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Temporal solitons in nano-photonic microresonators: from fundamental soliton dynamics to ultrashort laser pulses to visible frequency combs

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14. ABSTRACT
Our research has firstly focused on development of the platform for on-chip DKS-based frequency comb generation. Primarily, this platform consists of chip-integrated silicon nitride waveguides. Improvements to pumping techniques has resulted in the formation of large-bandwidth, smooth single-DKS combs spanning first two-thirds of an octave, then a full octave. DKS have also been generated centered at 1 m, and in three separated spatial modes of the microresonator. Further improvements to the quality and loss characteristics of these waveguides enabled generation of DKS combs at lower input threshold powers and at lower microwavedomain line spacing. Secondly, we have demonstrated techniques for applications using microresonator-based DKS. In collaboration with the group of Prof. Christian Koos at KIT, we demonstrated a source for massively parallel telecommunications, and a dual-comb based method for ultrafast distance measurement. We engaged in a fruitful collaboration as part of this project with the group of Prof. Alan Willner at the University of Southern California, producing works such as optical multicasting and electro-optic augmentation of the frequency comb. In further collaborations, we have also demonstrated astro-spectrometer calibration, optical coherence tomography, and ultralow-noise microwave generation. Finally, we have experimentally investigated the fundamental physics and dynamics of DKS and their relationship to dissipative systems in general. Such dynamics include the emission of analogous 'Cherenkov' radiation from DKS, the impact of stimulated Raman scattering, breathing of dissipative solitons based on the intrinsic dynamics of Kerr resonators or caused by interactions between different spatial modes, and the formation of perfect 'crystal' states of DKS. Our research has been further supplemented with advancements in soliton-based supercontinu

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“Exploring temporal soliton Physics in micro-resonator frequency combs”

Final Performance Report

03.01.2015 to 02.28.2019

Tobias J. Kippenberg
EPFL, Institute of Physics
Lausanne, Switzerland,

Award N° FA9550-15-1-0099
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Air Force Office of Scientific Research

Figure 1: Chip-integrated microring resonators based on Si_3N_4 waveguides with 10 GHz (lower) and 20 GHz (upper) free-spectral ranges, and 1 euro-cent for size comparison.

1. Abstract

As discussed in our recently published review paper [1], temporal dissipative Kerr solitons (DKS) in microresonators have opened immense opportunities for the development of microscale, highly efficient optical frequency comb sources that can be applied in the areas of telecommunication, frequency metrology, and spectroscopy. Microresonators operating in the soliton regime provide broadband and fully coherent optical frequency combs with repetition rates from the microwave to the terahertz domain. As nonlinear systems, microresonators allow for rich soliton dynamics, as well as novel observations that impact on the soliton formation process.

Our research has firstly focused on development of the platform for on-chip DKS-based frequency comb generation. Primarily, this platform consists of chip-integrated silicon nitride waveguides. Improvements to pumping techniques has resulted in the formation of large-bandwidth, smooth single-DKS combs spanning first two-thirds of an octave, then a full octave. DKS have also been generated centered at 1 µm, and in three separated spatial modes of the microresonator. Further improvements to the quality and loss characteristics of these waveguides enabled generation of DKS combs at lower input threshold powers and at lower microwave-domain line spacing. Secondly, we have demonstrated techniques for applications using microresonator-based DKS. In collaboration with the group of Prof. Christian Koos at KIT, we demonstrated a source for massively parallel telecommunications, and a dual-comb based method for ultrafast distance measurement. We engaged in a fruitful collaboration as part of this project with the group of Prof. Alan Willner at the University of Southern California, producing works such as optical multicasting and electro-optic augmentation of the frequency comb. In further collaborations, we have also demonstrated astro-spectrometer calibration, optical coherence tomography, and ultralow-noise microwave generation.

Finally, we have experimentally investigated the fundamental physics and dynamics of DKS and their relationship to dissipative systems in general. Such dynamics include the emission of analogous ‘Cherenkov’ radiation from DKS, the impact of stimulated Raman scattering, breathing of dissipative solitons based on the intrinsic dynamics of Kerr resonators or caused by interactions between different spatial modes, and the formation of perfect ‘crystal’ states of DKS. Our research has been further supplemented with advancements in soliton-based supercontinuum generation in silicon nitride waveguides, generating light into the mid-IR domain.

2. Summary of Accomplishments during the period

2.1 03.01.2015 – 02.29.2016

Raman Self-Frequency Shift of Dissipative Kerr Solitons in an Optical Microresonator (published in *Physical Review Letters*)

We have demonstrated a novel regime of dissipative Kerr solitons resulting from the presence of material’s Raman effects [2]. In this regime, the soliton-based comb envelope shows a dramatic redshift from the pump frequency. It was concluded that the novel regime is a result of a triple-balance of soliton dynamics; i.e. the energy balance between the cavity dissipation and the pump-induced gain, the phase balance between the dispersive and nonlinear effects, and the intrapulse dynamical balance initiated by the

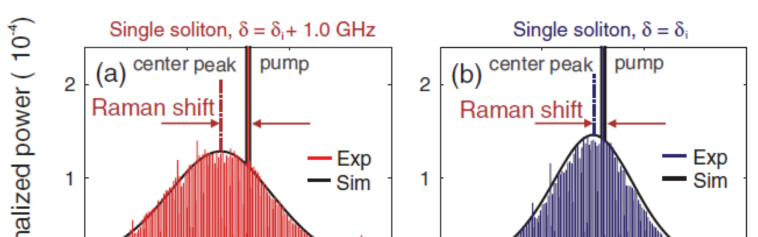

Figure 2: (a),(b) Experimentally generated single soliton combs demonstrating the Raman shift in a 100-GHz Si3N4 microresonator, shown in linear scale, at two different detunings δ. The envelopes are from numerical simulations.

Raman Effect. Moreover, the comb spectral redshift can be manipulated by tuning the soliton pulse intensity and temporal duration.

Photonic chip–based optical frequency comb using soliton Cherenkov radiation (published in *Science*)

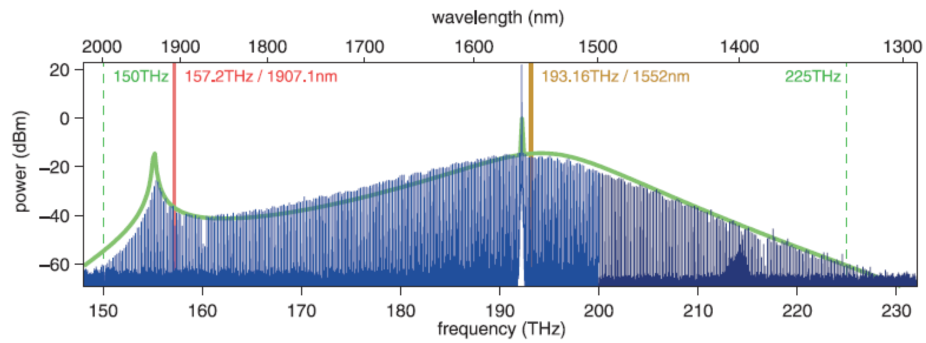

Figure 3: Soliton optical spectrum featuring soliton Cherenkov radiation at 155 THz. The green dashed lines mark a span of two-thirds of an octave. The green solid line denotes the simulated spectral envelope.

We have observed soliton induced Cherenkov radiation, which is also known as a dispersive wave, for the first time in a microresonator [3]. In the spectral domain, the dispersive wave manifests itself as a local maximum offset from the pump wavelength. This effect can broaden the useful spectral width significantly and provides additional power at a particular wavelength. This power can be used, for example, in self-referencing and spectroscopy experiments. The demonstrated spectral bandwidth covers two-thirds of an octave, which is used for self-referencing in a scheme known as the 2f-3f scheme [4]. We demonstrated that the dissipative Kerr soliton based frequency comb can be fully stabilized with respect to one optical and one radio frequency reference.

2.2 03.01.2016 – 02.28.2017

Universal dynamics and deterministic switching of dissipative Kerr solitons in optical microresonators (published in *Nature Physics*)

We have discovered a deterministic access to preferable-for-application single soliton states in microresonators, associated with the nonlinear thermal effect [5]. We demonstrated a successive decay of intracavity solitons by tuning the pump laser in the direction of increasing frequency, which we have named *backward tuning*. We have also implemented a pump-modulation based response measurement technique, which enables probing of the effective pump-to-resonance detuning and identification of the soliton state by a characteristic double-resonance feature.

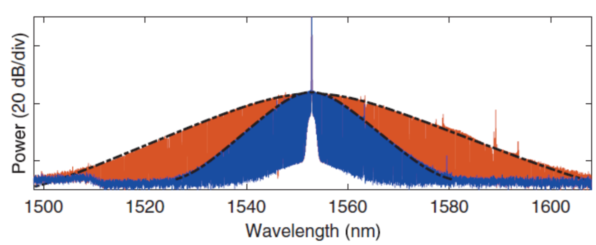

Figure 4: Single soliton spectra at the minimum (blue) and maximum (red) limits of detuning. As predicted by theory, the comb bandwidth increases with larger effective detuning.

Detuning-dependent properties and dispersion-induced instabilities of temporal dissipative Kerr solitons in optical microresonators (published in *Physical Review A*)

Effective detuning is the key parameter for dissipative soliton physics, which defines the temporal soliton pulse duration as well as its peak intensity. By measuring the system's response, we further accomplished a feedback stabilization on the effective detuning, and for the first time, experimentally verified the theory of dissipative Kerr solitons that are derived from a damped driven Nonlinear Schrödinger Equation [6].

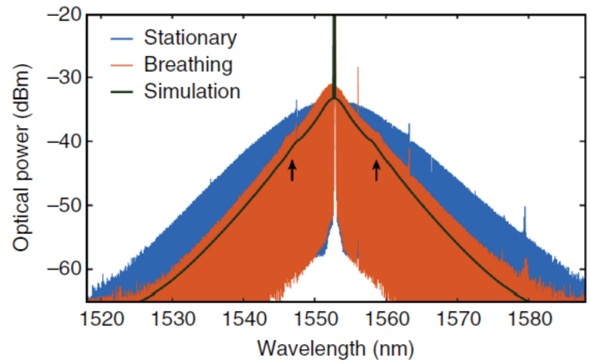

Figure 5: Experimental optical spectra of a stationary (blue) and breathing soliton states (red), in the 14 GHz FSR MgF_2 crystalline resonator, with the simulated optical spectrum (black) averaged over one breathing period. The arrows mark the positions of weak sidebands visible in both the simulated and measured spectra.

Breathing dissipative solitons in optical microresonators (published in *Nature Communications*)

Using the backward tuning method, we experimentally observed a novel state of dissipative Kerr solitons that features breathing – a periodic oscillation in both the duration and intensity [7]. For the first time, we revealed a correlation between the breathing frequency and the effective detuning. Furthermore, we implemented a direct observation of the spatiotemporal soliton dynamics in microresonators. These works contribute to the understanding of the fundamental properties of dissipative-soliton dynamics.

Optical coherent communications with dissipative Kerr solitons (published in *Nature*, and *Optics Letters*)

The soliton tuning and probing techniques developed during this past year have enabled further advances in the application of silicon nitride microresonator based Kerr frequency combs for telecommunications. Through our ongoing collaboration with the group of Prof C. Koos (KIT, Germany), we extended the large-capacity, coherent data transmission experiments to employ two soliton Kerr combs simultaneously either as two transmitters or as a transmitter and receiver. This enabled 50 Tbit/s data transmission rates and demonstrated the technical maturity of our devices [8]. The soliton excitation techniques developed by our group were transferred to Prof A. Willner's group and together we demonstrated optical multicasting using chip-scale Kerr combs and studied the influence of the pump linewidth on the data transmission quality [9-13].

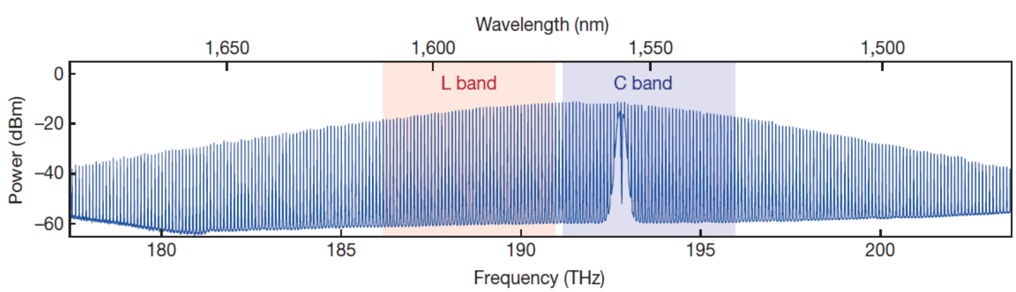

Figure 6: Measured spectrum of a single-soliton frequency comb, after suppression of residual pump light, used as the source of massively parallel telecommunications. The frequency comb features a smooth spectral envelope with a 3-dB bandwidth of 6 THz comprising hundreds of optical carriers extending beyond the telecommunication C and L bands (blue and red, respectively).

Octave-spanning Kerr soliton frequency combs with THz mode spacing (published in *Optica*)

Octave-spanning bandwidth is a key enabling factor for frequency combs and its coherent generation is a long-standing challenge for Kerr frequency combs. By precise dispersion design and optimization of the photonic Damascene fabrication process, we could achieve octave-spanning bandwidth in silicon nitride microresonators with THz free spectral range [14]. Moreover, the reduced power requirements allowed for generation of the broadest Kerr soliton frequency comb to date, spanning more than 200THz of bandwidth around the novel pump wavelength of 1.3µm. Such Kerr soliton combs are important for self-referenced Kerr frequency combs or applications in optical coherence tomography.

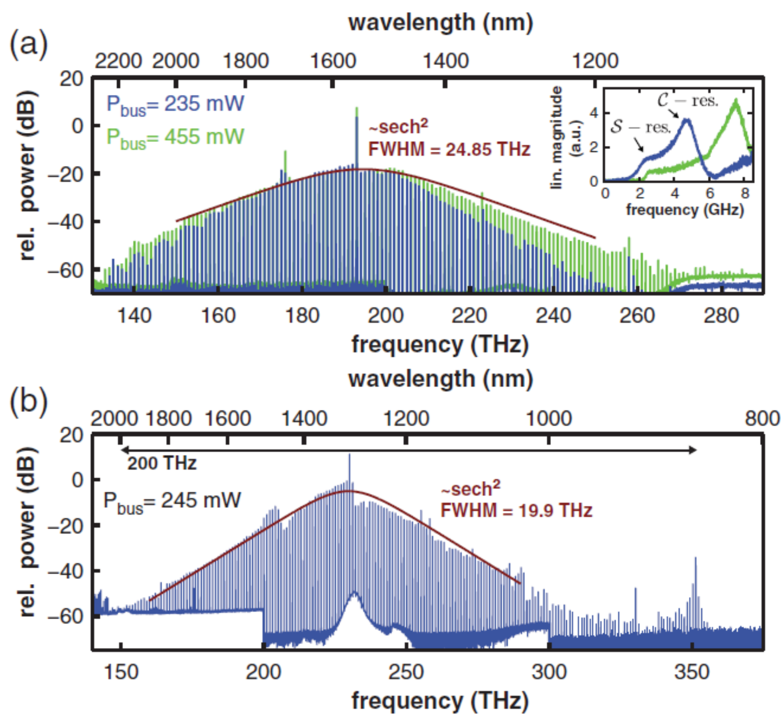

Figure 7: Octave-spanning single soliton generation at 1.55 µm and 1.3 µm pump wavelengths. (a) Single soliton state shown for two different pump laser powers and cavity detunings. (b) Single soliton spanning 200 THz in optical bandwidth with a DW at 850 nm.

2.3 03.01.2017 – 02.28.2018

Dissipative Kerr solitons generated at 1µm (published in *Nature Communications*)

We demonstrated that the Si_3N_4 microresonator platform can be used to generate DKS-based frequency combs with a 1060-nm CW laser, thereby allowing access to the optical wavelength window for biological imaging (0.7 – 1.4 µm) [15]. The typical signatures of dissipative Kerr solitons in microresonators, including low-phase-noise operation, Raman-induced red spectral shift, soliton switching dynamics and the bistability-related double-peak response of the microresonator system were observed and provided unambiguous identification of the DKS states. Equally important, we demonstrated the formation of octave-spanning soliton states in this wavelength region by exploiting the coherent dispersive wave emission for efficient spectral broadening towards visible wavelengths. Finally, we reported on soliton formation in hybridised microresonator modes, which represents an alternative approach to extend the DKS operation further into the visible domain where normal group velocity dispersion (GVD) is usually dominant. The DKS states are achieved in the region of an avoided modal crossing, where the strong interaction between resonator modes leads to locally enhanced anomalous GVD allowing the DKS formation. We show that the bandwidth of such soliton states is highly sensitive to the pumped resonance within the interaction region – a behavior contrasting the behavior in the absence of modal crossings.

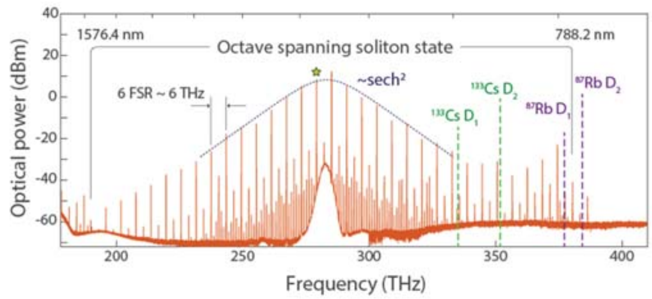

Figure 8: Octave-spanning DKS state driven with 1 µm pump. The spectrum is fitted with sech^2 envelope (dashed dark blue), from which a soliton duration of 17 fs is inferred. Green and purple dashed vertical lines indicate the spectral locations of Cs and Rb optical atomic transitions.

Ultrafast optical distance ranging using dissipative Kerr solitons (published in *Science* jointly with C. Koos at KIT)

In collaboration with the group of Prof. Christian Koos at KIT, we have shown that dissipative Kerr soliton states in microresonator-based optical frequency combs provide a route to integrated LIDAR (Light Detection and Ranging) systems that combine subwavelength accuracy and unprecedented acquisition speed with scalable fabrication, robust implementation, and compact form factors [16].

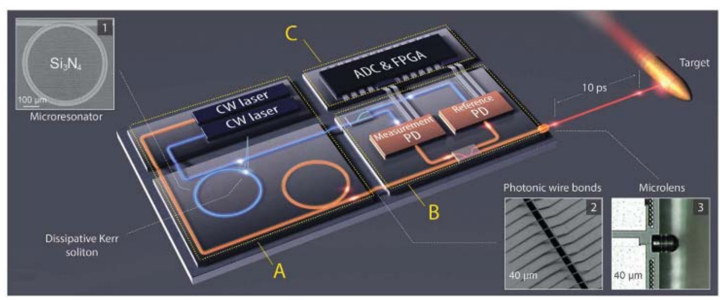

Figure 9: Artist’s view of a dual-comb chip-scale LIDAR engine, consisting of dual-frequency comb source (A), a photonic integrated circuit (PIC) for transmission and detection of the LIDAR signal (B), and data acquisition and signal processing electronics (C).

In our demonstrations, we exploit DKS combs for synthetic-wavelength interferometry with massively parallel multiheterodyne detection. Our scheme is based on a pair of free-running comb generators and does not require phase locking of the combs to each other. The large optical bandwidth of more than 11 THz leads to highly precise distance measurements with Allan deviations reaching 12 nm at an average time of 14 ms, whereas the large free spectral range (FSR) enables high-speed measurements at rates of up to 100 MHz. We prove the viability of our technique by sampling the naturally scattering surface of air-gun projectiles in flight, achieving lateral spatial resolutions of more than 2 µm for object speeds of more than 150 m/s.

Inter-mode breather solitons (published in *Physical Review X*)

As a follow up study on breather solitons in optical microresonators, we further discovered that the cavity dissipative soliton can feature breathing via energy exchange with other optical modes of the resonator, which is termed as the inter-mode breather soliton [17].

Indeed, optical microresonators are usually multi-mode either intrinsically or designed for the purpose of dispersion engineering. Therefore, due to imperfections of the resonator, light coupling in between different types of transverse modes can occur, particularly for those having close resonance frequencies. When the soliton is formed within the cavity, supported in one type of transverse modes (one mode family), light coupling could be featured as certain teeth of the soliton-based frequency comb is abruptly enhanced in the power. Significantly, with such light coupling, the soliton itself will feature breathing, meaning its energy is actively exchanging with other modes. In experiments, we captured and characterized such breathing dynamics, and demonstrated an out-of-phase power oscillation in between the cavity soliton and the light power in a second mode. Numerical simulations based on a group of coupled Lugiato-Lefever equations could exactly reproduce such phenomena and therefore confirm our observations.

In contrast to previously reported soliton breathers that exist when the optical resonator is operated at a small laser-to-resonance detuning, inter-mode breather solitons could exist with the laser detuning in the stable soliton operation region, and therefore lead to soliton decay and switching to a lower number of cavity solitons. Inter-mode breather solitons represent a novel type of breathing dynamics that was not previously realized but are important to several applications. It reveals a new panel of instability, which should be avoided in applications particularly for e.g. low-noise microwave generation.

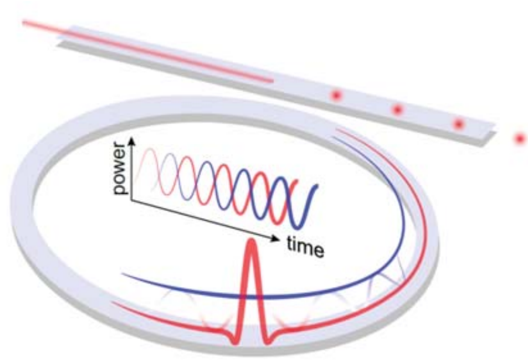

Figure 10: Conceptual picture of intermode breather soliton. The red curve in the ring resonator corresponds to the soliton wave form and the blue curve to the second mode coupling with the soliton. Inset shows the out-of-phase power oscillation between the soliton and the other mode, indicating the energy exchanging regime.

Mid-infrared frequency comb generation via coherent supercontinuum process (published in *Nature Photonics*)

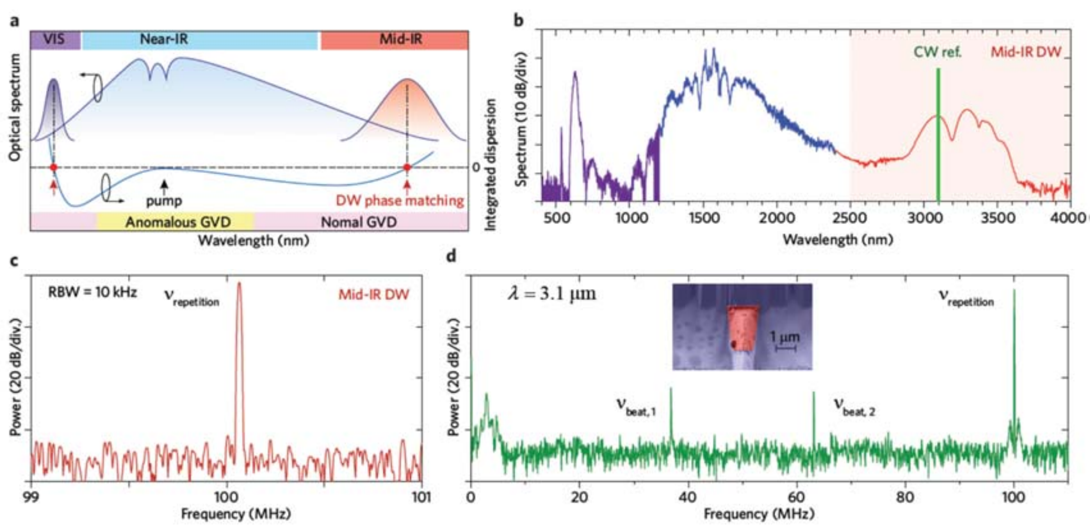

Figure 11: (a) Schematic representation of soliton induced dispersive wave generation. (b) Spectrum of the generated supercontinuum in a large-cross-section Si_3N_4 waveguide. (c) The repetition beatnote of the mid-IR wave, which is filtered by a long-pass edge-filter (cut on wavelength 2.5 micron). (d) The heterodyne beatnote of the mid-IR wave with a CW reference laser (3.1 micron); inset shows the cross-section SEM picture of the Si_3N_4 waveguide.

Mid-infrared (Mid-IR) optical frequency combs are of significant interest for molecular spectroscopy, due to the many molecules having strong vibrational transitions in this spectral region. Triggered by a significant number of applications such as pharmaceutical, environmental or medical breath analysis, mid-IR spectroscopy has attracted substantial attention in the past decade.

Recent work has also highlighted the potential to generate mid-IR optical frequency combs from the coherent supercontinuum process. When applying this process in chip-based nano-photonic waveguides, the pulse energy can be substantially reduced owing to the large Kerr nonlinearity and tight confinement. For accessing the mid-IR, dispersion engineering plays the key role in extending the long wavelength portion of the supercontinuum. Dispersive wave generation can induce a coherent and efficient light conversion over a large frequency span, and facilitate ultra-broadband SCG beyond the self-phase modulation (SPM) regime.

We have demonstrated herein the ability to synthesize mid-IR frequency combs in the range 2.5 – 4.0 micron, directly from an erbium-fiber based femtosecond laser in the telecom-band (at 1.55 micron), based on mid-IR dispersive wave generation, and using silicon nitride nano-photonic waveguides [18]. We further demonstrated that the dispersive wave inherits a high level of coherence from the seed laser and therefore serves as a mid-IR frequency comb. This approach has certain advantages such as being fully compatible with planar fabrication techniques and, with a compact telecom-band femtosecond fiber laser, can be readily extended for mid-infrared dual-comb spectroscopy.

2.4 03.01.2018 – 02.28.2019

Microphotonic Astrocomb (this work was led by T. Herr at CSEM, EPFL only provided the samples)

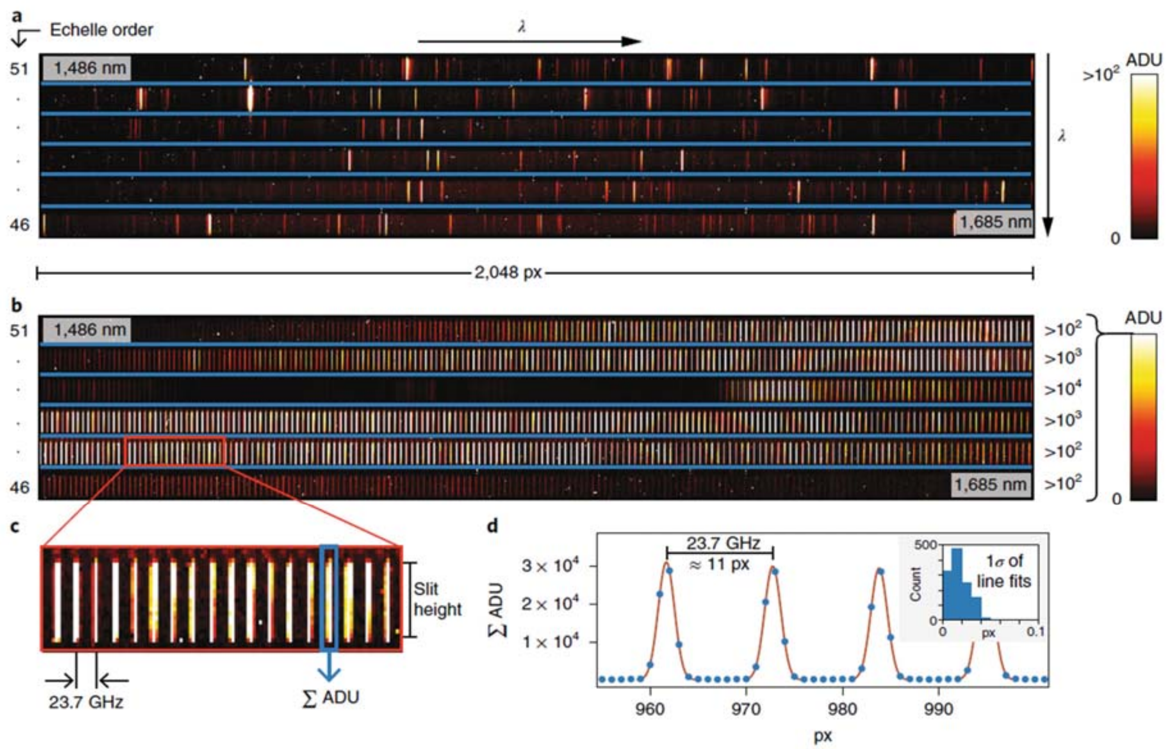

Figure 12: (a) Calibration spectrum of a U–Ne hollow-cathode lamp. The graph shows 6 echelle orders covering the wavelength range from 1,486 to 1,685 nm. The wavelength increases from left to right and from top to bottom. The optical intensity is measured in analogue-to-digital units (ADU). (b) Spectrum of the microresonator-based frequency comb. (c) Zoom-in of b showing well-resolved comb lines spaced by 23.7 GHz. Summing of ADU in the vertical direction (slit height) results in 1D data (blue dots) along the Gaussian line-fitting (red line) as shown in (d). (d) Gaussian line-fitting is used to determine the exact pixel positions of the comb lines. The inset shows the histogram of 1σ fit-uncertainties.

As part of a collaboration with Dr. Tobias Herr and CSEM, photonic silicon nitride-based DKS microcombs were deployed in astro-spectrometer calibration [19]. Frequency combs, being intrinsically equi-spaced arrays of optical lines, present a powerful tool for highly-accurate, broadband spectrometer calibration. Whereas conventional light sources such as hollow cathode lamps, in this case a Uranium-Neon based cathode lamp, provide a broadband, but highly sparse and irregular spectrum. Frequency combs derived from broadened mode-locked laser sources have been used for astro-spectrometer calibration, but their line-spacing has been typically restricted to sub-GHz, too small to be easily resolved by diffraction. High quality, nonlinear microresonators operating in the single-dissipative soliton regime naturally generate smooth frequency comb spectra, typically with >100 GHz line spacing. However, accurate spectrometer calibration benefits most from a spectrally efficient line-spacing from 1-20 GHz.

At the time of the experiment, the DKS with sub-100 GHz line-spacing in photonic-integrated silicon nitride was not readily accessible due to the high powers required due the intrinsically low conversion efficiency in continuous-wave driven microresonators, and also particularly due to the high thermal instability during dissipative soliton generation. These challenges were overcome by employing the novel pulse-driving technique, where a single, ultra-short dissipative soliton is efficiently formed from a longer injected seed pulse. In this case the pulse train was provided in the form of an electro-optic frequency comb, with an RF-source controlled frequency spacing of 11.85 GHz. In this way, a smooth 23.7 GHz-spaced single-DKS state was generated in a silicon nitride microresonator, seeded by, and phase-locked to the doubled-frequency of the input electro-optic comb, which itself was referenced via GPS to the Caesium time standard along with the laser centre frequency, providing a fully referenced frequency comb. The precision of the frequency-comb calibrated spectrometer was determined to be 25 cm/s of radial velocity, making exo-planet detection viable.

Triple-comb generation in crystalline microresonators via spatial multiplexing (published in *Nature Photonics*)

We have observed that cavities that sustain a very large number of modes can support solitons in more than a single mode family. We have demonstrated simultaneous generation of multiple frequency combs from a single optical microresonator and a single continuous-wave laser followed by a single sideband modulator. Similar to space-division multiplexing, we generated several dissipative Kerr soliton states in different spatial (or polarization) modes of a MgF_2 microresonator [20]. Up to three distinct combs were produced simultaneously, featuring excellent mutual coherence and substantial repetition rate differences, useful for fast acquisition and efficient rejection of soliton intermodulation products. Dual-comb spectroscopy with amplitude and phase retrieval, as well as optical sampling of a breathing soliton was realized with the free-running system. The compatibility with photonic-integrated resonators could enable the deployment of dual- and triple-comb-based methods to applications where they remained impractical with current technology.

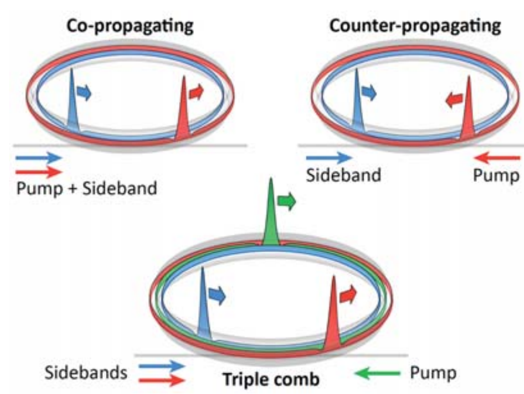

Figure 13: Conceptual scheme used for dual and triple comb generation in a single resonator by simultaneous pumping of three mode families.

Dynamics of soliton crystals in optical microresonators (arXiv:1903.07122 , accepted to *Nature Physics*)

We have investigated the nonlinear dynamics of recently discovered soliton crystal states in optical microresonators, which represent temporally ordered co-propagating ensembles of dissipative Kerr solitons (DKS). We have demonstrated the existence of *perfect* soliton crystal states in optical microresonators, representing defect-free crystal lattices of DKS, which could be generated in a deterministic fashion. Moreover, for the first time the full range of dynamical properties of soliton crystals was studied [21].

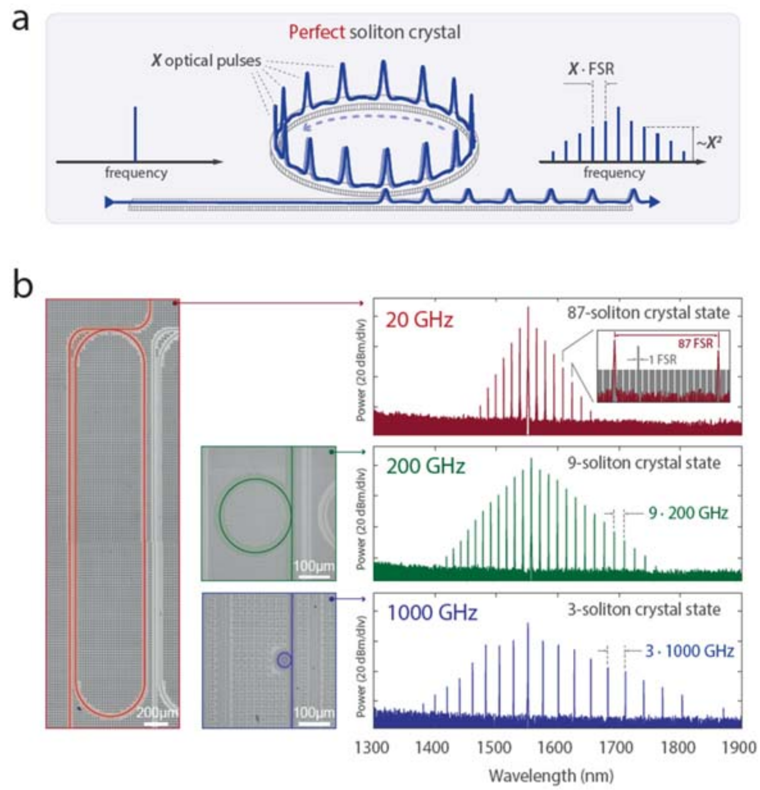

Figure 14: Perfect soliton crystals in Si3N4 microresonators (a) Sketch of the perfect soliton crystal consisting of X pulses formed in the CW-driven nonlinear optical microcavity. (b) Optical microscope images of Si3N4 microresonators with different free spectral ranges of 20 GHz, 200 GHz and 1000 GHz (left), and perfect soliton crystal states generated in each device (right).

First, we shed light on the formation process of these states, and discovered the existence of a critical pump power, below which the originally stochastic process of soliton excitation becomes deterministic and provides faultless access to perfect soliton crystals. Second, we demonstrated that soliton crystals can be reliably translated in the two-dimensional parameter space of the system (pump power and detuning). Using such translations, we experimentally investigated their behavior in different stability regimes and demonstrated that soliton crystal states can be switched. A fundamental link between the soliton switching phenomenon and the regime of transient chaos was established and proved solely responsible for DKS elimination. Finally, we presented a rich panel of experimentally observed, novel dynamical phenomena appearing in soliton crystals, including the first observation of soliton crystal breathers, switching between perfect soliton crystals, as well as controllable soliton crystal melting, disordering and recrystallization.

The demonstrated perfect soliton crystal states are able to provide several important advantages for soliton comb applications, due to their symmetrical nature allowing for lossless energy redistribution in a set of supermodes spaced by several FSR. First, the perfect soliton crystals (PSC) states establish a natural phase-coherent link between the THz and microwave domain. Second, PSC states can be used as high-purity, ultra-high-repetition rate soliton combs, reaching a mode spacing of several THz (which is challenging for small microresonators due to bending losses and limitations on the dispersion control). We have completed the manuscript on the abovementioned results, which is now in review in Nature Physics.

Nanophotonic soliton-based microwave synthesizers (arXiv:1901.10372 , under review)

A particularly promising application using soliton microcombs at microwave repetition rates is to build microwave oscillators based on integrated photonics, whose center frequency is determined by the microresonator free spectral range (FSR) and actively tunable using heaters, for example. Microwave oscillators are of paramount interest in a large variety of modern applications, spanning from detection, ranging, time-frequency metrology and wireless broadband communications, as well as in fundamental research involving the testing of physical constants. So far, soliton microcombs at microwave repetition rates, e.g. f_{rep} < 20 GHz in the microwave K-band, have been demonstrated only in silica and crystalline microresonators. The main challenges hindering the generation of single soliton states in integrated microresonators at microwave repetition rates were related to the comparatively low quality factor and strong thermal effects. The lower Q is exacerbated by the fact that the diameter and perimeter of the microresonator increases with decreasing repetition rate, therefore increasing the probability of suffering loss from fabrication defects, such as stitching misalignment during photolithography.

Using the photonic Damascene reflow process, we have fabricated integrated Si_3N_4 microresonators with quality factor exceeding 22 million, and demonstrated a 19.6 GHz, K-band single soliton microcomb at an ultralow input power of 35 mW, without requiring any complex soliton initiation technique [22]. This power level is on a par with silica and crystalline resonators, and compatible with integrated lasers. We utilize the device to create low-noise K-band microwave oscillators, with phase noise levels at -65 dBc/Hz at 1 kHz and -115 dBc/Hz at 100 kHz offset frequency, and study the phase noise performance limitations. Equally important, we demonstrate a single soliton at X-band repetition rate of only 9.77 GHz. Our results establish integrated Si_3N_4 soliton microcombs as photonic microwave oscillators, which may form central elements for future microwave photonic systems.

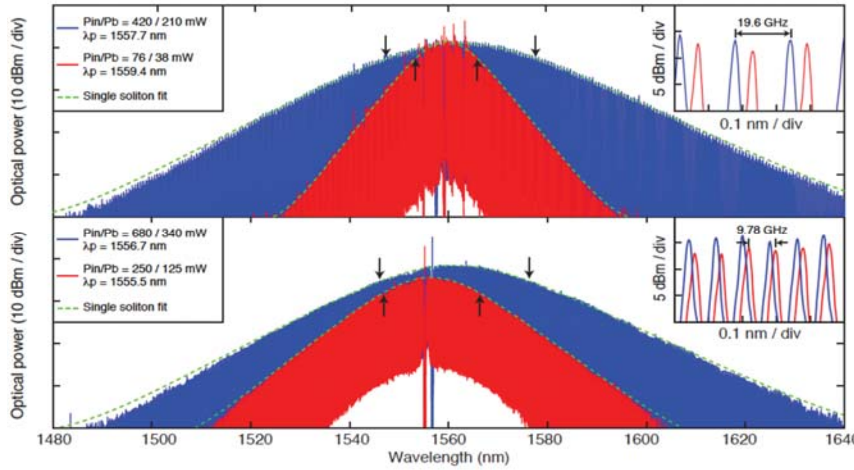

Figure 15: Top: Single soliton spectra of 19.6 GHz repetition rate with 38 mW power in sample A (red, 3-dB-bandwidth of 11.0 nm), and with 210 mW power in sample B (blue, 3-dBbandwidth of 26.9 nm), and their spectrum fit (green). Arrows mark the 3-dB-bandwidths, which contain 69 (red) and 170 (blue) comb lines, respectively. Inset: Spectrum zoom-in showing the 19.6 GHz mode spacing. Bottom: Single soliton spectra of 9.78 GHz repetition rate with 125 mW power in sample C (red, 3-dB-bandwidth of 17.4 nm), and with 340 mW power in sample D (blue, 3-dB-bandwidth of 25.8 nm), and their spectrum fit (green). Arrows mark the 3-dB-bandwidths, which contain 139 (red) and 327 (blue) comb lines, respectively.

Optical to microwave frequency division using a Kerr comb and auxiliary fiber-based comb (arXiv:1903.01213, under review)

We have implemented an optical frequency division scheme using our Kerr frequency comb pumped with an ultrastable laser (USL). Extending the transfer oscillator method to Kerr-combs, we present the first demonstration of ultralow-noise RF generation via frequency division of an optical reference using this approach [23]. This technique does not require any lock of the comb to the optical reference, but uses a judicious combination of signals to cancel the comb phase noise and to electrically-divide the phase noise of the USL to the RF domain. The phase noise of the generated ultralow-noise signal was measured with a cross-correlator phase noise analyzer. It shows a shot-noise floor lower than -150 dBc/Hz and a value of -110 dBc/Hz at 200-Hz Fourier frequency (Fig. 1b), 15 dB lower than the best micro-resonator-based photonics oscillator at 10 GHz. The transfer oscillator offers an improvement by at least 40 dB at 1-Hz offset frequency compared to the direct detection of the Kerr-comb repetition rate, and the measurement is limited by the instrumental noise floor.

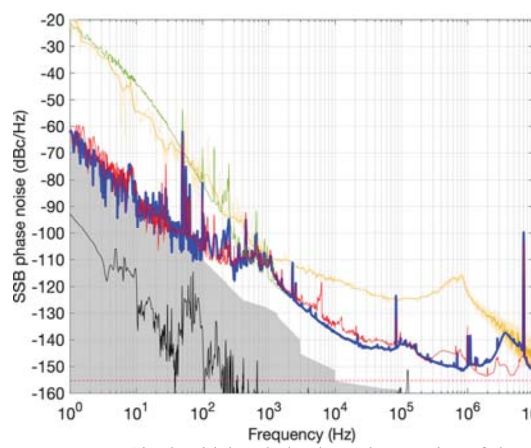

Figure 16: Single-sideband absolute phase noise of the 14-GHz signal generated by optical-to-RF division of the USL via the Kerr-comb transfer oscillator (blue/red in 2 different soliton states) and directly from the Kerr-comb repetition rate for comparison (green). The yellow curve indicates the current state of the art of a free running Kerr comb. The gray area shows the instrumental limitation and the black curve is the lower limit inferred from optical phase noise.

Nanophotonic supercontinuum based mid-infrared dual-comb spectroscopy (under review)

Supercontinuum processes have been essential and widely used for laser stabilization, as well as in difference frequency generation (DFG), yet to date they have rarely been applied for direct mid-IR dual-comb spectroscopy. In collaboration with Menlo Systems GmbH, in EPFL we demonstrated a broadband mid-IR dual-comb spectrometer for parallel gas-phase detection in the 2800 − 3600 cm^{-1} spectral range, using photonic chip-based Si_3N_4 waveguides seeded in the telecom band.

In experiments, the pump sources are ultralow-noise fiber-based frequency combs (Menlo Systems) centered at the wavelength of 1.55 µm. The comb mode spacing (i.e. the repetition rate) is ~ 250 MHz, with a mutual repetition rate difference of ~ 320 Hz. In contrast to a conventional single-core waveguide, here we use a dual-core coupled structure that induces supermode dispersion as the result of mode coupling. In principle, this effect can be engineered at an arbitrary wavelength range, particularly capable of producing anomalous dispersion in the mid-IR. As a result, we generated a broadband mid-IR supercontinuum covering the 2.5 − 3.7 µm spectral range, with power > 1 mW. Using two mid-IR continua, dual-comb spectroscopy was carried out for the parallel gas-phase detection of both methane and acetylene. The retrieved mid-IR frequency combs have a large span from 2800 − 3600 cm^{-1}. The normalized signal-to-noise ratio (SNR) has a peak value of 25/√s at 3400 cm^{-1}, and overall the figure of merit (averaged SNR multiplying the total number of comb modes) is ~ 10^6/√s.

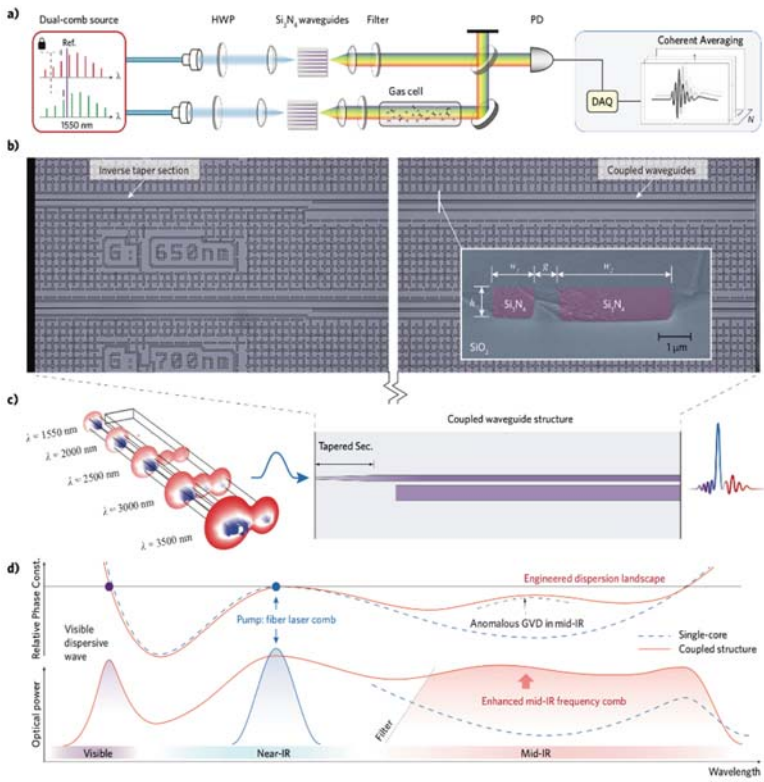

Figure 17: (a) Schematic setup for mid-IR dual-comb gas-phase spectroscopy. (b) Microscopic pictures of a photonic integrated chip with coupled Si_3N_4 waveguides. The false-colored scanning electron microscopic (SEM) picture of the waveguide cross section is also presented. (c) Illustration of the supercontinuum process in a coupled waveguide, where the spatial mode distributions are calculated by means of the finite element method, at different wavelengths. (d) Principle of enhanced mid-IR continuum generation serving as the frequency comb.

Soliton microcomb based spectral domain optical coherence tomography (arXiv:1902.06985, under review)

In collaboration with Professor Theo Lasser at EPFL, we constructed the first dissipative soliton Kerr comb based Optical Coherence Tomography (OCT) and demonstrated its imaging capability on an *ex vivo* fixed mouse brain tissue [24]. The Kerr OCT opens up opportunities to downsize the bulky OCT setup to a portable size and to greatly enhance the current imaging speed.

In our demonstration, we generated a broadband frequency comb that exceeds the bandwidth of a standard OCT light source (super luminance diode). The broader bandwidth of the Kerr comb guarantees a better resolution in OCT imaging. In addition, the extremely long coherence length (> kilometers) inherited from the stability of the monolithic micro-resonator hints at a possibility to generate an interference signal without matching the reference arm length. Given the lifting of the path-length matching requirement, the OCT system can be further miniaturized. Optical subsampling, which will drastically enhance the data acquisition speed, can also be implemented.

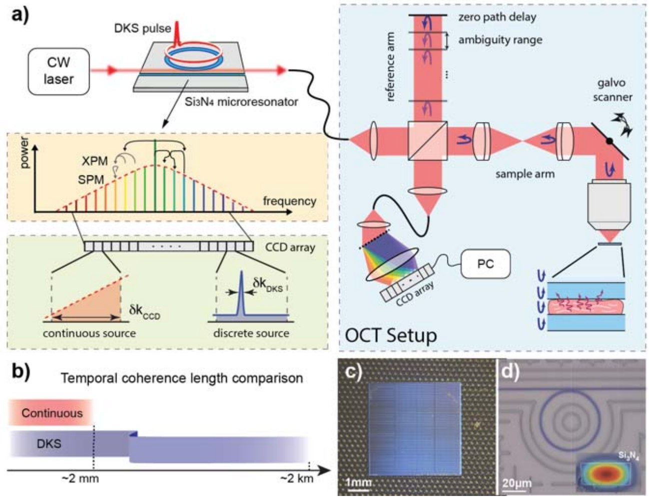

Figure 18: The principle of DKS-enabled spectral domain OCT. (a) DKS generated in a CW laser-driven photonic chip-based Si_3N_4 microresonator. The generated pulse train is coupled to the OCT system interrogating the sample (blue shaded box). The green shaded box illustrates the difference between signal sampling of continuous and discrete sources. (b) The coherence length comparison between the SLD and the Kerr comb (c,d) Microscope image of a chip with Si_3N_4 based microresonators.

Electrically Driven Soliton Microcomb (published in *Nature Communications*)

We have demonstrated fully integrated, chip-scale and current initiated soliton microcombs by using a commercially available multi-frequency laser diode (1535 nm) and a high-Q Si_3N_4 microresonator [25]. One of the important aspects of this project was to use high-Q (~10 million) Si_3N_4 microresonators in order to decrease the soliton excitation power level to that of an on-chip laser diode (~ few-mW). This has been achieved by fabricating Si_3N_4 microresonators using the photonic Damascene-reflow process enabling Q-factors in range of 10 million. The laser diode was directly butt-coupled to the Si_3N_4 microresonator and we observed self-injection locking when

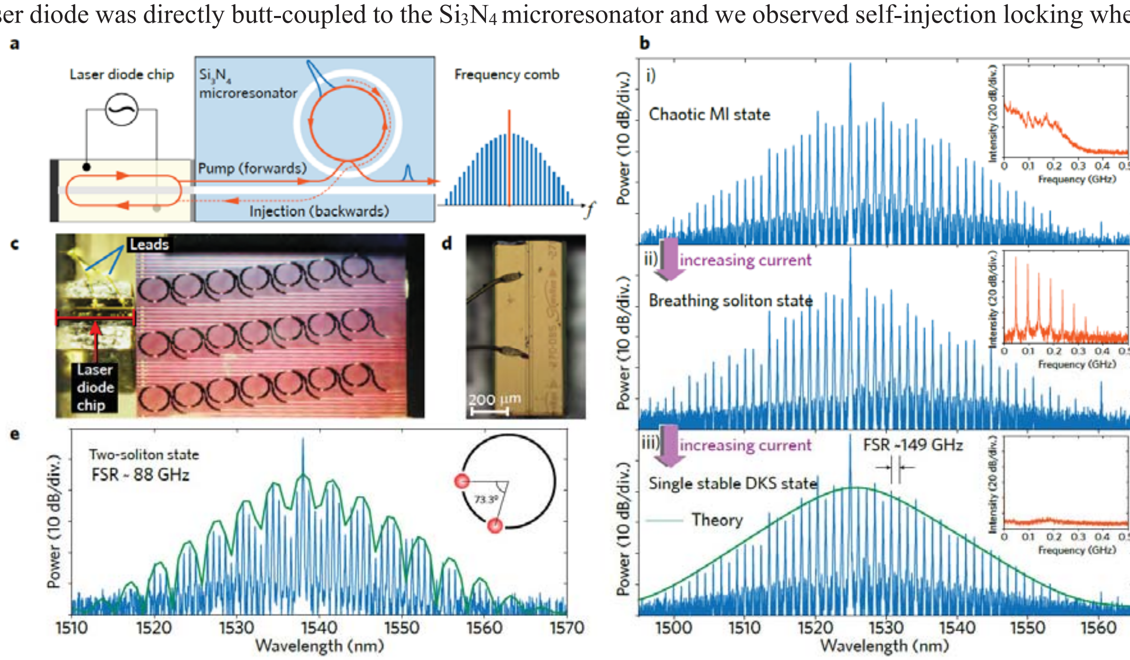

Figure 19: a) The experimental setup used to demonstrate the self-injection locking and the soliton microcombs simultaneously. TC: temperature controller, CC: current controller, OSA: optical spectrum analyzer, OSC: oscilloscope and ESA: electrical spectrum analyzer. b) Different combs and soliton states (150-GHz-FSR), generated by adjusting the current (~ 1 mA) of the laser diode, and corresponding low-RF noise spectra shown in the insets. c) A Fabry–Pérot laser diode butt coupled to a Si_3N_4 microresonator chip. d) An optical image of the InP laser diode chip showing the magnified view. e) A soliton microcomb generated in sub-100 GHz FSR microresonator using a chip-scale laser diode.

one of the laser diode mode matched the Si_3N_4 microresonator resonance. This effect arises due to bulk and Rayleigh backscattering in the Si_3N_4 microresonator. This not only leads to single-mode laser operation, but also reduces the linewidth of the laser by x1000 fold. Importantly, we further generated modulation instability (MI), breathing solitons, multi-solitons, and single stable solitons along with self-injection locking by adjusting the current of the laser diode. Additionally, soliton generation has been demonstrated in microresonators with an FSR ranging from 88 GHz to 1 THz. This approach simplifies the soliton excitation mechanism and reduces the footprint of the device for future high volume applications such as optical metrology, data center interconnects, and coherent communication. The work was carried out in close collaboration with Russian Quantum Center (RQC), Russia.

Ultralow-power chip-based soliton microcombs for photonic integration (published in *Optica*)

The generation of dissipative Kerr solitons in optical microresonators has provided a route to compact frequency combs of high repetition rate, which have already been employed for optical frequency synthesizers, ultrafast ranging, coherent telecommunication, and dual-comb spectroscopy. Yet to date, soliton formation in Si_3N_4 microresonators at electronically detectable repetition rates, typically less than 100 GHz, is hindered by the requirement of external power amplifiers, due to the low quality (Q) factors, as well as by thermal effects that necessitate the use of frequency agile lasers to access the soliton state. Here, we demonstrate that the newly developed variant of the photonic Damascene process can overcome the outlined challenges and significantly

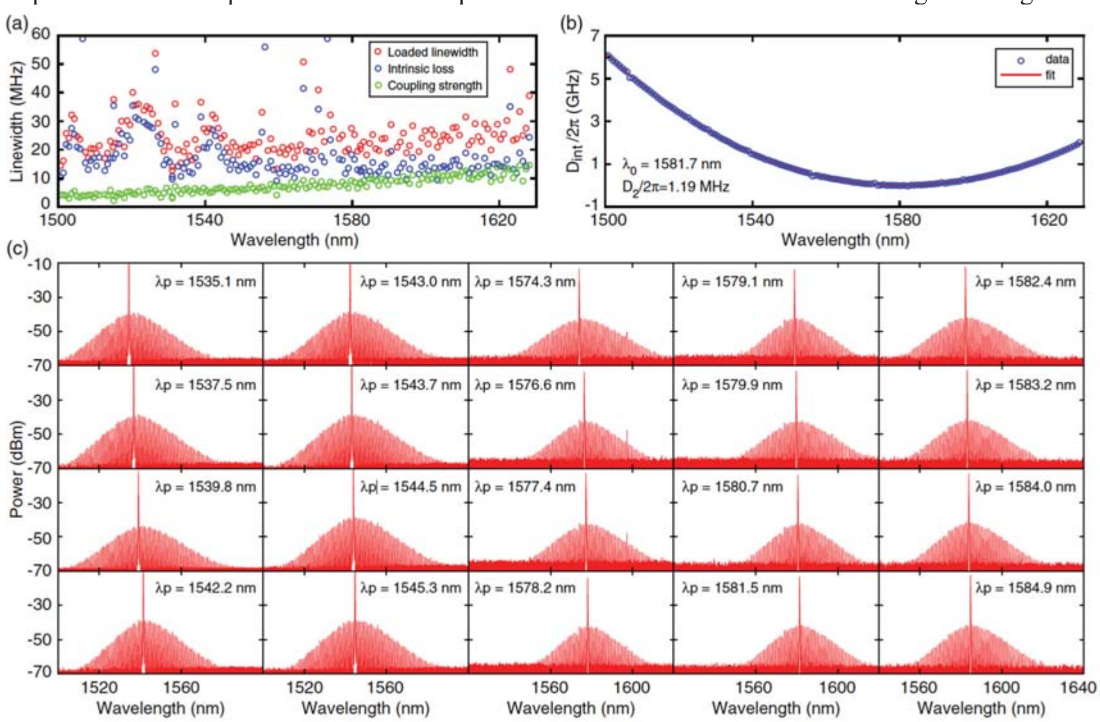

Figure 20: Characterization of a different 99-GHz-FSR microresonator, and single-soliton formation in multiple resonances. (a) Loaded linewidth, intrinsic loss, and coupling strength of each resonance. (b) Measured GVD. (c) Single-soliton formation in twenty selected resonances, eleven of which are consecutive in the telecom L-band, and five of which are consecutive in the telecom C-band.

reduce the required input power for soliton formation in Si3N4 microresonators [26]. We first show single-soliton formation in Si3N4 microresonators of $Q_0 > 8.2$ million at the lowest repetition rate to date of 88 GHz, which is electronically detectable, with 48.6 mW power at the chip input facet.

By further improving the microresonator Q factors to $Q_0 > 15$ million, we demonstrate single-soliton formation of 99 GHz repetition rate with a record-low input power of 9.8 mW. Using only a tunable diode laser without an optical amplifier, we access single-soliton states in eleven consecutive resonances in the telecom L-band and five in the telecom C-band, via simple laser piezo tuning. Such low-power soliton microcombs of sub-100-GHz repetition rate can significantly simplify the recently demonstrated dual-comb ultrafast distance measurements and optical coherent communication, which required erbium-doped fiber amplifiers (EDFAs) to amplify the input power to above 1 W. In addition, the soliton microcombs demonstrated here have shown great potential for future photonic integrated microwave generators, and chip-based frequency synthesizers via integration of on-chip lasers, semiconductor optical amplifiers, and nonlinear microresonators. Soliton microcombs formed in wavelength regions where amplifiers are not available could unlock new applications such as optical coherent tomography (OCT) at 1.3 µm and sensing of toxic gases and greenhouse gases.

Integrated gallium phosphide nonlinear photonics (arXiv:1808.03554 , under review)

Gallium phosphide (GaP), a III-V semiconductor with an indirect bandgap, is one promising material presenting an alternative to Si_3N_4 for chip-based nonlinear photonics. GaP has its bandgap located at 2.26 eV (550 nm) giving negligible two-photon absorption above 1.1 µm, whilst having a high refractive index (n > 3) and a strong $\chi^{(3)}$ nonlinearity. It also possesses a high $\chi^{(2)}$ nonlinearity due to its non-centrosymmetric crystalline structure. Photonic-integrated GaP has thus far been inhibited by the lack of an appropriate bonded insulator which has a refractive index low enough to provide sufficient light confinement. Our collaborators at IBM Zurich have developed an effective GaP-on-insulator platform for integrated nonlinear photonics. The SiO_2 insulator (n = 1.44) provides more than sufficient index contrast for light confinement, and further provides a very small mode area resulting in an enhanced nonlinear propagation factor.

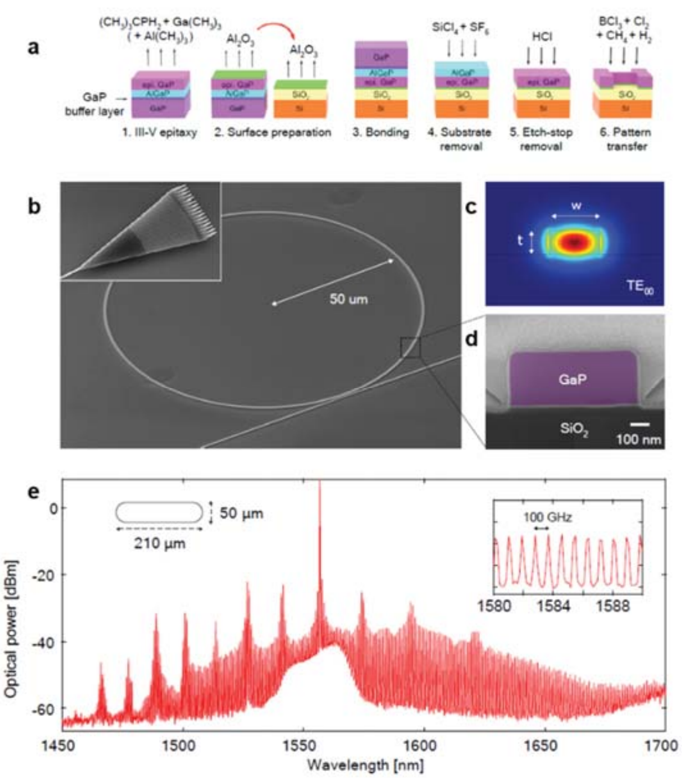

Figure 21: (a) Process flow for GaP-on-insulator. (b) Micrograph view of GaP ring-resonator with bus waveguide coupler, grating coupler in inset. (c,d) Calculated electric field of the most fundamental transverse waveguide mode, and physical waveguide cross-section respectively. (e) Broadband frequency comb generated in a resonator with a FSR of 100 GHz.

A recent collaborative work between EPFL and IBM Research Zurich has shown the potential for GaP in Kerr microcomb generation [27]. Fully loaded Q-factors of > 250,000 were achieved in the fabricated microresonators. Kerr comb generation occured at a threshold power of as little as 3mW, indicating a measured material nonlinear refractive index for GaP o $n_2 = 1.2 \times 10^{-17}$ m^2/W, 50 times greater than that of Si_3N_4. A separate direct measurement using a modulation transfer method yielded $n_2 = 1.1 \times 10^{-17}$ m^2/W, in firm agreement. Higher driving powers resulted in broadband comb formation spanning >200 nm. Additionally, as a result of the $\chi^{(2)}$ nonlinearity, a full frequency comb was also formed at the second harmonic of the pump wavelength centered at 780 nm. With further work on waveguide fabrication, this threshold power could also be pushed down, making GaP an ideal material for frequency comb generation fully integrated on chip where pump laser powers are limited to the mW level.

3. Patents

In relation to the *backward tuning* and response measurement techniques developed within our group [4], we have filed the following patent application:

US Patent Application No. 15/406,811 filed on January 16, 2017
Title: "SINGLE AND MULTIPLE SOLITON GENERATION DEVICE AND METHOD"
Applicant: ECOLE POLYTECHNIQUE FEDERALE DE LAUSANNE (EPFL)
Inventors: Maxim KARPOV, Victor BRASCH, Tobias KIPPENBERG

In relation to the *spatial multiplexing of solitons in microresonators* [16], we have filed the following patent application:

US Patent Application No. 62/655,248 filed on April 10, 2018
Title: "SPATIAL MULTIPLEXING OF TEMPORAL DISSIPATIVE SOLITON COMBS IN OPTICAL MICROSESONATOR FOR MULTIPLE FREQUENCY COMBS GENERATION"
Applicant: ECOLE POLYTECHNIQUE FEDERALE DE LAUSANNE (EPFL)
Inventors: Tobias KIPPENBERG, Erwan LUCAS, Grigory LIHACHEV, Nikolay PAVLOV, Michael GORODETSKY.

In relation to the *nanophotonic supercontinuum-based dual-comb spectroscopy in the mid-infrared*, we disclosed the following invention:

US Patent Application to be filed
Title: NANOPHOTONIC INTEGRATED COUPLED WAVEGUIDE BRIDGING MID-INFRARED SUPERCONTINUUM GENERATION WITH NEARINFRARED LASER SOURCES
Applicant: ECOLE POLYTECHNIQUE FEDERALE DE LAUSANNE (EPFL)
Inventors: Tobias KIPPENBERG, Hairun GUO, Junqiu LIU, Wenle WENG

4. Publications

[1] T. J. Kippenberg, A. L. Gaeta, M. Lipson, and M. L. Gorodetsky, “Dissipative Kerr solitons in optical microresonators,” *Science*, vol. 361, no. 6402, p. eaan8083, Aug. 2018. https://doi.org/10.1126/science.aan8083

[2] M. Karpov *et al.*, “Raman Self-Frequency Shift of Dissipative Kerr Solitons in an Optical Microresonator,” *Phys. Rev. Lett.*, vol. 116, no. 10, p. 103902, Mar. 2016. https://doi.org/10.1103/PhysRevLett.116.103902

[3] V. Brasch *et al.*, “Photonic chip–based optical frequency comb using soliton Cherenkov radiation,” *Science*, vol. 351, no. 6271, pp. 357–360, Jan. 2016. https://doi.org/10.1126/science.aad4811

[4] V. Brasch, E. Lucas, J. D. Jost, M. Geiselmann, and T. J. Kippenberg, “Self-referenced photonic chip soliton Kerr frequency comb,” *Light Sci. Appl.*, vol. 6, no. 1, p. e16202, Jan. 2017. https://doi.org/10.1038/lsa.2016.202

[5] H. Guo *et al.*, “Universal dynamics and deterministic switching of dissipative Kerr solitons in optical microresonators,” *Nat. Phys.*, vol. 13, no. 1, pp. 94–102, Jan. 2017. https://doi.org/10.1038/nphys3893

[6] E. Lucas, H. Guo, J. D. Jost, M. Karpov, and T. J. Kippenberg, “Detuning-dependent properties and dispersion-induced instabilities of temporal dissipative Kerr solitons in optical microresonators,” *Phys. Rev. A*, vol. 95, no. 4, p. 043822, Apr. 2017. https://doi.org/10.1103/PhysRevA.95.043822

[7] E. Lucas, M. Karpov, H. Guo, M. L. Gorodetsky, and T. J. Kippenberg, “Breathing dissipative solitons in optical microresonators,” *Nat. Commun.*, vol. 8, no. 1, p. 736, Sep. 2017. https://doi.org/10.1038/s41467-017-00719-w

[8] P. Marin-Palomo *et al.*, “Microresonator-based solitons for massively parallel coherent optical communications,” *Nature*, vol. 546, no. 7657, pp. 274–279, Jun. 2017. https://doi.org/10.1038/nature22387

[9] C. Bao *et al.*, “Demonstration of optical multicasting using Kerr frequency comb lines,” *Opt. Lett.*, vol. 41, no. 16, pp. 3876–3879, Aug. 2016. https://doi.org/10.1364/OL.41.003876

[10] C. Bao *et al.*, “Dual-pump generation of high-coherence primary Kerr combs with multiple sub-lines,” *Opt. Lett.*, vol. 42, no. 3, pp. 595–598, Feb. 2017. https://doi.org/10.1364/OL.42.000595

[11] P. Liao *et al.*, “Dependence of a microresonator Kerr frequency comb on the pump linewidth,” *Opt. Lett.*, vol. 42, no. 4, pp. 779–782, Feb. 2017. https://doi.org/10.1364/OL.42.000779

[12] P. Liao *et al.*, “Pump-linewidth-tolerant wavelength multicasting using soliton Kerr frequency combs,” *Opt. Lett.*, vol. 42, no. 16, pp. 3177–3180, Aug. 2017. https://doi.org/10.1364/OL.42.003177

[13] C. Bao *et al.*, “Tunable insertion of multiple lines into a Kerr frequency comb using electro-optical modulators,” *Opt. Lett.*, vol. 42, no. 19, pp. 3765–3768, Oct. 2017.
https://doi.org/10.1364/OL.42.003765

[14] M. H. P. Pfeiffer *et al.*, “Octave-spanning dissipative Kerr soliton frequency combs in Si_3N_4 microresonators,” *Optica*, vol. 4, no. 7, pp. 684–691, Jul. 2017.
https://doi.org/10.1364/OPTICA.4.000684

[15] M. Karpov, M. H. P. Pfeiffer, J. Liu, A. Lukashchuk, and T. J. Kippenberg, “Photonic chip-based soliton frequency combs covering the biological imaging window,” *Nat. Commun.*, vol. 9, no. 1, Dec. 2018.
https://doi.org/10.1038/s41467-018-03471-x

[16] P. Trocha *et al.*, “Ultrafast optical ranging using microresonator soliton frequency combs,” *Science*, vol. 359, no. 6378, pp. 887–891, Feb. 2018.
https://doi.org/10.1126/science.aao3924

[17] H. Guo *et al.*, “Intermode Breather Solitons in Optical Microresonators,” *Phys. Rev. X*, vol. 7, no. 4, p. 041055, Dec. 2017.
https://doi.org/10.1103/PhysRevX.7.041055

[18] H. Guo *et al.*, “Mid-infrared frequency comb via coherent dispersive wave generation in silicon nitride nanophotonic waveguides,” *Nat. Photonics*, p. 1, Apr. 2018.
https://doi.org/10.1038/s41566-018-0144-1

[19] E. Obrzud *et al.*, “A microphotonic astrocomb,” *Nat. Photonics*, vol. 13, no. 1, p. 31, Jan. 2019.
https://doi.org/10.1038/s41566-018-0309-y

[20] E. Lucas *et al.*, “Spatial multiplexing of soliton microcombs,” *Nat. Photonics*, vol. 12, no. 11, p. 699, Nov. 2018.
https://doi.org/10.1038/s41566-018-0256-7

[21] M. Karpov, M. H. P. Pfeiffer, H. Guo, W. Weng, J. Liu, and T. J. Kippenberg, “Dynamics of soliton crystals in optical microresonators,” *ArXiv190307122 Phys.*, Mar. 2019.
https://arxiv.org/abs/1903.07122

[22] J. Liu *et al.*, “Photonic microwave oscillators based on integrated soliton microcombs,” *ArXiv190110372 Phys.*, Jan. 2019.
https://arxiv.org/abs/1901.10372

[23] E. Lucas, P. Brochard, R. Bouchand, S. Schilt, T. Südmeyer, and T. J. Kippenberg, “Ultralow-Noise Photonic Microwave Synthesis using a Soliton Microcomb-based Transfer Oscillator,” *ArXiv190301213 Phys.*, Mar. 2019.
http://arxiv.org/abs/1903.01213

[24] P. J. Marchand *et al.*, “Soliton microcomb based spectral domain optical coherence tomography,” *ArXiv190206985 Phys.*, Feb. 2019.
https://arxiv.org/abs/1902.06985

[25] A. S. Raja *et al.*, "Electrically pumped photonic integrated soliton microcomb," *Nat. Commun.*, vol. 10, no. 1, p. 680, Feb. 2019.
https://doi.org/10.1038/s41467-019-08498-2

[26] J. Liu *et al.*, "Ultralow-power chip-based soliton microcombs for photonic integration," *Optica*, vol. 5, no. 10, pp. 1347–1353, Oct. 2018.
https://doi.org/10.1364/OPTICA.5.001347

[27] D. J. Wilson, K. Schneider, S. Hoenl, M. Anderson, T. J. Kippenberg, and P. Seidler, "Integrated gallium phosphide nonlinear photonics," *ArXiv180803554 Phys.*, Aug. 2018.
https://arxiv.org/abs/1808.03554

5. Conference Proceedings

[28] J. Pfeifle *et al.*, "Full C and L-Band Transmission at 20 Tbit/s Using Cavity-Soliton Kerr Frequency Combs," in *CLEO: 2015 Postdeadline Paper Digest (2015), paper JTh5C.8*, 2015, p. JTh5C.8.

[29] D. Grassani *et al.*, "Mid-infrared supercontinuum generation in a SiN waveguide pumped at 1.55 micron," in *Frontiers in Optics 2016 (2016), paper FTu5D.3*, 2016, p. FTu5D.3.

[30] P. Marin *et al.*, "34.6 Tbit/s WDM Transmission Using Soliton Kerr Frequency Combs as Optical Source and Local Oscillator," in *ECOC 2016; 42nd European Conference on Optical Communication*, 2016, pp. 1–3.

[31] P. Marin *et al.*, "50 Tbit/s Massively Parallel WDM Transmission in C and L Band Using Interleaved Cavity-Soliton Kerr Combs," in *Conference on Lasers and Electro-Optics (2016), paper STu1G.1*, 2016, p. STu1G.1.

[32] D. Ganin *et al.*, "Ultrafast Dual-Comb Distance Metrology Using Dissipative Kerr Solitons," in *Conference on Lasers and Electro-Optics (2017), paper STh4L.6*, 2017, p. STh4L.6.

[33] H. Guo *et al.*, "Soliton breathing induced by avoided mode crossing in optical microresonators," in *Conference on Lasers and Electro-Optics (2017), paper FTh4D.4*, 2017, p. FTh4D.4.

[34] C. Herkommer *et al.*, "A chip-based silicon nitride platform for mid-infrared nonlinear photonics," in *Conference on Lasers and Electro-Optics (2017), paper SM2K.6*, 2017, p. SM2K.6.

[35] M. Karpov *et al.*, "Dynamics of soliton crystals in optical microresonators," in *Conference on Lasers and Electro-Optics (2017), paper FTu1D.2*, 2017, p. FTu1D.2.

[36] M. Karpov, M. H. P. Pfeiffer, and T. J. Kippenberg, "Chip-scale dissipative Kerr soliton-based frequency combs driven with 1µm source," in *Conference on Lasers and Electro-Optics (2017), paper JTh5B.6*, 2017, p. JTh5B.6.

[37] H. Guo, J. Liu, W. Weng, and T. J. Kippenberg, "Soliton-induced mid-infrared Cherenkov radiation in nano-photonic hybrid waveguides," in *Advanced Photonics 2018 (BGPP, IPR, NP, NOMA, Sensors, Networks, SPPCom, SOF) (2018), paper JTu6B.1*, 2018, p. JTu6B.1.

[38] H. Guo, W. Weng, M. H. P. Pfeiffer, and T. J. Kippenberg, "Mid-infrared Optical Frequency Comb via Coherent Supercontinuum Processes in Nano-photonic Waveguides," in *CLEO Pacific Rim Conference 2018 (2018), paper Th2B.6*, 2018, p. Th2B.6.

[39] M. Karpov, M. H. P. Pfeiffer, J. Liu, A. Lukashchuk, and T. J. Kippenberg, “Dissipative Kerr soliton states in hybridized microresonator modes,” in *2018 Conference on Lasers and Electro-Optics (CLEO)*, 2018, pp. 1–2.

[40] E. Lucas *et al.*, “Multiplexing Soliton-Combs in Optical Microresonators,” in *Frontiers in Optics / Laser Science (2018), paper FW1C.2*, 2018, p. FW1C.2.

[41] E. Lucas, G. Lihachev, G. Lihachev, M. L. Gorodetsky, M. L. Gorodetsky, and T. J. Kippenberg, “Spatially-Multiplexed Solitons in Optical Microresonators,” in *Conference on Lasers and Electro-Optics (2018), paper SW4M.7*, 2018, p. SW4M.7.

[42] E. Lucas *et al.*, “Multiplexing soliton-combs in optical microresonators,” in *Laser Resonators, Microresonators, and Beam Control XXI*, 2019, vol. 10904, p. 109040O.