Frequency combs

Fundamentals & Applications

September 12-13, 2022
Brussels, Belgium

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Access to the dinner

The dinner is organized at "Taverne du Passage," a typical Belgian restaurant:

Galerie de la Reine 30, 1000 Brussel

The restaurant is located in a gallery and is a 10-minute walk from the conference room. We recommend passing by the "Mont des Arts", a beautiful square in Brussels with a distant view of Grand Place.

Sponsors:

Monday, September 12: Program

FREQUENCY COMBS

Fundamentals & Applications

09:30 **Welcome - Coffee**

Chairman: Bart Kuyken, Ghent University (Belgium)

10:00 **Opening session**
Nicolas Englebert, Bart Kuyken, and François Leo

10:10 **Dissipative structures in dispersive cavities: Bifurcation structure and stability**
Pedro PARRA-RIVAS, La Sapienza University of Rome (Italy)

10:35 **Chi-2 combs and solitons in high-finesse microresonators**
Dmitry SKRYABIN, Bath University (England)

11:00 **Self emerging laser cavity solitons as dominant attractor of a microcomb system**
Alessia PASQUAZI, Loughborough University (England)

11:25 **Efficient soliton crystal microcomb generation by interferometric back-coupling**
Stefan WABNITZ, La Sapienza University of Rome (Italy)

11:50 **Cavity Solitons in Externally Driven Active Fiber Resonators**
Simon-Pierre GORZA, Université libre de Bruxelles (Belgium)

12:15 **Lunch**

Chairman: Nicolas Englebert, Université libre de Bruxelles (Belgium)

14:00 **Photonic Crystal Parametric Oscillator**
Alfredo DE ROSSI, Thales (France)

14:25 **Dissipative Quadratic Solitons: Few-Cycle Frequency Combs in the Mid-IR**
Alireza MARANDI, Caltech (United States)

14:50 **All-fiber frequency-agile triple-frequency comb light source**
Arnaud MUSSOT, Université de Lille (France)

15:15 **Bound States of Dark and Bright Soliton Molecules**
Pascal DEL'HAYE, Max Planck Institute (Germany)

15:40 **Soliton microcombs in photonic crystal Fabry-Pérot resonators**
Tobias HERR, CFEL (Germany)

16:05 **Coffee Break and group picture**

16:45 **Magritte Museum Private Tour**

18:00 **Poster session and appetizers**

20:00 **Dinner - La Taverne du Passage**

Poster session

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Fundamentals & Applications

The session will take place on **Monday 12 September at 6 pm**, with some drinks and crisps. The titles and abstracts of the 33 posters are given below. The author's last name alphabetically sorts posters.

All-fiber coherent tricomb light source

We demonstrate the generation of a tricomb light source at 1.5 µm, from the electro-optic modulation of a continuous-wave laser. The combs are spectrally broadened by Self Phase Modulation in one tricore non-linear fiber.

Evelyne Bancel, Université de Lille (France)
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Frequency combs and new nonlinear parametric dynamics in optical cavity

Temporal structures in optical resonators are currently attracting a lot of attention, espe- cially for the generation of frequency combs. In the time domain, these combs consist of regularly spaced pulses called cavity solitons (CSs). So far, the vast majority of studies focus on driving cavity solitons close to their carrier frequency. However, CSs can also be parametrically driven at twice their carrier frequency. This type of forcing allows to obtain a dynamic close to the one of the optical parametric oscillator (OPO). Here, we study the influence of walk-off, induced by the quadratic nonlinearity, on the dynamics and stability of parametric soliton.

Brahim Baydi , Université de Lille (France)
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III-V-on-silicon-nitride heterogenous mode-locked laser

Mode-locked lasers find their use in a large number of applications. We present here an integrated heterogeneous III-V-on-silicon-nitride mode-locked laser where the III-V amplifier integration on the silicon nitride circuit is done by micro-transfer-printing.

Maxilimien Billet, Ghent University (Belgium)
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Generation of optical frequency combs in fiber Fabry-Pérot resonators

The objective of this project is to theoretically and experimentally investigate the nonlinear dynamics of fiber Fabry-Pérot resonators in a way to reach later on more applicative works, such as cavity soliton generation and multiple frequency combs generation with multimode resonators.

Thomas Bunel, Université de Lille (France)
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Polarization dynamics in passively mode-locked VECSEL

We investigate experimentally the polarization dynamics of passively mode-locked VECSEL. We demonstrate that the normalized Stokes parameters and degree of polarization are functions of time reaching extreme values during the pulse peaks. Our experiments show that light is elliptically polarized. Furthermore, the sign of circular component of the polarization can be changed by modifying the orientation of the saturable absorber mirror.

Camila Castillo, Vrije Universiteit Brussel (France)
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Adaptive liquid-core fibres allow for broadband dispersive wave control

We highlight the potential of liquid-core fibers as adaptive nonlinear devices that allow for gaining dynamic, local control over the radiation characteristics of optical solitons, selectively excited in low-order spatial modes at picojoule pump energies.

Mario Chemnitz, Leibniz Institute of Photonic Technology (Germany)
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High Power, Mid-Infrared Electro-Optic Frequency Comb

Techniques and measurements are presented demonstrating that singly resonant, single frequency optical parametric oscillators (OPO's) are a powerful platform for generating mid-IR optical frequency combs with unique properties not shown by other mid-IR light sources.

Matthew Cich, TOPTICA Photonics, Inc. (United States)
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Non-linear effects with ultrashort pulses in integrated 4H-SiC waveguides

Second harmonic and sum frequency generation are demonstrated experimentally in silicon carbide waveguides, using a fs pulse laser source. Supercontinuum simulations additionally open interesting prospects for on-chip spectroscopy or comb self-referencing in the 4H-SiC platform.

Lucas Deniel, Max Planck institute of quantum optics (Germany)
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Mode-division demultiplexing of frequency combs with temporal cavities

We developped a new approach for demultiplexing temporal modes of ultrashort pulses using a temporal cavity with mode-dependant resonances in the frequnecy comb modes basis, a temporal analogy of spatial-mode cleaners.

Bakhao Dioum, Université de Lille (France)
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Controlling chaos properties of a laser diode with an optical frequency comb

We experimentally study the nonlinear dynamics of a laser diode subjected to optical comb injection. We observe chaotic dynamics with a bandwidth of 32.8 GHz and a spectral flatness up to 0.78.

Yaya Doumbia, CentraleSupélec (France)
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Time-domain spectroscopy with a passively enhanced octave-spanning mid-infrared comb

We passively amplify an offset-free comb spanning 22-40 THz by coherent stacking in a femtosecond enhancement cavity, and demonstrate quantitative, sensitive and broadband electric-field resolved spectroscopy of impulsively excited molecules in the gas phase.

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Philipp Sulzer, University of British Columbia (Canada)
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Modelling of Brillouin activated microcombs in a double-stripe silicon nitride platform

To activate microcombs in normal dispersion it requires either thermally unstable, red-detuned pumping or activation via effective anomalous dispersion regimes. Here we show modelling results of microcomb generation in double-stripe silicon nitride via Brillouin scattering.

Yvan Klaver, University of Twente (Netherlands)
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Vectorial dark dissipative solitons in Kerr resonators

We present a bifurcation diagram in the form of a double collapsed snaking originating from the inclusion of the polarization degree of freedom in a Lugiato-Lefever model, describing high-Q Kerr resonators.

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Hyperparametric oscillation via bound states in the continuum

In a two-mode silicon nitride microring resonator, we achieved high-power and high-efficiency hyperparametric oscillation by exploring the concept of bound states in the continuum.

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Low repetition rate optical frequency combs generated by pulsed gain-switching of semiconductor lasers

We report an experimental analysis of the impact of the switching conditions on the spectral width of the optical frequency combs (OFCs) generated by pulsed gain-switching of optically injected laser diodes. The analysis is performed for a 100 MHz repetition rate and the examined switching conditions are the amplitude and the duration of the switching pulses. OFCs as wide as 133 GHz at 10dB are obtained. This width is the highest ever reported for 100 MHz OFCs generated by gain-switching. In addition, wide OFCs suitable for dual-comb spectroscopy are demonstrated for a repetition rate as low as 5 MHz.

Pablo López Querol, Universidad Politécnica de Madrid (Spain)
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Reservoir Computing based on frequency combs

Reservoir Computing (RC) is a recursive neural network able to process time series (e.g.: compensating a distortion in a nonlinear communication channel). We present a photonic implementation of RC based frequency combs, where each comb line represents a neuron.

Alessandro Lupo, Université libre de Bruxelles (Belgium)
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Mode-locking induced by continuous wave driving in a fiber laser

We analyze the formation of solitons in a coherently driven fiber laser. By means of bifurcation analysis, we demonstrate that coherent continuous wave driving can induce mode-locking without saturable absorption.

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Machine Learning assisted spatiotemporal chaos forecasting

The predictions of chaotic systems are ubiquitous in optics. We used a passive Kerr resonator, the emission of this cavity can be highly chaotic with the generation of large amplitude peaks, which we aim to predict before they occur using machine learning algorithms.

Georges Murr, Université de Lille (France)
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Coexistence of Gain through Filtering and Parametric Instability in a Fiber Ring Cavity

We experimentally and numerical investigate the coexistence of Gain through Filtering and parametric instability in a fiber ring cavity, and their dependency from input power and cavity phase detuning.

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Silicon-Germanium Ring Resonator in the Mid-Infrared with High Q-Factor

We report a high-Q ring resonator in the mid-infrared in a silicon-germanium on silicon chip-based platform. The side-coupled ring exhibits a loaded Q-factor of 176,000 at the operating wavelength around 4.18 µm.

Marko Perestjuk, Institut des Nanotechnologies de Lyon & RMIT University (France)
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Dual-comb interferometry using gain-switched semiconductor lasers and optical injection

We report the generation of low repetition rate dual frequency combs generated by gain switching laser diodes with external optical injection and show the capabilities of these combs by conducting dual-comb spectroscopy and dual-comb ranging experiments.

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Dual-comb interferometry based on a photonic molecule microcomb

We present the architecture of a dual-comb spectroscopy based on a photonic molecule with a 50 GHz repetition rate operating in the normal dispersion. The microcomb generated displays a symmetric spectral envelope and a quiet point of operation.

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Enhanced Generative Adversarial Learning with a Quantum Frequency Comb

The potential of two-photon Quantum Frequency Combs towards applications in quantum-enhanced distribution sampling via quantum Generative Adversarial Networks (qGANs) is explored numerically. Our results indicate that compared to a conventional GAN, the qGAN needs fewer epochs to converge to the Nash equilibrium.

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Coupled active cavities for all-fiber optical frequency comb generation

We introduce coupled cavities as a new way to generate solitons train in active cavities. We prevent the gain saturation by sharing the gain medium with a laser, which allows higher intracavity power than in previous work.

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Dissipative Free-Space Cavity Solitons

We explore temporal soliton formation and dynamics in a spectrally tailored free-space cavity driven by a 100-MHz frequency comb. Dispersive Fourier Transform measurements reveal the shot-to-shot evolution of the circulating spectrum.

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Philipp Sulzer, University of British Columbia (Canada)
philipp.sulzer@ubc.ca

Dissipative Kerr solitons, breathers, and chimera states in coherently driven passive cavities with parabolic potential

We analyze the dynamics of dissipative Kerr solitons in the presence of a parabolic potential. This potential stabilizes oscillatory and chaotic regimes and induces new dissipative structures, such as asymmetric breathers and chimera-like states.

Yifan Sun, Sapienza University of Rome (Italy)
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Fast dispersion tailoring of multimode photonic crystal resonator

We introduce a fast and reliable solver for photonic crystal (PhC) resonators systematic design capable of tailoring dispersive effects, answering to the crucial problem of designing a comb of cold resonances for a PhC structure.

Francesco Rinaldo Talenti, Sapienza university of Rome (Italy)
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Generation of electro-optic frequency combs with minimal power imbalance in a silicon ring resonator modulator

Electro-optic frequency combs are generated with a silicon ring-resonator modulator (RRM). The comb is generated by employing harmonic superposition in the driving signal and is optimized with a differential evolution algorithm in conjunction with an RRM model.

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AlGaAs-on-Insulator Microresonators for Nonlinear Photonics

We present generic design methods to suppress the avoided mode crossing and show high-Q AlGaAsOI microresonators towards ultra-low threshold Kerr frequency comb generation.

Chaochao Ye, Technical University of Denmark (Denmark)
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Asymmetrically-Driven dissipative Bose-Hubbard dimer

We explore the bifurcation structure and stability emerging in a pair of linearly coupled nonlinear optical resonators. Besides self-pulsing, we report on the observation of period doubling cascade, chaotic pulsing and excitability.

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AlGaAs-on-insulator waveguide for nonlinear optics

Aluminum gallium arsenide (AlGaAs) exhibits very high material nonlinearity and low nonlinear loss. Here, we demonstrate broadband four-wave-mixing with high parametric gain and octave-spanning coherent supercontinuum generation using low-power picsecond pulses in AlGaAs-on-insulator waveguide.

Yanjing Zhao, Technical University of Denmark (Denmark)
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Silicon Carbide-on-Insulator for Nonlinear Photonics

We will present the silicon carbide-on-Insulator platform for nonlinear photonics, including waveguide devices for second-harmonic and supercontinuum generation and resonator devices for soliton comb generation.

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Tuesday, September 13: Program

Chairman: Carlos Mas Arabí, Université libre de Bruxelles (Belgium)

09:00 **Semiconductor ring laser frequency combs: From phase turbulence to solitons**
Marco PICCARDO, Istituto Italiano di Tecnologia (Italy)

09:25 **Self-symmetrization of spontaneous symmetry-breaking in driven Kerr resonators**
Julien FATOME, Université de Bourgogne (France)

09:50 **Photo-induced nonlinearities in silicon nitride microresonators**
Camille-Sophie BRES, EPFL (Switzerland)

10:15 **Coffee Break**

Chairman: Simon-Pierre Gorza, Université libre de Bruxelles (Belgium)

10:45 **Power-efficient soliton microcombs**
Victor TORRES-COMPANY, Chalmers University (Sweden)

11:10 **Bridging soliton microcombs and inverse-designed photonic circuits**
Kiyoul YANG, Max Planck Institute (Germany), and Stanford University (United States)

11:35 **Dual comb spectroscopy for electronic fingerprinting**
Birgitta BERNHARDT, Graz University of Technology (Austria)

12:00 **Three-dimensional imaging with laser frequency combs**
Nathalie PICQUÉ, Max Planck Institute (Germany)

12:30 **Lunch**

Chairman: François Leo, Université libre de Bruxelles (Belgium)

13:30 **Dynamics of multi-wavelength lasers: the key role of cross-saturation and modal gain**
Martin VIRTE, Vrije Universiteit Brussel (Belgium)

13:55 **Time-Localized Patterns in Vertical External-Cavity Surface-Emitting Lasers (VECSELs)**
Massimo GIUDICI, Université de Nice (France)

14:20 **Optical injection dynamics of frequency combs**
Marc SCIAMANNA, CentraleSupélec (France)

14:55 **Highly-efficient dispersive wave generation in the AlGaAs-on-insulator platform**
Minhao PU, DTU (Denmark)

15:20 **Closing session**
Nicolas Englebert, Bart Kuyken, and François Leo

15:30 **Coffee Break - Last dicussions**

Chi-2 combs and solitons in high-finesse microrings

Dmitry SKRYABIN,
Bath University (England)

I will outline some topics the Bath group has examined recently concerning the operation of the high-finesse chi-2 microring resonators with the large difference in the omega and two-omega group velocities. I will consider both the OPO and SHG pump arrangements. First, I will discuss the phase-matching conditions and demonstrate that the adiabatic elimination of the SHG component cannot be typically applied for all the modes, but that one or several modes should often be treated separately and present the respective reduced model [1]. Then, I will demonstrate that the tuning of the frequency of the parametric down-conversion is described by a discrete ladder-like sequence of the Eckhaus instabilities [1]. I will introduce and explain the staggered spectral patterns of frequency combs that are specific to OPOs [1]. In the SHG case I will demonstrate that the non-adiabatic modes lead to the Rabi flops and photon-photon polaritons [2,3]. I will then introduce physical mechanisms that allow to modelock dense two-color spectra and lead to the generation of chi-2 solitons despite the large offset of the group velocities across the optical octave. I will also propose a criterion for distinguishing the quasi-Kerr and quasi-Pockels solitons [4]. I will compare the theory and experiments where possible.

[1] Puzyrev, DN, Skryabin, DV, *Commun Phys* **5,** 138 (2022).
[2] DV Skryabin, VV Pankratov, A Villois, DN Puzyrev, *Phys. Rev. Research* **3**, L012017 (2021).
[3] DN Puzyrev, VV Pankratov, A Villois, DV Skryabin, *Physical Review A* **104**, 013520 (2021).
[4] DV Skryabin, *Optics Express* **29**, 28521 (2021).

Self emerging laser cavity solitons as dominant attractor of a microcomb system

Alessia PASQUAZI
Loughborough University (England)

Optical frequency comb in microresonators, or 'microcombs', are optical sources composed of a set of equally spaces frequency lines obtained in nonlinear microcavities usually by Kerr nonlinearity. The discovery of dissipative temporal cavity solitons has been a fundamental breakthrough and allowed to achieve a broad, smooth spectrum particularly suitable for metrological comb applications.

More recently, we demonstrated that it is possible to generate localized pulses in a configuration where the micro-cavity is inserted in a fiber laser loop. We reported the observation of laser cavity-solitons [1], which have previously attracted large attention, especially in spatial configurations. By merging their properties with the physics of both micro-resonators and multi-mode systems, this scheme represents a fundamentally new paradigm for the generation, stabilization, and control of solitary optical pulses in micro-cavities.

In this framework, it is important to discuss the main physical features of these types of waves, including the energy efficiency and their dynamical properties, which are key for the initiation and recovery of the system. Moreover, we recently demonstrated that they can self-emerge and robustly recover [2].
Here we discuss the fundamental mechanism that transforms the laser cavity solitons in the dominant attractors of a microcomb system based on a Kerr microresonator nested in an amplifying cavity. Particularly, we discuss the effect of the slow nonlinearities of the system and how they allow the robust emergence of solitary waves in our system.

[1] H. Bao, et al. Laser Cavity-Soliton Microcombs. Nat. Photonics **13**, 384 (2019).
[2] M. Rowley, et al., "Self-Emergence of Robust Micro Cavity-Solitons,"

Dissipative Quadratic Solitons: Few-Cycle Frequency Combs in the Mid-IR

Alireza MARANDI
California Institute of Technology (United States)

A plethora of applications have recently motivated extensive efforts on the generation of low noise Kerr solitons and coherent frequency combs in various platforms ranging from fiber to whispering gallery and integrated microscale resonators. However, the Kerr (cubic) nonlinearity is inherently weak, and in contrast, strong quadratic nonlinearity in optical resonators is expected to provide an alternative means for soliton formation with promising potential. In this talk we overview recent experimental results on formation of two types of dissipative quadratic solitons in optical parametric oscillators, namely temporal simultons in the mid-infrared [1, 2] and temporal walk-off induced solitons [3]. Unlike Kerr solitons, these quadratic solitons occur in low-finesse resonators and can provide substantial pulse compression and high conversion efficiencies. We present a route to significantly improve the performance of these demonstrated quadratic solitons when extended to an integrated nonlinear platform [4, 5].

[1] M. Liu, R. M. Gray, A. Roy, K. A. Ingold, E. Sorokin, I. T. Sorokina, P. Schunemann, A. Marandi, "High-Power Mid-IR Few-Cycle Frequency Comb from Quadratic Solitons in an Optical Parametric Oscillator," arXiv:2205.00591 (2022)

[2] M. Jankowski, A. Marandi, C. R. Phillips, R. Hamerly, K. A. Ingold, R. L. Byer, M. M. Fejer, "Temporal simultons in optical parametric oscillators," Physical Review Letters **120** (5), 053904 (2018).

[3] A. Roy, R. Nehra, S. Jahani, L. Ledezma, C. Langrock, M. Fejer, A. Marandi, "Temporal Walk-off Induced Dissipative Quadratic Solitons," Nature Photonics **16** (2), 162-168 (2022).

[4] L. Ledezma, R. Sekine, Q. Guo, R. Nehra, S. Jahani, A. Marandi, "Intense optical parametric amplification in dispersion engineered nanophotonic lithium niobate waveguides," Optica **9** (3), 303-308 (2022).

[5] L. Ledezma, A. Roy, L. Costa, R. Sekine, R. Gray, Q. Guo, R. M. Briggs, A. Marandi, "Widely-tunable optical parametric oscillator in lithium niobate nanophotonics," arXiv:2203.11482 (2022).

All-fiber frequency agile triple-frequency comb light

Arnaud MUSSOT
University of Lille (France)

An optical frequency comb is a multimode coherent light source, emitting a broad spectrum of evenly spaced narrow frequency lines [1]. It is used as graduated frequency rulers in many application fields [1]. In dual comb spectroscopy, two combs of slightly different repetition rates are combined, before/after interacting with a sample [2]. That leads to multiheterodyne beat note detection, with high spectral resolution, fast acquisition and no moving part. However, it requires a high coherence between the different combs. Cavity based techniques made with active or passive cavities, have their own advantages but the repetition rates of the combs are fixed by the cavity parameters and they must be phase locked through complex electronic devices. At variance to all fiber cavity less solutions for which, the pulses counter-propagate to preserve the coherence [3]. However, this limits the system to dual-combs. In recent years, tri-frequency comb systems, have gained significant interest [4,5]. They promise multi-dimensional spectroscopy in the study of ultrafast dynamics or precise distance measurement, motivating the search for speed, precision and accuracy.

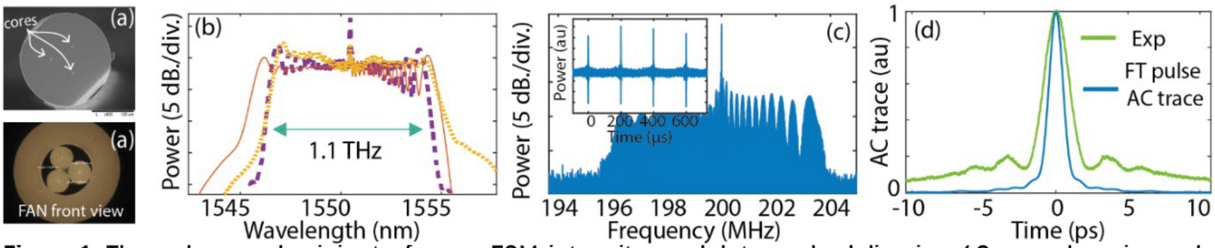

Figure 1: The pulse seed originate from a EOM intensity modulator only delivering 60 ps pulses in each arms. (a) tri-core fiber input face and FAN front view, (b) output spectra in each arm, (c) interferogram example and (d) compressed pulse with a waveshaper and transform limited AC trace calculated from the spectrum in (b) . 1 THz width, 0.5 nJ, 0.5 GHz, 2000 teeth, recompression <1ps

We experimentally demonstrate a novel approach to generate an all fiber, frequency agile tri-comb light source with a high mutual coherence, by propagating the pulses within a multicore nonlinear fiber. We used a continuous wave laser at 1550 nm, divided into three arms, each feeding a modulator. The pulses are amplified through EDFAs. Then they undergo spatial light multiplexing in a 3-cores optical fiber, which broaden their spectrum. Each comb propagates in its own core, independently from the others. We obtain 3 coherent combs of different repetition rates. Their output spectra is flat-top, spanning over 14 nm, an energy of 3 nJ at 250 MHz. Their mutual coherence leads to a beat notes with SNR around 15 dB as illustrated in Fig. 1.

We expect this all fiber light source should open the way to the use multiple frequency combs for several applications ranging from LIDARs to nonlinear spectroscopy.

[1] T. Fortier and E. Baumann, "20 years of developments in optical frequency comb technology and applications," Communications Physics **2**, 1-16 (2019).

[2]I. Coddington, N. Newbury, and W. Swann, "Dual-comb spectroscopy," Optica, OPTICA **3**, 414–426 (2016).

[3] G. Millot, S. Pitois, M. Yan, T. Hovhannisyan, A. Bendahmane, T. W. Hänsch, and N. Picqué, "Frequency-agile dual-comb spectroscopy," Nature Photonics **10**, 27–30 (2016).

[4] B. Lomsadze, B. C. Smith, and S. T. Cundiff, "Tri-comb spectroscopy," Nature Photonics **12**, 676 (2018).

[5] E. Lucas, G. Lihachev, R. Bouchand, N. G. Pavlov, A. S. Raja, M. Karpov, M. L. Gorodetsky, and T. J. Kippenberg, "Spatial multiplexing of soliton microcombs," Nature Photonics **12**, 699 (2018).

Soliton microcombs in photonic crystal Fabry-Pérot resonators

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Microresonator-based frequency combs ("microcombs") [1] in particular when operated in the regime of femtosecond temporal dissipative Kerr solitons (DKS) [2] have generated vast opportunities for novel studies, applications, and markets [3].

Usually, microcombs are generated in ring-type travelling-wave resonators. These resonators can offer high-quality (Q) factors and a clean mode-structure (free of unwanted mode-coupling) which is key to controlled and reproducible comb formation. At the same time however, current platforms offer only few design parameters (such as waveguide width and height) for tailoring resonator dispersion and in consequence, the spectral operation window of microcombs, and more broadly speaking, the control of nonlinear optical processes is restricted. Inspired by the transformational success of dielectric Bragg-mirrors in addressing similar limitations in mode-locked lasers, microcombs have been explored in unconventional standing-wave cavities with Bragg-type reflectors: A fiber-based cavity, achieved formation of DKS, however, only under pulsed driving condition due to low effective nonlinearity [4]. Further, a chip-integrated cavity with chirped mirrors achieved cascaded four-wave mixing [5].

Here, we show for the first time DKS formation in a chip-integrated standing-wave Fabry-Pérot microresonator. DKS form under continuous-wave driving with directly detectable repetition rate of 20 GHz. Both single and multiple soliton states can be generated (implying counter-propagating solitons). The chip-integrated resonator is formed by a silicon nitride waveguide with two photonic crystal reflectors (here: highly reflective from 1560 to 1590 nm) and supports a directly detectable repetition rate signal. The cavity's loaded Q-factor exceeds 1 million and is only limited by the waveguide propagation loss, on par with ring resonators implemented in the same platform. In contrast to the usual ring-type resonators, the new resonator offers a dramatic increase of design space and may in the future contribute to extending microcomb technology into new wavelength domains relevant for sensing, quantum photonics and astronomical spectrograph calibration.

References

[1] P. Del'Haye, A. Schliesser, O. Arcizet, T. Wilken, R. Holzwarth, T.J. Kippenberg, Nature, **450** (2007)

[2] T. Herr, V. Brasch, J.D. Jost, C.Y. Wang, N.M. Kondratiev, M.L. Gorodetsky, T.J. Kippenberg, Nature Photonics, **8** (2014)

[3] T. J. Kippenberg, A.L. Gaeta, M. Lipson, Science, **6402** (2018)

[4] E. Obrzud, S. Lecomte, T. Herr, Nature Photonics, **11** (2017)

[5] S.P. Yu, H. Jung, T.C. Briles, K. Srinivasan, S.B. Papp, ACS Photonics **6** (2019)

Photo-induced nonlinearities in silicon nitride microresonators

Camille-Sophie BRES
École Polytechnique Fédérale de Lausanne (Switzerland)

Photo-induced second order nonlinearities in silicon nitride microresonators offer new opportunities for integrated nonlinear optics and frequency conversion. I will discuss how, similar to the effect observed in fibers and waveguides, all-optical poling occurs in resonators via the photogalvanic process. Second order frequency conversions can reach high efficiencies owing to resonant enhancement without sacrificing versatility and tunability. We also show that, owing to the large efficiency, cascaded nonlinear effects and comb generation occur in normal dispersion microresonators once second and third order nonlinearities are combined, expanding the scope and potential of silicon nitride nonlinear photonics.

Power-efficient soliton microcombs

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Microcombs are strong contenders for attaining the frequency stability and performance of standard passively modelocked lasers on a chip scale. Understanding the optical phase noise dynamics in soliton microcombs and enhancing the power efficiency are crucial directions for the development of ultra-low timing jitter pulsed sources on-chip with enhanced repetition rate stability and ultra-low optical linewidth. The potential applications include next generation of optical clocks, pure microwave signal generation, optical frequency synthesis, broadband and high-resolution analog to digital converters, high-resolution spectroscopy, phase-coherent lightwave communications and the dynamic calibration of external cavity tunable lasers.

In this invited contribution, we will present our results on the phase noise dynamics of soliton microcombs and the development of record-efficiency soliton microcombs in coupled cavities (photonic molecules) made of silicon nitride.

Dual Comb Spectroscopy for Electronic Fingerprinting

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Dual Comb Spectroscopy combines high spectral resolution with broad spectral coverage and short measurement times. In the recent years, this spectroscopic method has proven its capabilities in molecular spectroscopy in different spectral regions ranging from the visible across the infrared spectral region into the THz domain [1-3]. The UV has so far been neglected for fingerprinting although electron transitions are as element specific as rovibrational transitions and the corresponding absorption cross sections can be huge (> 100 Mb). Especially molecular gasses of astrophysical and environmental relevance have strong and congested absorption characteristics in this spectral region (few examples: NO_2 , CO, SO_2 , HCHO). I will present our latest efforts on expanding dual comb spectroscopy via nonlinear frequency up-conversion into the ultraviolet region. The challenges include UV frequency comb generation with a high photon flux, efficient UV interferometry and fast UV signal detection [4].

Figure 1 shows the principle of ultraviolet dual comb spectroscopy (UV-DCS) and a state of the art NUV absorption spectrum of HCHO recorded with a traditional scanning technique yielding a relative spectral resolution of 10^{-6}. This resolution has not been sufficient to determine the absolute absorption cross section of formaldehyde so far [5]. UV-DCS has the potential to eliminate this shortcoming by improving the relative spectral resolution by one order of magnitude in single shot measurements. By further improving the long-term performance, an ultra-high relative resolution of up to 10^{-10} and an unrivaled simultaneous spectral coverage on the order of 100 THz comes within reach.

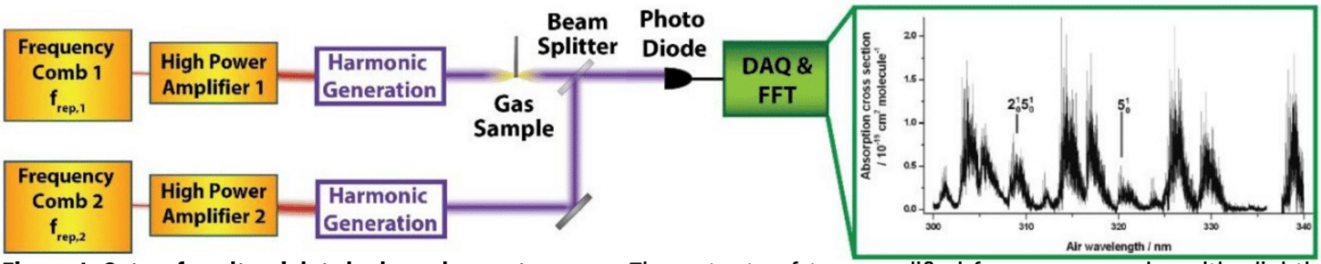

Figure 1: Setup for ultraviolet dual comb spectroscopy. The outputs of two amplified frequency combs with slightly different repetition rates are frequency-up-converted into the ultraviolet spectral range were many molecular and atomic samples exhibit strong and congested absorption features. After one comb interacted with the sample, the two beams are superimposed and the interference is detected with a photodiode. The Fourier transformation of the time-domain interferogram reveals the absorption spectrum of the sample (DAQ & FFT). Example: state-of-the-art NUV spectrum of HCHO whose spectral resolution has not been sufficient for determining the absolute absorption cross section [3]. UV-DCS promises at least a 10-fold improved spectral resolution in single shot operation.

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Dynamics of multi-wavelength lasers: the key role of cross-saturation and modal gain

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Because lasing is intrinsically a 'winner takes it all' process, achieving multi-wavelength emission is a challenge which requires fine parameter tuning. In this framework, the cross-saturation and the modal gain are essential pieces in the coupling mechanism.

Here, we highlight the impact of these two parameters on the nonlinear dynamics of multi-wavelength lasers when subject to optical injection or feedback. We show that they have a direct influence on the injection locking range and the wavelength switching capability induced by optical feedback.

Time-Localized Patterns in Vertical External-Cavity Surface-Emitting Lasers (VECSELs)

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We have investigated large aspect-ratio VECSELs in the regime of temporal localized structures (TLS) and we report on the experimental observation of individually addressable pulsating patterns. The characteristics of the patterns depend on the sign of the B and C coefficients of the ABCD round-trip matrix describing the propagation in the external cavity. While B controls the diffraction coefficient, C introduces a quadratic mask phase profile which may have a focusing (C<0) or defocusing effect (C>0). For C<0 the patterns observed consist of a combination of an axial plane-wave with a set of tilted waves having a nearly hexagonal arrangement in the Fourier space. These plane waves are locked in phase and their interference gives birth to a honeycomb profile in near-field. For C>0 the patterns observed consist of a set of counterpropagating tilted waves with opposite transverse wavevectors. These wavevectors share the same modulus and they draw a circle in the far field profile. When the rotational symmetry is broken by some anisotropy in the cavity, only two spots are observed in the far field and a roll pattern appears in the near-field. All the points of the patterns observed are spatially correlated. However, the pump profile can be modified to introduce spots of high gain in the transverse plane of the VECSEL. These spots emit temporally localized pattern which are spatially independent, thus suggesting the possibility of multiplexing TLS sources on the same device. Our results pave the way towards spatio-temporal information processing and to multi frequency-combs sources.

Highly-efficient dispersive wave generation in the AlGaAs-on-insulator platform

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Dispersive wave generation may enable octave-spanning supercontinuum (comb) in integrated nonlinear waveguides and benefit metrology applications. However, such a nonlinear spectral broadening process typically rely on femto-second pulse pumping with high peak power, which makes integrating integrated pump source with the comb generator challenging. in this talk, a highly-efficient method for dispersive wave generation will be introduced.