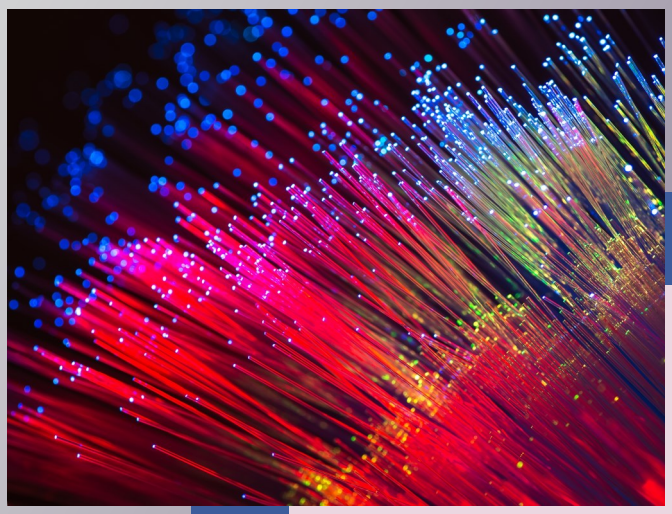
Optical Frequency Combs Workshop

11-12 April, 2022

AiPT, Aston University

About the Workshop



The workshop will bring together leading researchers in the field of optical frequency combs science and technology to discuss its fundamentals, applications, and future opportunities. The topics covered include recent development of innovative sources based on lasers, waveguides and microresonators, novel nonlinear dynamics effects in optical resonators, and diverse applications of optical frequency combs in astronomy, quantum technologies, and photonic computing.

The Workshop is organised by Aston Institute of Photonic Technologies with support of projects MOCCA, MEFISTA, MULTIPLY, FONTE. These projects have received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreements No 814147, 861152, 713694, 766115.

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Agenda

Optical Frequency Combs Workshop Agenda

Room MB653, Wright Lecture Theatre, main building 6th floor

DAY 1: 11th April

9:30-10:00 Welcome Coffee (NW708)

10:00-10:05 Welcome by the organisers

10:05-10:15 Introduction by Prof. S. Turitsyn, AIPT Director

Session 1: Quantum & Unconventional Combs

Chair: Auro Perego

10:15-10:45 Talk 1 **Dr. Lucia Caspani**, University of Strathclyde: "Integrated frequency combs for quantum applications"

10:45-11:15 Coffee Break (NW708)

11:15-11:45 Talk 2 **Prof. Dmitry Skryabin**, University of Bath: "From combs to topology in space and time"

11:45-12:15 Talk 3 **Prof. Alessia Pasquazi**, University of Sussex: "Sability properties of soliton and Turing pattern states in microresonator filtered lasers"

12:15-13:45 Lunch Break (Conference Aston)

Session 2: Laser combs and their applications

Chair: Manuel Crespo-Ballesteros

13:45-14:15 Talk 4 **Prof. Arnaud Mussot**, University of Lille: "All-fiber frequency agile triple-frequency comb light source"

14:15-14:45 Talk 5 **Prof. Zhixin Liu**, UCL: "Cavity-less frequency comb for optical-assisted signal processing"

14:45-15:15 Coffee Break (NW708)

Session 3: Aston combs

Chair: Manuel Crespo-Ballesteros

15:15-16:00 AIPT Research on Combs, (Speakers: M. Sumetsky, A. Perego, S. Sergeyev)

16:00-17:00 Lab Tour

19:00 Speakers Dinner (Pasta di Piazza, B3 1SA)

Agenda

DAY 2: 12th April

Room MB653, Wright Lecture Theatre, main building 6th floor

Session 4: Combs in macroscopic systems

Chair: Misha Sumetsky

10:00-10:30 Talk 6 **Prof. Derryck Reid**, Heriot-Watt University: "Frequency comb development for the extremely large telescope"

10:30-11:00 Coffee Break (NW708)

Session 5: Combs in microresonators

Chair: Misha Sumetsky

11:00-11:30 Talk 7 **Prof. Victor Torres Company**, Chalmers University: "Low-noise, power-efficient soliton microcombs"

11:30-12:00 Talk 8 **Dr. Wen Zhou**, University of Oxford: "Neuro-inspired photonic computing using microcombs"

12:00-13:00 Lunch (Conference Aston)

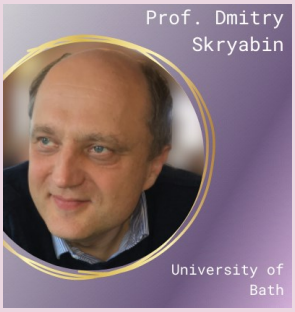
13:00-13:30 Talk 9 **Dr. Jonathan Silver**, NPL: "Kerr nonlinear optics with whispering-gallery-mode microresonators"

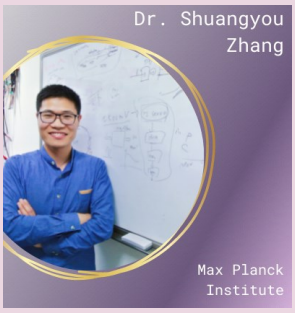
13:30-14:00 Talk 10 **Dr. Shuangyou Zhang**, Max Planck Institute: "Dispersive Kerr Soliton in a Microresonator via Bichromatic Pumping

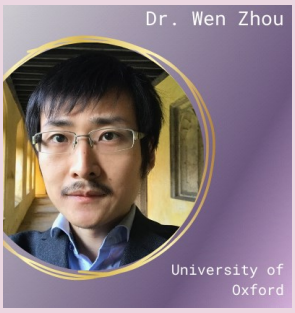
14:00-14:30 Talk 11 **Dr. Sivaraman Subramanian**, University of Exeter: "Optical whispering gallery modes as a platform for single molecule biosensing"

14:30-14:35 Concluding remarks

Speakers







Organising committee

Integrated frequency combs for quantum applications

Dr. Lucia Caspani

University of Strathclyde

Bio

Dr Lucia Caspani is a Senior Lecturer at the Institute of Photonics, Department of Physics, University of Strathclyde. Her work focuses on multiphoton and multimode quantum states of light for quantum metrology, communication, and computing applications. Lucia received her Bachelor (2003), Master (2006) and PhD Degree (2010) in Physics from Insubria University (Como, Italy), focusing on theoretical Quantum Optics. She then moved to Canada at INRS-EMT (Montreal) from 2011 to 2014, where she shifted her research interests towards experimental quantum optics, working on the generation of quantum states of light on-chip. She came back to Europe in 2014 with a Marie Curie Fellowship at Heriot-Watt University (Edinburgh), where she investigated entangled photon triplets and the enhancement of nonlinear effects in epsilon-near-zero materials. Lucia joined Strathclyde's Institute of Photonics in February 2017 as Research Fellow first and as an independent researcher since June 2018. She is now developing her research group, QuaSAp (Quantum Sources and Applications) that focuses on the generation and application of complex quantum states of light in collaboration with academics, industries, and research organisations (e.g., the Fraunhofer Centre for Applied Photonics).

Abstract

The generation of quantum states of light featuring entanglement over many photons and multiple modes allows to access larger Hilbert spaces, thus increasing the resources for applications in, e.g., quantum metrology, communications, and computing.

In this context, integrated frequency combs are a powerful resource offering access to many modes in a compact form. This talk will review how frequency combs generated in integrated microring resonators can be used as a powerful resource for quantum technologies. The possibility to independently manipulate each tooth of the comb, made possible by the small size of the resonator, allows the generation of different quantum states. Here we focus on cluster states, the primary resource for the so-called one-way (or measurement -based) quantum computation, and we will show our approach for generating this fundamental resource in integrated platforms.

From combs to topology in space and time

Prof. Dmitry Skryabin

University of Bath

Bio

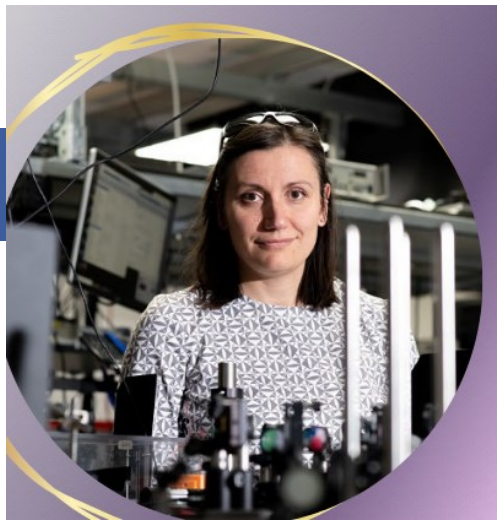
Dmitry Skryabin is fascinated by how light interacts with matter and enjoy the beauty and power of physics. His research focuses on the physics of ultrashort pulses, multi-mode complexity and frequency conversion in nonlinear photonic devices, e.g., in microresonators, waveguides, optical fibres, and semiconductors. Solitons in optics have always been a particular topic of his interest.

Abstract

Designing metamaterials with the required band structure, topology and chirality using nanofabrication technology revolutionise modern science and impacts daily life. The approach introduced in this talk is, however, different. We take a periodic sequence, i.e., crystal or metacrystal, of the dissipative optical solitons rotating in a single ring microresonator and demonstrate its properties as of the

electromagnetic metamaterial acting in the radio to terahertz frequency range. The metacrystal unit cell consists of the bound pair of solitons, and the distance between them is used as a control parameter. We are reporting the soliton metacrystal band structure and its topological properties. The latter is confirmed by the existence of the π steps experienced by the crystal phonons' geometrical (Zak) phase. Furthermore, we found the phononic edge states in the metacrystals with defects made by removing several solitons. Optical frequency combs corresponding to the soliton metacrystals reveal the spectral butterfly pattern serving as a signature of the spatio-temporal chirality and bearing a resemblance to the butterfly wings illustrating natural occurrences of chirality.

Sability properties of soliton and turing pattern states in microresonator filtered lasers



Prof. Alessia Pasquazi

Emergent Photonics (EPic) Lab, University of Sussex

Bio

Prof. Alessia Pasquazi received her PhD in Engineering from the University of Roma Tre in 2009. She has been MELS fellow (Quebec, Canada) from 2010-2011 and EU Marie-Curie Fellow from 2013-2015, Ernest Rutherford Fellow (2018-2022), ERC Starting Grant Laureate (2020-2024). She works in the field of nonlinear photonics and microcombs. Alessia led the research in ultrafast integrated optics at the EPic Lab (http://www.sussex.ac.uk/physics/epic/) at the university of Sussex (2014-2022) and currently at the university of Loughborough. She serve as member and chair of panels for several conferences, organised by SPIE, OSA and IEEE societies. She has been program chair of the OSA 'Nonlinear Photonics conference' (2018) and general chair of the OSA 'Nonlinear Photonics conference' (2020).

Abstract

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 microcavity 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.

Here we discuss the figures of merit which allow us to evaluate the performance of laser cavity soliton microcombs produced by a system based on a Kerr microresonator nested in an amplifying cavity.

References

[1] H. Bao, et al. Laser Cavity-Soliton Microcombs. *Nat. Photonics* **13**, 384 (2019).

All-fiber frequency agile triple-frequency comb light source

Prof. Arnaud Mussot

University of Lille

Bio

Arnaud Mussot received the Ph.D. in Physics from University of Besancon in 2004. Until 2005 he had a post doc position at the French Atomic Agency (CEA) in Bordeaux in France. In 2005 he joined the University of Lille as a lecturer and he was appointed full professor in 2014. Since 2015, he is junior member of the Institut Universitaire de France (IUF). His interests focus on nonlinear fiber optics. He has co-authored more than 140 papers in peer-review journals, 33 Invited Talks at international conferences 2 Post-Deadline Papers at international conferences and 8 patents.

Abstract

Optical frequency combs (OFC) are coherent light sources emitting a broad spectrum of evenly spaced narrow frequency lines. Dual- and now multi-frequency comb systems, made of several mutually coherent OFC with slightly different repetition rates, have gained significant interest. They promise multi-dimensional spectroscopy in the study of ultrafast dynamics or precise distance measurement, motivating the search for speed, precision and accuracy. Progress in the field is limited due to the complexity to phase-lock several mode-locked lasers. Another approach consists in using a single continuous wave laser followed by electro-optics modulators (EOM) which spectrum is broaden into a nonlinear fiber. The pulses counter-propagate to maintain a high mutual coherence, *de facto*, limiting the system to dual-combs. We experimentally demonstrate a novel approach to generate a multi-frequency comb light source with a high mutual coherence in an all fiber system. Starting from EOM combs, we exploit spatial light multiplexing in a 3-cores optical fiber. Each pulse propagates in its own core to experience a nonlinear broadening but within the same fiber, allowing to keep a high degree of mutual coherence. We report an all-fiber, frequency agile (since based on EOMs) multi-frequency comb light source in a 3-core all normal highly nonlinear silica fiber at 1550 nm. We obtained 3 almost similar output flat-top spectrum spanning over 12 nm with 0.5 nJ per pulse at 0.5 GHz enabling to record clean interferograms.

Cavity-less frequency comb for optical-assisted signal processing

Prof. Zhixin Liu

University College London

Bio

Zhixin Liu received his PhD degree in Information Engineering from the Chinese University of Hong Kong and joined the Optoelectronics Research Centre (ORC) at the University of Southampton in 2013. In 2016, he joined the Department of Electronics and Electrical Engineering at UCL as a lecturer and was promoted to associate professor in 2021.

His research interests include optical signal processing and its applications in communication systems and scientific instruments. He has pioneered frequency comb assisted data conversion and low-latency data communications that have led to several world's first demonstrations. Dr Liu has co-authored more than 100 papers in international peer-reviewed journals and conferences with several high-profile papers and invited papers in top journals. He holds three patents, with two licenced to industrial companies. Dr Liu has been PI on over 10 grants from Industry and Research Councils. He is Co-I on the £6.1m EPSRC Programme grant TRANSNET.

Abstract

Originally developed for metrology, optical frequency combs are becoming increasingly pervasive in a wider range of research topics including optical communications, spectroscopy, and radio or microwave signal processing. However, application demands in these fields can be more challenging as they require compact sources with a high tolerance to temperature variations that are capable of delivering flat comb spectra, high power per tone, narrow linewidth and high optical signal-to-noise ratio (OSNR). In this talk, we will introduce our recent progress on cavity-less frequency comb generator and its applications with a focus on high performance photonic analog to digital conversions.

Frequency comb development for the extremely large telescope

Prof. Derryck Reid

Heriot-Watt University

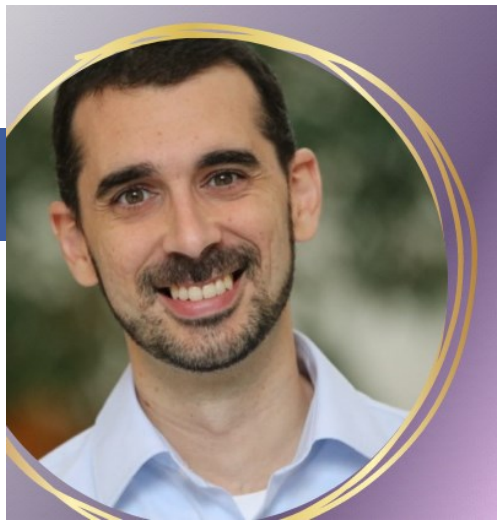
Bio

Derryck Reid obtained his MA from the University of Cambridge in 1991 and his PhD from the University of St Andrews in 1994 for thesis work on ultrafast optical parametric oscillators. A fellow of Optica and of the Royal Society of Edinburgh, he is best known for his invention of ultrafast pulse measurement using two-photon autocorrelation in semiconductor diodes, and his demonstration of the first femtosecond frequency comb based on an OPO.

Abstract

I discuss the underpinning comb technology and the prospects for addressing the 0.37–2.5-µm range demanded by HIRES, the high-resolution spectrograph currently being planned for the European Extremely Large Telescope (E-ELT). Results showing instantaneous comb coverage from 555–890 nm on the 10-m Southern African Large Telescope (SALT) will be discussed, along with comb-mode-resolving Fourier-transform spectroscopy and ultra-broadband optical parametric oscillators, technologies which will inform the final architecture of the E-ELT calibration instrumentation.

Low-noise, power-efficient soliton micro-combs



Prof. Victor Torres Company

Chalmers University

Bio

Victor Torres-Company is Professor at the Department of Microtechnology and Nanoscience (MC2). He obtained the PhD from the University of Valencia, Spain in 2008. Before joining Chalmers in 2012 he was a Postdoctoral Fellow at the Photonics Systems group in McGill University, Canada, and later a Marie Curie Research Fellow at Purdue University, USA. He leads the research group Ultrafast Photonics at Chalmers, working on chip-scale frequency comb technology, coherent optical communications and nonlinear silicon photonics. Prof. Torres-Company has co-authored more than 80 papers in leading optics journals and is Associate Editor in Optics Express. He has been awarded twice a Marie Curie Fellowship, was the recipient of a Young Research grant from the Swedish Research Council (VR) in 2013, a European Research Council Consolidator Grant in 2017 and a Consolidator grant from VR in 2020. For his PhD work, he won the Best Thesis award. At Chalmers he is the responsible for the courses *Photonic Integration* and *Advanced Measuring Techniques*.

Abstract

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 made of silicon nitride.

Neuro-inspired photonic computing using microcombs

Dr. Wen Zhou

University of Oxford

Bio

Wen Zhou received the Ph.D. degree in electronic engineering from The Chinese University of Hong Kong in 2018. He was a Postdoctoral Fellow supported by the Hong Kong Postdoctoral Hub—Innovation and Technology Fund from September 2018 to June 2019. He is currently a Postdoctoral Researcher supported by the EU Horizon 2020 Fun-COMP project in Prof. Harish Bhaskaran's group at University of Oxford. His research interests include silicon photonics, phase change materials, and in-memory photonic computing.

Abstract

In this talk, we will overview our recent works on neuro-inspired photonic computing using microcombs. We will introduce our novel designs of a high-Q racetrack resonator based on the multimode waveguides with build-in ion-implanted PIN diodes to effectively reduce free carriers generated by two-photon absorption, which enables demonstration of integrated frequency combs and Anti-Stokes Raman lasing. In the second part, we will introduce an emerging application of microcombs for in-memory photonic computing based on a photonic crossbar array consisting of photonic synapses using non-volatile phase-change materials to achieve record high computing density and computing efficiency for the parallel matrix-vector multiplication. And this talk will cover some emerging AI tasks, e.g., spiking neural networks and convolutional neural networks enabled by powerful integrated frequency combs.

Kerr nonlinear optics with whispering-gallery-mode microresonators

Dr. Jonathan Silver

NPL

Bio

Jonathan Silver is a Senior Research Scientist at the National Physical Laboratory in Teddington, where he heads a team researching microresonator -based frequency combs, or microcombs. He is currently funded by the UK Quantum Technology Hub in Sensors and Timing to develop integrated self-referenced microcombs for portable optical clocks and radar, in collaboration with the Universities of Glasgow and Southampton. Jonathan joined NPL in 2015 to work with Pascal Del'Haye on optical microresonators and microcombs after completing a PhD in ultracold atoms at the universities of Cambridge and Bonn, Germany. From 2018 to 2020, he held a Royal Academy of Engineering UK Intelligence Community Postdoctoral Research Fellowship hosted by City, University of London, during which time he continued to work at NPL as a Visiting Researcher. He took over the leadership of the team when Pascal moved to Germany in 2019. He grew up in London and holds bachelor's and master's degrees in Natural Sciences from the University of Cambridge.

Abstract

Ultrahigh-Q optical microresonators have the unique ability to store light for a long time in a very small space, allowing a range of optical nonlinear effects to be observed at input optical powers of milliwatts or even microwatts, and enabling many important new technologies. For example, microresonator Kerr frequency combs could have applications in portable optical clocks, telecoms, radar, lidar, airport security, health monitoring, and astrophysics. In this talk I will present a summary of NPL's work on nonlinear optics with microresonators over the last few years, starting with our discovery of spontaneous symmetry breaking between counterpropagating light in 2016, which led to the realisation of novel optical isolators, memories, logic gates, and gyroscopes, amongst other experimental and theoretical developments. I will then touch upon our demonstration of the first soliton combs in silica microresonators, before moving on to our most recent work on self-referenced and integrated microcombs for optical clocks and radar.

Dispersive Kerr Soliton in a Microresonator via Bichromatic Pumping

Dr. Shuangyou Zhang

Max Planck Institute

Bio

Shuangyou Zhang received his Bachelors in Electronics from Jilin University, and PhD in Electronics from Peking University, China. He was Multiply fellow (Marie S.-Curie Postdoctoral Fellowships in Photonics) from 2018 to 2020. His research interests include optical frequency combs and their applications, microresonator-based frequency combs, integrated photonics, and chip-scale atomic clock.

Abstract

Chip-scale optical frequency combs have attracted significant research interest and can be used in applications ranging from precision spectroscopy to telecom channel generators and LIDAR systems. Importantly, the discovery of dissipative Kerr solitons in microresonators has demonstrated new ways to generate low-noise and broadband frequency combs. In the time domain, microresonator based frequency combs correspond to self-stabilized soliton pulses. In two distinct regimes, microresonators have shown to emit either bright solitons in the anomalous dispersion regime or dark solitons (a short time of darkness in a bright background signal) in the normal dispersion regime.

Most of the microcomb research has been focused on pumping a microresonator with a single CW laser. In this talk, I will present the ideas and experimental results for dispersive Kerr soliton generation in a microresonator via bichromatic pumping. Bichromatic pumping of a resonator is shown to enable rich nonlinear dynamics including:

1. Deterministic soliton generation
2. Spectral extension and synchronization of microcombs
3. Bright-dark soliton bound state in a microresonator
4. Soliton dynamics crossing different dispersion regime, from anomalous to normal dispersion regime. In particular, the generation of soliton molecules in the zero-dispersion regime.

Optical whispering gallery modes as a platform for single molecule biosensing

Dr. Sivaraman Subramanian

University of Exeter

Bio

Sivaraman Subramanian received his Ph.D. in Physics from University of Exeter in 2021. He is currently a postdoctoral research associate at the Living Systems Institute at the University of Exeter, UK. His research is focused on developing a label-free optical biosensing platform based on whispering gallery modes. His research interests include micro/nanosensors, biophotonics, plasmonics, and light–matter interaction.

Abstract

Optical whispering gallery modes have found wide applications in the field of photonics owing to their high Q factors. Our group focuses mainly on utilizing optical whispering gallery modes for biosensing applications. By combing the high Q whispering gallery modes with the extreme localization of optical fields by plasmonic nanostructures, we have achieved biosensing at the ultimate level of single molecules. In this talk, I will provide an overview of how we utilize optical whispering gallery modes and their combination with plasmonic nanostructures to enable the detection of various chemical species from DNA to proteins and even down to single ions in solution. I will then briefly summarize the current directions of research in the group to push this sensor system beyond classical limits and create a platform lab-on-a-chip sensor for single-molecule enzymology, fundamental protein research, drug discovery and point-of-care devices.