. Additional to the gain section they inhibit a saturable absorber section, which leads to pulsed regime that are energetically favourable compared to continuous wave operation. Under certain conditions, e.g. a large cavity round-trip time T relative to the carrier recovery in the gain γ_g^{-1} ,a multi-stability can be found between the stable off-solution and the periodic fundamental and harmonic mode locking solutions [1], which is an indication for localized structures in the time domain. As the gain recovery time is the slowest time scale of the system, pulses propagating along the cavity only interact via the charge carriers in the gain medium. Therefore, additional pulses can be individually addressed inside the cavity by inducing a modulation to the gain. These localized structures have been investigated experimentally and theoretically by using a generic model based on delay differential equations. In order to describe the effects of the cavity configuration on the emergence of localized structures, we utilize a DDE model also considering the characteristics of a V-shaped external cavity geometry [2]. These types of lasers qualify for possible applications of localized pulses such as optical buffers or on demand pulse systems. We perform a bifurcation analysis as well as direct numerical integration, in order to unravel the influence of the cavity geometry on the existence of localized pulses in these types of lasers. We find a multi-stability of the fundamental and harmonic mode-locking solutions below the lasing threshold. From this starting point, we show that introducing asymmetries to the cavity, i.e. shifting the gain-ship to either the absorber or the out-coupling lens, can be beneficial for the formation of localized structures.

References:

[1] M. Marconi, J. Javaloyes, S. Balle, M. Giudici, *How Lasing Localized Structures Evolve out of Passive Mode Locking*, Phys Rev Lett. **112**, 223901 (2014).

[2] J. Hausen, S. Meinecke, B. Lingnau, and K. Lüdge, *Pulse Cluster Dynamics in Passively Mode-Locked Semiconductor Vertical-External-Cavity Surface-Emitting Lasers*, Phys. Rev. Appl. **11**, 044055 (2019).

Dissipative solitons for delayed-feedback systems

Yuriy Maistrenko

Institute of Mathematics NAS of Ukraine

We demonstrate how nonlinear delayed-feedback in the Ikeda equation can induce solitary impulses, i.e. dissipative solitons. The soliton state is clearly identified in a virtual space-time representation of the equations with delay, under a condition of bi-stability of the nonlinear function. The phenomenon is revealed for a nonlinear photonic system with two highly asymmetric delays [1], and for an electronic experiment with only one delay with negative feedback [2]. Along with the single spiking soliton, a variety of compound soliton-based structures is obtained. The number of coexisting multi-soliton states is fast growing with delay opening new perspectives in the context of information storage.

References:

[1] D. Brunner, B. Penkovsky, R. Levchenko, E. Schöll, L. Larger, and Yu. Maistrenko. Two-dimensional spatiotemporal complexity in dual-delayed nonlinear feedback systems: Chimeras and dissipative solitons. Chaos 28, 103106 (2018).

[2] V. Semenov and Yu. Maistrenko. Dissipative solitons for bistable delayed-feedback systems. Chaos 28, 101103 (2018).

Polarization dynamics of mode-locked VECSELs

Krassimir Panayotov[1,2], Andrei G. Vladimirov[3] and Mustapha Tlidi[4]

[1] *Vrije Universiteit Brussel*
[2] *Institute of Solid State Physics*
[3] *WIAS Berlin*
[4] *Universit libre de Bruxelles (ULB)*

VCSELs exhibit interesting polarization dynamics due to the lack of strong polarization selectivity mechanism [1]. Well accepted model reproducing these intriguing polarization dynamics is the so called Spin-Flip Model or SFM [2], which takes into account the carrier spin-dynamics during transitions between conduction band and heavy hole valence band in quantum well active material. SFM also explains the peculiar polarization properties of cavity solitons in broad area VCSELs [3, 4]. Recently, a spin-flip model for a broad-area VCSEL with a saturable absorber predicted a period doubling route to spatially localized chaos of elliptically polarized cavity solitons [5]. Although many research has been devoted to polarization dynamics of VCSELs, such studies for Vertical External-Cavity Surface-Emitting Lasers (VECSELs) are lacking. VECSELs are very well-suited for mode-locked (ML) operation by utilizing saturable absorber either as a mirror in the external cavity [6] or integrated in the gain-chip [7]. To the best of our knowledge, the impact of spin-flip dynamics on light polarization emission in ML operating VECSELS has not been considered. Here, we introduce a time-delayed SFM for VECSELs with saturable absorber mirror based on extension of the Vladimirov-Turaev model for ML semiconductor lasers [8] and reveal the existence of polarization multistability of the system. First, by including the spin-flip dynamics and phase and amplitude anisotropies we demonstrate that Vladimirov-Turaev SFM reproduces the existence of polarization instabilities and polarization switching in a similar fashion as the original SFM. Time trances for parameters typical for the VECSEL configuration are presented in Fig. 1, where (a) and (b) show that the fundamental ML can actually be realized for two orthogonal linear polarizations “X” and “Y” and (c) demonstrates more complicated dynamics with the two linear polarizations competing.

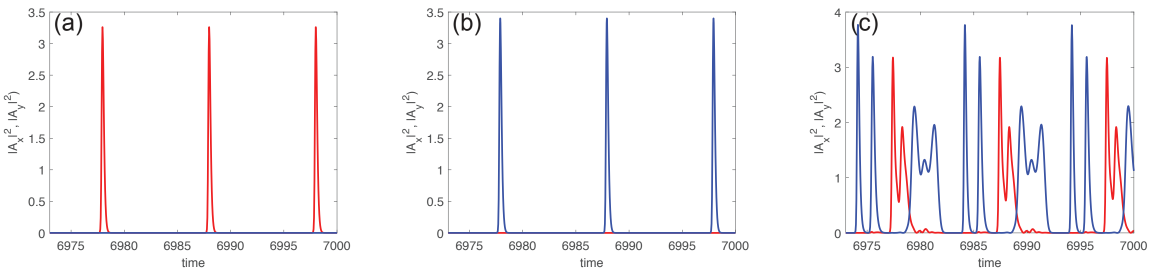

Figure 1: Time trances in different dynamical regimes of Vladimirov-Turaev SFM: fundamental mode-locking for “X” (a) and “Y” (b) linear polarization emission and multipulse regime in alternating “X” and “Y” polarization states (c).

K.P. acknowledges the FWO-Vlaanderen project GOE5819N and A.G.V. acknowledges the DFG project SFB 787.

References:

[1] K. Panajotov, F. Prati, Polarization Dynamics of VCSELs, ch.6 in VCSELs, R. Michalzik (ed), Springer Ser. Opt. Sciences 166, 181-232 (2013).

[2] M. San Miguel, Q. Feng, J. V. Moloney, ”Light-polarization dynamics in surface-emitting semiconductor lasers”, Phys. Rev. A 52, 1728 (1995).

[3] X. Hachair, G. Tissoni, H. Thienpont, K. Panajotov, ”Linearly polarized bistable localized structure in a medium size vertical-cavity surface-emitting laser”, Phys. Rev. A 79, 011801(R) (2009).

[4] E. Averlant, M. Tlidi, H. Thienpont, T. Ackemann, K. Panajotov, ”Vector cavity solitons in broad area Vertical-Cavity Surface-Emitting Lasers”, Sci. Rep. 6, 20428 (2016).

[5] K. Panajotov, M. Tlidi, Localized chaos of elliptically polarized cavity solitons in broad-area VCSEL with a saturable absorber, Opt. Lett. 43, 5663 (2018).

[6] Keller, U., Tropper, A. C., Passively modelocked surface-emitting semiconductor lasers, Phys. Reports, 429, 67-120 (2006).

[7] Maas, D.C., Bellancourt, A.R., Rudin, B., Golling M, Unold, H. et al., Vertical integration of ultrafast semiconductor lasers, Appl. Phys. B 88, 493-495 (2007).

[8] A. Vladimirov, D. Turaev, ”Model for passive mode locking in semiconductor lasers”, Phys. Rev. A 72, 033808 (2005).

Localized structures and frequency combs in dispersive optical parametric oscillators

Pedro Parra-Rivas

OPERA-photonics, Université libre de Bruxelles, Laboratory of Dynamics in Biological Systems, KU Leuven Department of Cellular and Molecular Medicine, University of Leuven

Recently quadratic dispersive optical resonators have been considered as new sources for frequency comb generation [1-3]. In contrast to Kerr combs, quadratic ones may operate with decreased pump power and can achieve spectral regions non accessible before. These combs in the frequency spectrum correspond to different type of dissipative structures circulating inside the cavity. Therefore the understanding of the dynamics of such structures is of crucial importance. In particular here we focus on the study of localized structures (LSs) since they correspond to broadband, coherent temporal pulses with a fixed repetition rate, which are one of the most important waveforms for frequency comb generation. To do so we consider a dispersive cavity with a quadratic medium phase matched for degenerate optical parametric oscillations (OPOs), and driven by an electric field at frequency $2\omega_0$ in a doubly resonant configuration. This type of cavities can be described by a mean-field model for the slowly varying envelopes A, and B, of the electric field centered at frequencies ω_0 and $2\omega_0$, respectively [4]:

$$\partial_t A = -(1 + i\Delta_1)A - i\eta_1\partial_\tau^2 A + iBA^* \tag{1}$$

$$\partial_t B = -(1 + i\Delta_2)B - \left(d\partial_\tau + i\eta_2\partial_\tau^2\right) B + iA^2 + S, \tag{2}$$

These equations are formally equivalent to those describing diffracting cavities [5], although in this case a large walk-off d, related with the difference of group velocities between the fields A and B, is present. Often this walk-off avoids the formation of LSs, and therefore it is desirable to suppress it. This can be done by dispersion engineering as already shown in [6]. In what follows we consider that $d = 0$ and that we have natural phase-matching such that the phase detuning for A and B relates as $\Delta_2 = 2\Delta_1$ [2]. When bistability between trivial and non-trivial continuous wave (CW) solutions is achieved, LSs of different widths can be formed through the locking of domain walls [4,7].

Using numerical continuation techniques we find that these LSs undergo a *collapsed snaking* bifurcation structure when varying the pump intensity S [8]. The LSs' solution branches oscillate back and forth in S around the Maxwell point of the system, and collapse to that point as increasing the energy of the cavity. These types of LSs and its associated collapsed snaking have been studied in detail in the context of Kerr cavities [7]. We find that when increasing the value of η_2 these type of solutions tend to disappear. However, when decreasing η_2, the region of existence broadens, and therefore LSs are easier to find. This type of solutions have not yet been studied in the context of dispersive OPO cavities, and we strongly believe that these LSs may be very relevant for the generation of frequency combs in this type of systems.

References:

[1] I. Ricciardi, *et al.*, Phys. Rev. A **91**, 063839 (2015).

[2] F. Leo, *et al.*, Phys. Rev. Lett. **116**, 033901 (2016).

[3] S. Mosca, *et al.*, Phys. Rev. Lett. **121**, 093903 (2018).

[4] P. Parra-Rivas, *et al.* (submitted).

[5] G.-L. Oppo, A. J. Scroggie, and W. J. Firth, J. Opt. B: Quantum Semiclass. Opt. **1** 133–138 (1999).

[6] T. Hansson, *et al.*, Opt. Lett. **43**, 6033 (2018).

[7] P. Parra-Rivas, *et al.*, Opt. Lett. **41**, 2402 (2016).

[8] P. Parra-Rivas, L. Gelens, and F. Leo, Phys. Rev. E. (submitted) (2019).

Physics and applications of nano- and microlasers operating close to the thresholdless regime

Stephan Reitzenstein

Technische Universität Berlin

Nano- and microlasers are exciting devices to explore the limits of semiconductor lasers. Of particular interest is the ultimate limit of thresholdlesss lasing where all spontaneously emitted photons are coupled into the laser mode. I present examples of such lasers and highlight difficulties in demonstrating laser action in these devices. Moreover, I present the application of a microlaser to trigger the emission of indistinguishable photons in the field of quantum nanophotonics.

Introducing the random anti-laser: Coherent perfect absorption in disordered media

Stefan Rotter

Institute for Theoretical Physics, Vienna University of Technology (TU Wien)

In my talk I will present the concept of random anti-lasing, i.e., the time-reverse of random lasing. In the same way as a random laser emits a spatially complex but coherent wave at its first lasing threshold, the random anti-laser absorbs such a complex incoming field perfectly. We recently implemented this concept in a microwave experiment, where an absorber is embedded in the middle of a disordered medium [1]. Measuring the 8x8 scattering matrix of this structure allows us to calculate and then generate an incoming wave field that gets absorbed by more than 99.7 percent inside the disorder. Our setup is scalable in the number of involved modes and can easily be transferred to other wave scattering systems. I will conclude with an outlook on the possible applications of this novel technology and with a discussion of how to generate wave fields with optimal properties in general [2].

References:

[1] K. Pichler, M. Kühmayer, J. Böhm, A. Brandstötter, P. Ambichl, U. Kuhl, and S. Rotter, Nature 567, 351 (2019).

[2] M. Horodynski, M. Kühmayer, A. Brandstötter, K. Pichler, Y. V. Fyodorov, U. Kuhl, and S. Rotter, arXiv:1907.09956

Tunable Kerr frequency combs and cavity solitons in a nonlinear time-delayed Gires–Tournois interferometer

Christian Schelte

Nonlinear Waves Group, Departament de Física & IAC-3 , Universitat de les Illes Balears

We study theoretically a new set-up allowing for the generation of cavity solitons and frequency combs. The setup is compact (a few cm) and can be implemented using established technologies, while offering tunable repetition rates and potentially high power operation. It consists in a vertical micro-cavity, operated in the Gires-Tournois regime, containing a Kerr medium. The micro-cavity experiences strong time-delayed optical feedback as well as detuned optical injection. We present sets of multistable dark and bright cavity solitons coexisting on their respective bistable homogeneous backgrounds. Cavity solitons appear through the locking of pairs of front. The third order dispersion induced by the Gires-Tournois interferometer causes the further locking of the cavity solitons via their oscillating tails, which leads to regular and potentially useful frequency combs for optical data transmission and metrology.

On the formation of frequency combs in Fourier domain mode-locked (FDML) lasers

Mark Schmidt

Department of Electrical and Computer Engineering, Technical University of Munich

Fourier domain mode-locked lasers are broadband tunable light sources with record sweep rates in which a tunable bandpass filter is synchronized with the roundtrip time of the optical field. Recently, an ultra-stable operating regime with a nearly shot-noise limited intensity trace over a sweep bandwidth of more than 100 nm and a repetition rate of 3.2 MHz was experimentally demonstrated featuring a highly coherent output. Beating experiments have additionally shown that a well defined phase relationship between consecutive sweeps exists. We demonstrate a numerical model describing ultra-stable operation in single polarization setups. This model shows excellent agreement with experimental data and is able to reproduce noise patterns in the intensity trace when the laser is operated beyond the ultra-stable regime inducing non-stationary phase fluctuations. In particular, we investigate the sweep to sweep evolution in different operating regimes and discuss the formation of frequency combs in ultra-stable FDML lasers.

Vector spatiotemporal structures in mode-locked fibre lasers

Sergey Sergeyev

Aston Institute of Photonic Technologies, Aston University

For Erbium-doped fibre laser, we review our recent theoretical results on emergence of different spatiotemporal structures including rogue waves driven by polarisation instabilities [1-4]. The recent theoretical analysis demonstrated that the vector model of mode-locked fibre laser presents a heteroclinic system where the laser's eigenstates – orthogonal states of polarisation (SOPs) – are quasi-equilibrium points [1-4]. The heteroclinic orbit is a trajectory periodically evolving nearby the neighbourhood of one of the orthogonal SOPs with further switching to and evolving nearby the other SOP [1-4]. The dwelling time for the trajectory near each orthogonal SOP is determined by the cavity anisotropy controlled by the pump power distribution between the eigenstates adjustable with the help of the polarisation controller for the pump wave [1-4]. The escape from the neighbourhood of each SOPs is driven by the in-cavity birefringence tunable with the help of the in-cavity polarisation controller. It has been shown theoretically that adjustment of the in-cavity polarisation controller can result in matching conditions of the Shilnikov chaos [5, 6] and so dynamics quite similar to the experimental was observed [1-4].

References:

[1] S. V. Sergeyev, Optics Lett. 41, 4700-4703 (2016).

[2] S V Sergeyev, et al. In book "Nonlinear Guided Wave Optics: A testbed for extreme waves", Chapter 9 "Vector rogue waves driven by polarisation instabilities", ed. by Stefan Wabnitz (IOP Publishing, 2018) p. 9-01 - 9-24.

[3] H. Kbashi, S. V. Sergeyev, et al. Annalen der Physik, 530, 1700362 (2018).

[4] S.V. Sergeyev et al. Phys. Rev. Lett. 118(3), 033904 (2017).

[5] G. Tigan and D. Opriş. Chaos, Solitons & Fractals 36, 1315 (2008).

[6] C. P. Silva, Shil'nikov's theorem-a tutorial. IEEE Transactions on Circuits and Systems I: Fundamental Theory and Applications, 40, 675-682 (1993).

Parametric frequency comb in microresonators

Dmitry Skryabin

University of Bath

Microresonator optical frequency comb devices is a disruptive technology in the area of precision spectroscopy and information processing rapidly entering into the application markets and generating a plethora of fundamental problems to address. One such problem is using materials with quadratic, $\chi^{(2)}$, nonlinearity for the microresonator frequency comb generation and, within such devices, distinguishing between the $\chi^{(2)}$ and Kerr effect induced frequency conversions. In this work we report the soliton frequency comb generation in microring optical parametric oscillators operating in the down-conversion regime and with the simultaneous presence of the $\chi^{(2)}$ and Kerr nonlinearities. The combs are studied considering a typical geometry of a bulk $LiNbO_3$ toroidal resonator with the normal group velocity dispersion spanning an interval between the pump and the down-converted signal. We have identified critical power signaling a transition between the relatively low pump power predominantly $\chi^{(2)}$ combs and the high pump power ones shaped by the competition between the $\chi^{(2)}$ and Kerr nonlinearities.

Dynamics of long cavity lasers

Svetlana Slepneva

Université Côte d'Azur, CNRS, INPHYNI

We will discuss the properties of long cavity frequency sweeping lasers and demonstrate various scenarios of coherence deterioration in such lasers. The long cavity lasers are known to demonstrate rich variety of dynamical regimes including formation of localised structures and transition to turbulence. The interest to frequency sweeping long cavity lasers has also recently increased due to their application for imaging and sensing. For these applications, the stability of the laser is an important parameter as it directly influences its coherence and therefore, for example, the quality of the obtained images. We investigated static, quasi static and synchronisation regimes of such lasers and analysed possible instabilities in such system. Experimentally, we considered different laser configurations which has allowed us to study the influence of the cavity length, frequency sweeping speed and the detuning. Numerically, we used a model based on a system of delayed differential equations. The numerical simulation of our model showed excellent agreement with the experimental data. In particularly, we studied the formation of dark pulses, and showed that they are closely connected to Nozaki–Bekki holes previously predicted in the complex Ginzburg-Landau equation.

Gain-through-filtering enables tuneable frequency comb generation in passive optical resonators

Kestutis Staliunas[1], **Florent Bessin**[2], **Auro M. Perego**[3], **Sergei K. Turitsyn**[3], **Alexandre Kudlinski**[2], **Matteo Conforti**[2], **and Arnaud Mussot**[2]

[1] *Universitat Politecnica Catalunya (UPC)*
[2] *Université de Lille*
[3] *Aston University*

Optical frequency combs, consisting of a set of phase locked equally spaced laser frequency lines, have led to a great leap in precision spectroscopy and metrology since seminal works of Hänsch et al. at the beginning of 21-st century. Nowadays, OFCs are cornerstones of a wealth of applications ranging from chemistry and biology to astrophysics including ultra-precise metrology, spectroscopy, molecular fingerprinting, new generation of LIDARs and others. Driven passive optical resonators constitute the ideal platform for OFC generation in terms of compactness and low energy footprint. We propose here a new technique for generation of OFCs with tuneable repetition rate inexternally driven optical resonators based on the gain-through-filtering process, a simple and elegant passive method, due to an asymmetricspectral filtering on one side of the pump wave. We demonstrate a proof-of-concept experimental result in a fibre resonator, pioneering a new technique that does not require specific engineering of the dispersion to generate frequency agile frequency combs.

Pseudo mode-locking

Günter Steinmeyer

Max-Born-Institut, Berlin

Today the generation of femtosecond laser pulses nearly exclusively relies on passive mode-locking, which requires a phase lock between the longitudinal modes of a laser. In order to overcome the non-equidistance of the cold cavity modes, it is generally considered necessary to include an effective saturable absorption mechanism in the laser cavity. However, there exists a number of experimental demonstrations of mode-locking in which saturable absorption was clearly absent. Here we show that four-wave mixing may equally well lead to a mode-locking effect. However, the resulting pulse trains are only partially coherent, and the comb structures lack perfect equidistance. Operation of lasers in the pseudo mode-locked regime can easily be confused with traditional mode-locking. We discuss indications and characterization approaches for unveiling pseudo mode-locking.

Spatiotemporal extreme events in spatially extended lasers

Giovanna Tissoni

Université Côte d'Azur, Institut de Physique de Nice (INPHYNI)

In the last decades, extreme events have been under study in many different physical systems, from hydrodynamics to optics, where they have been identified as optical rogue waves. Here we present some recent results about extreme events in spatially extended laser systems with different geometries and configurations, spanning from broad area semiconductor microlasers (2D) with saturable absorber or coherent injection, to macroscopic ring semiconductor lasers (1D) with coherent injection. In all of them we can identify regimes where the light emitted shows huge intensity peaks. We study the statistics of these peaks and shed some light on their possible generating mechanisms. Strong similarities with different types of dissipative solitons (cavity solitons, phase solitons) are also enlightened.

Nonlocal-delayed Raman effect induces moving localized structures in optical resonators

Mustapha Tlidi

Université Libre de Bruxelles

This contribution aims to investigate the formation of moving localized structures in bistable systems subjected to time-delayed response. So far, however, the interaction between fronts leading to moving localized structures has neither been experimentally investigated nor analytically performed. We address the theoretical side of this problem. We provide an analytical understanding of the generation of moving localized structures induced by the time-delayed nonlocal response in a generic bistable model. Through fronts interaction, we characterize these structures by deriving their shape, their width, and their speed. We show that fronts interaction modifies the dynamics of many bistable systems drastically. We propose a realistic and experimentally relevant system, namely optical frequency comb generators such as all fiber cavity, whispering-gallery-mode resonators or microresonators that the time-delayed nonlocal response stabilizes traveling localized structures. In this respect, frequency combs generated in optical Kerr resonators are nothing but the spectral content of the stable localized structure occurring in the cavity. The enormous impact of frequency comb sources on science and technology has been widely recognized. Besides their impact on fundamental physics, optical frequency combs have led to a significant advance in many real-life applications, such as precision distance measurements, optical waveform and microwave synthesis, and optical spectroscopy. Despite the high impact of frequency comb sources on many branches of physical sciences, development of these sources is still a relatively young research field. When two fronts are well separated from each other, due to time delayed response, the nature of the interaction is altered in depth and leads to the stabilization of moving localized structures. This opens new possibilities for practical devices taking into account the fundamental aspects of the nonlinear physics associated with the optical cavities.

Characterisation of solitons in fibre lasers

Sergei Turitsyn

Aston University/Aston Institute of Photonic Technologies

Understanding of the properties of nonlinear photonic systems is important both for the fundamental science and because of their relevance to numerous applications of light technology, from fibre-optic communication links to high power lasers. However, many measurement techniques and signal processing methods have been developed and optimised for linear systems. In this talk I will discuss our recent works on applications of the machine learning methods and nonlinear Fourier transform to analysis of dynamics of pulses in fibre lasers.

Temporal dissipative solitons in delay feedback systems

Serhiy Yanchuk

Technische Universtität Berlin

Driven primarily by applications from fiber or semiconductor lasers, temporal dissipative solitons (TDS) are gaining attention recently. In the talk, we summarize a corresponding theory for systems with time-delayed feedback. In particular, we derive a system with an advanced argument, which determines the profile of the TDS. We also provide a complete classification of their spectrum into interface and pseudo-continuous parts. We illustrate the theory with two examples: a generic delayed phase oscillator, which is a reduced model for an injected laser with feedback, and the FitzHugh–Nagumo neuron with delayed feedback. Finally, we discuss possible destabilization mechanisms of TDS.

Spontaneous symmetry breaking and the formation of nonlinear optical patterns in the systems with bound states in the continuum

Alexey Yulin

Centre for nanophotonics and metamaterials, ITMO University, St. Petersburg

The effect of bound state in the continuum (BIC) consists in the overlap of the discrete and continuum parts of the spectrum of the eigenmodes. In the context of the quasi-guided modes experiencing radiative losses this can be seen as the existence of a 'dark' (non-radiating) mode having high Q factor. The radiating 'bright' states can be directly excited by the external pump, but the 'dark' state cannot. In the talk it will be discussed how parametric effects can lead to spontaneous symmetry breaking and to the formation of the hybrid mode due to parametric excitation of the 'dark' mode by the 'bright' ones. The dynamics of the bright and grey dissipative solitons nestling on the hybrid mode is considered. The spontaneous symmetry breaking and the pattern formation in the arrays of the lasing BIC states is also considered.

Participants

Akhmediev, Nail	Optical Sciences Group Research School of Physics and Engineering Australian National University nna124@rsphysse.anu.edu.au
Amiranashvili, Shalva	WIAS Berlin shalva.amiranashvili@wias-berlin.de
Arkhipov, Rostislav	St. Petersburg State University ITMO University Ioffe Institute arkhipovrostislav@gmail.com
Bandelow, Uwe	WIAS Berlin uwe.bandelow@wias-berlin.de
Biancalana, Fabio	Heriot–Watt University, Edinburg f.biancalana@hw.ac.uk
Chernysheva, Maria	Leibniz Institute of Photonic Technology, Jena maria.chernysheva@leibniz-ipht.de
Eydam, Sebastian	WIAS Berlin sebastian.eydam@wias-berlin.de
Genty, Goëry	Tampere University goery.genty@tuni.fi
Gerdes, Alexander	WIAS Berlin alexander.gerdes@wias-berlin.de
Giudici, Massimo	Institut de Physique de Nice Université Côte d'Azur massimo.giudici@inphyni.cnrs.fr
Gurevich, Svetlana	Institute for Theoretical Physics University of Münster gurevics@uni-muenster.de
Heinrich, Matthias	Experimental Solid-State Optics Group Institute of Physics University of Rostock matthias.heinrich@uni-rostock.de

Huyet, Guillaume	Université Côte d'Azur CNRS INPHYNI guillaume.huyet@inphyni.cnrs.fr
Javaloyes, Julien	Nonlinear Waves Group Departament de Física & IAC-3 Universitat de les Illes Balears julien.javaloyes@uib.es
Kantner, Markus	WIAS Berlin markus.kantner@wias-berlin.de
Konotop, Vladimir	Department of Physics Faculty of Sciences University of Lisbon vvkonotop@fc.ul.pt
Leonhardt, Ulf	Weizmann Institute of Science, Rehovot ulf.leonhardt@weizmann.ac.il
Lüdge, Kathy	Technische Universität Berlin Institut für Theoretische Physik kathy.luedge@tu-berlin.de
Maistrenko, Yuriy	Institute of Mathematics NAS of Ukraine y.maistrenko@biomed.kiev.ua
Panayotov, Krassimir	Vrije Universiteit Brussel kpanajot@b-phot.org
Parra-Rivas, Pedro	OPERA-photonics Université libre de Bruxelles Laboratory of Dynamics in Biological Systems KU Leuven Department of Cellular and Molecular Medicine University of Leuven pparrari@ulb.ac.be
Pimenov, Alexander	WIAS Berlin alexander.pimenov@wias-berlin.de
Radziunas, Mindaugas	WIAS Berlin mindaugas.radziunas@wias-berlin.de
Reitzenstein, Stephan	Technische Universität Berlin stephan.reitzenstein@physik.tu-berlin.de

Rotter, Stefan	Institute for Theoretical Physics Vienna University of Technology (TU Wien) stefan.rotter@tuwien.ac.at
Schelte, Christian	Nonlinear Waves Group Departament de Física & IAC-3 Universitat de les Illes Balears c.schelte@uib.cat
Schmidt, Mark	Department of Electrical and Computer Engineering Technical University of Munich mark.schmidt@tum.de
Sergeyev, Sergey	Aston Institute of Photonic Technologies Aston University s.sergeyev@aston.ac.uk
Skryabin, Dmitry	University of Bath d.v.skryabin@bath.ac.uk
Slepneva, Svetlana	Université Côte d'Azur CNRS INPHYNI svetlana.slepneva@gmail.com
Staliunas, Kestutis	Universitat Politecnica Catalunya (UPC) kestutis.staliunas@icrea.cat
Steinmeyer, Günter	Max-Born-Institut steinmey@mbi-berlin.de
Tissoni, Giovanna	Université Côte d'Azur Institut de Physique de Nice (INPHYNI), giovanna.tissoni@inphyni.cnrs.fr
Tlidi, Mustapha	Université Libre de Bruxelles mtlidi@ulb.ac.be
Turitsyn, Sergei	Aston University Aston Institute of Photonic Technologies s.k.turitsyn@aston.ac.uk
Vladimirov, Andrei	WIAS Berlin andrei.vladimirov@wias-berlin.de
Yanchuk, Serhiy	Technische Universtität Berlin yanchuk@math.tu-berlin.de

Yulin, Alexey
Centre for nanophotonics and metamaterials
ITMO University, St. Petersburg
a.v.yulin@corp.ifmo.ru

For your notes

For your notes