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Programme de la première réunion du GDR ELIOS

-3 décembre 2020-

10 min de présentation+2 min de questions

9:00	Arnaud Mussot	*Message de bienvenue/présentation du GDR ELIOS*
09:30	Poeydebat Etienne	All-fiber Mamyshev oscillator with high average power and harmonic-mode-locking
9:45	Marconi Mathias	Analysis of the phase-locking dynamics of a III-V-on-silicon frequency comb laser
10:00	Sylvestre Thibaut	Cascaded Fiber-Based Mid-Infrared Supercontinuum Source
10:15	Baudin Kilian	Condensation of optical waves in multimode fibers
10:30	Negrini Stefano	Effect of synchronization mismatch on modulation instability in passive fiber-ring cavity
		Pause café
11:00	Becheker Rezki	Experimental and numerical demonstration of fiber optical parametric chirped-pulse oscillator at 1220 nm
11:15	Rigneault Herve	Flexible lensless endoscope with a conformationally invariant multi-core fiber
11:30	Mas Arabi- Carlos	Formation of Localized Structures in Doubly Resonant Cavity-Enhanced Second Harmonic Generation
11:45	Valero Nicolas	High-power amplified spontaneous emission pulses with tunable temporal coherence for efficient non-linear processes
12:00	Touil Mohamed	Investigation of the spectro-temporal dynamics in a fiber optical parametric oscillator
12:15	Parriaux Alexandre	Isotopic ratio measurements with mid-infrared electro-optic dual-comb spectrometer
		Pause déjeuné
13:30	Della Torre Alberto	Mid-infrared supercontinuum generation in pure germanium waveguides
13:45	Vanderhaegen Guillaume	Loss induced multiple symmetry breaking in the Fermi Pasta Ulam recurrence process
14:00	Ceppe Jean-Baptiste	Mobius fibre cavity : early experimental works
14:15	Gajendra Kumar Naveen	Modified conformationally invariant MCFs for lensless endoscopy
14:30	Mytskaniuk Vasyl	Multimodal imaging of biological tissues with help of a miniature flexible endoscope
14:45	Finot Christophe	Nonlinear fiber propagation of partially coherent fields exhibiting temporal correlations
		Pause café
15:15	Alix Malfondet	Optimum setup of NOLM-driven mode-locked fiber lasers
15:30	Yelo-Sarrion Jesus	Self-Pulsing in mutually coupled cavities
15:45	Sheveleva Anastasiia	Temporal analogue of the Fresnel diffraction by a phase plate in linear and nonlinear optical fibers
16:00	Englebert Nicolas	Temporal Cavity Solitons in an Active Fiber Resonator
16:15		*Discussion/message de clôture*
16:30		**FIN**

All-fiber Mamyshev oscillator with high average power and harmonic-mode-locking

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Abstract: Mode-locked (ML) fiber lasers are very attractive for scientists and industrialists due to their compactness, sturdiness, superior thermo-optical properties and excellent beam quality. ML fiber lasers deliver high peak power but they can't (or with difficulty) compete with Ti:Sapphire lasers because of nonlinear parasites effects in the fiber which set a peak power limit ***[1]***. But recently, a new architecture of passive ML fiber laser called Mamyshev oscillator and based on cascaded spectral broadening and spectral filtering ***[2]***, has allowed reaching very high peak power (~MW). This technology takes advantage of the self-phase modulation and allows the oscillator working in high nonlinear regime ***[3,4]***

In the conference we will present a truly all-fiber Mamyshev oscillator entirely realized with few commercially available polarization maintaining components and standard step-index fibers able to deliver 80nm spectral width pulses ***(fig.a)*** with high average power ***[5].*** A parametric study allowed us to determine stable, metastable, unstable or impossible conditions for mode-locking in the cavity. By fine optimization of the cavity, time stable pulses train with average power reaching 1.3W has been obtained ***(fig.b)***. In fact, such high average power is achieved thanks to self-division and self-organization of high energy pulses ***(fig.c)*** which increase the repetition rate and leads to a harmonic mode locking regime ***(fig.d)***. The 14th harmonic ML regime corresponding to a 107.8MHz pulse repetition rate has been obtained but we were limited by available pump power and we think that even higher harmonic order with higher power could be easily obtained.

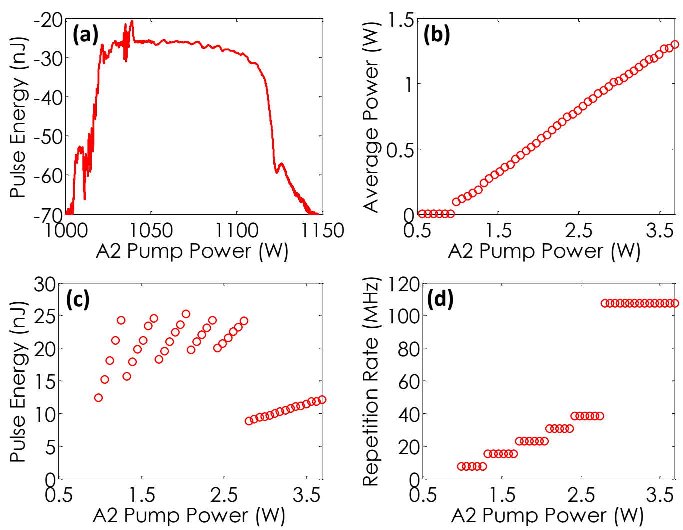

Figure 1 : Experimental oscillator output: optical spectrum for the highest pulse energy value (~25nJ) in fundamental regime **(a),** average output power **(b)**, pulse energy **(c)** and repetition rate **(d)** in function of A2 pump power.

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Analysis of the phase-locking dynamics of a III-V-on-silicon frequency comb laser

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Abstract: We present the detailed phase-locking analysis of a telecom III-V-on-silicon passively mode-locked laser with a ring cavity and quantum wells as active region. We use a stepped-heterodyne measurement to quantify the modal phase chirp and reconstruct the pulse envelop. With this technique we are able to identify the causes of pulse broadening and rippling from the spectral phase dispersion as a function of saturable absorber bias variation.

The demand for on-chip optical combs, essential building blocks for LIDAR [1] and spectroscopy systems-on-a-chip [2], have driven the development of the on-chip mode-locked laser (MLL), realized using either III-V-on-silicon [3] or InP active-passive photonic integration technology [4]. However, to design and characterize the next generation of these devices a deeper insight in the complex dynamics of semiconductor-based MLL is needed. Our work provides new insights into the phase-locking of these semiconductor MLL via a stepped-heterodyne (SH) technique [5]. SH allows for a temporally-resolved reconstruction of the envelop of picosecond and low-power (1-100 µW) pulses with precision unmatched by auto-correlation approaches. Thanks to SH, we demonstrate near transform-limited (TL) pulsed operation from the III-V-on-Si MLL (Fig. 1a). On the right panel, the reconstructed pulse envelop (red) is compared to a simulated perfect TL pulse (dotted blue line) having no modal phase dispersion. Furthermore, this work sheds light on the fundamental role played by the saturable absorber (SA) in the pulse formation. In Fig. 1b we show how the pulse envelop degrades when V_{SA} is slightly modified with respect to Fig. 1a. Thus, SH measurement allows for investigating in detail the evolution of the dispersion when the SA bias voltage is changed and its impact on the output pulse shape. Lastly, we provide to our knowledge the first experimental assessment of the spectral phase during hybrid mode-locking operation in III-V-on-Si lasers. We reveal that the electrical modulation of the SA bias voltage resonant with the laser FSR allows to shape perfect TL pulses [6]. Our analysis paves the way for further exploration, modeling and potential manipulation of the phase dynamics in semiconductor mode-locked lasers, with particular focus on the hybrid III-V-on-Si technologies where very long cavities can be fabricated [3].

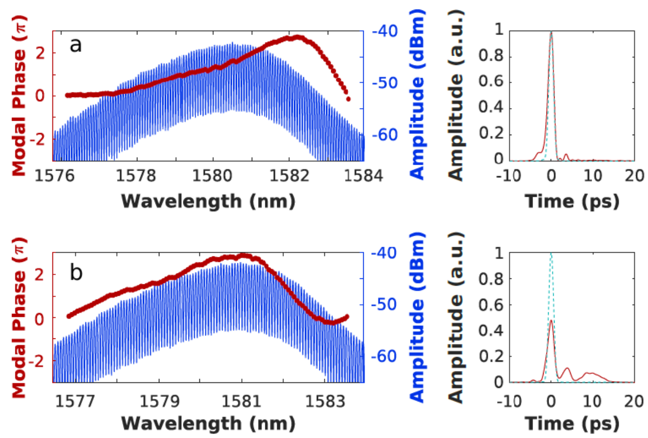

Figure 1: Reconstructed pulse envelops (right, red) from modal phase measurement with SH (left, red) for two V_{SA} values and I = 170 mA. a) V_{SA} = -1V. b) V_{SA} = -1.1 V. Blue , left: optical spectra.

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Cascaded Fiber-Based Mid-Infrared Supercontinuum Source

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Abstract: Mid-infrared supercontinuum (SC) sources in the 2–20 µm molecular fingerprint region are in high demand for a wide range of applications including optical coherence tomography, remote sensing, molecular spectroscopy, and hyperspectral imaging [1]. Here, we review all our collaborative works on mid-IR SC generation using different soft-glass photonic crystal fibers [1-3]. We describe in particular a broadband fiber-based SC source spanning from 2 to 10 µm. This was achieved using a cascaded silica-ZBLAN-chalcogenide optical fiber system directly pumped by a compact 1550-nm pulsed fiber laser without using thulium-doped fiber amplifiers, as shown in Fig. 1. This technique paves the way for low cost, practical, and robust broadband SC sources in the mid-IR without the requirement of mid-infrared pump sources or Thulium-doped fiber amplifiers. A fully realistic numerical model used to simulate the nonlinear pulse propagation through the cascaded fiber system is also described and the numerical results are used to discuss the physical processes underlying the spectral broadening in the cascaded system. We conclude with recommendations to optimize the current cascaded SC systems based on the simulation results.

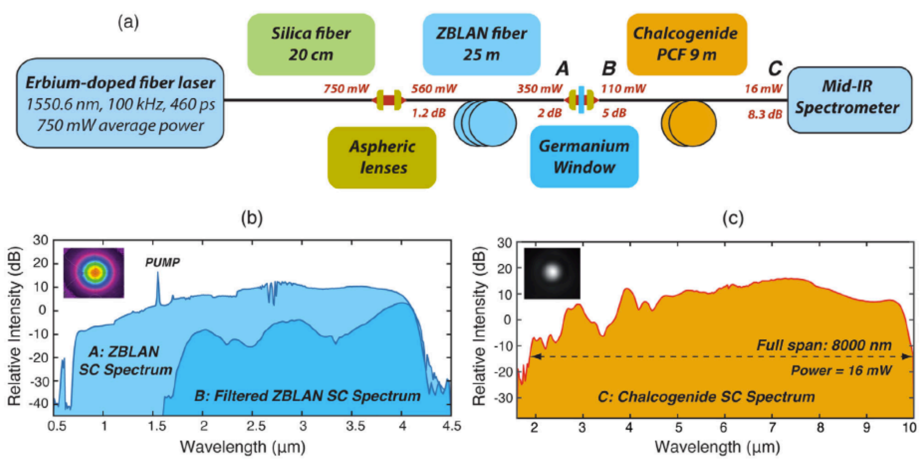

Figure 1 : (a) Experimental setup for mid-infrared SC generation in a cascaded silica-ZBLAN-chalcogenide optical fiber system. (b) Experimental SC spectra at the ZBLAN fiber output (light blue) and after the long-pass filter (dark blue). (c) Experimental SC spectrum at the chalcogenide fiber output (yellow). The insets show the optical mode profiles out of both the ZBLAN (b) and chalcogenide (c) optical fibers.

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Condensation of optical waves in multimode fibers

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Abstract: We report the observation of the transition to condensation of optical waves propagating in multimode fibers: below a critical value of the energy, the fundamental mode gets macroscopic populated, in agreement with the equilibrium theory.

Recent studies in wave turbulence have shown that a classical random wave system can exhibit a condensation process resulting from the divergence of the Rayleigh-Jeans (RJ) equilibrium distribution, in analogy with the Bose-Einstein condensation (refs. in [1]). However, the observation of condensation of freely propagating optical waves is hampered by the long propagation lengths required by the process of thermalization to reach the RJ equilibrium distribution.

A remarkable effect of spatial beam cleaning has been recently discovered in multimode optical fibers (FMM) whose underlying mechanism remains poorly understood [2,3]. We have developed a theory of wave turbulence taking into account for the structural disorder inherent to light propagation in MMF [1,4]. The theory reveals a dramatic acceleration of condensation induced by the disorder, which can help to explain the beam cleaning effect as a macroscopic population of the fundamental mode of MMFs [1,4].

We report in this work experimental evidence of the phase transition to condensation driven by optical wave thermalization towards the RJ thermal equilibrium [5]. The experiments are performed in a graded-index MMF (fiber radius R = 26μm). Sub-nanosecond pulses delivered by a Nd:YAG laser (1.06 μm) are passed through a diffuser before injection of the speckle beam into the MMF. After propagation through a fiber length L = 12 m, the near-field (NF) and the far-field (FF) intensity patterns are recorded on a camera. This allowed us to retrieve a measurement of the two conserved quantities during the propagation through the MMF: the power $N = \Sigma_p n_p$, and the energy $E = \Sigma_p \beta_p n_p$, where n_p denotes the power in the mode $\{p\}$ and $\beta_p=\beta_0(p_x+p_y+1)$ the corresponding eigenvalue of the parabolic potential [1]. During the propagation of the speckle beam through the fiber the nonlinearity is responsible for an irreversible process of thermalization towards the RJ spectrum $n_p^{eq} = T/(\beta_p - \mu)$ [1,4,5], where T and μ are the temperature and the chemical potential. By decreasing the energy below the critical value E_{crit}, the system exhibits a phase transition to condensation when $\mu \to \beta_0$: The divergence (vanishing denominator) of the RJ distribution leads to a macroscopic population of the fundamental mode of the MMF. Fig. 1 reports the measurements of μ vs E, and the corresponding fraction of condensed power into the fundamental mode n_0^{eq}/N vs E.

The thermodynamics of classical condensation has been studied through the analysis of the heat capacity, revealing noteworthy distinguished features with respect to the quantum Bose-Einstein condensation [5].

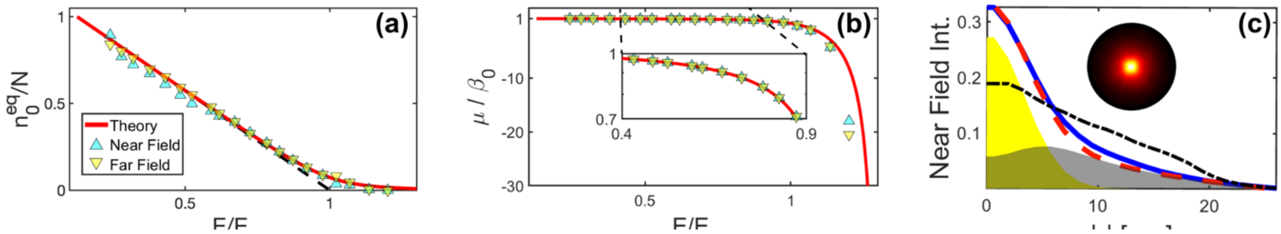

Figure 1: Experimental measurements of the condensate fraction n_0/N vs energy E/E_{crit} (a), and chemical potential μ vs energy E/E_{crit} (b), retrieved from the near-field (blue triangle), and far-field (yellow triangle) intensity distributions. The dashed black line in (a) denotes the condensation phase transition in the thermodynamic limit. (c) Experimental profiles from the near-field intensity distributions recorded at the output of the MMF for the same energy E/E_{crit} = 0.78 (i.e. n_0^{eq}/N = 0.27) with an average over the realizations (blue lines). Corresponding RJ theory showing the condensate contribution from the fundamental mode p = 0 (yellow region), the incoherent contribution from $p \neq 0$ (grey region), and their sums (dashed red). The dashed black line shows the injected beam ('initial condition').

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Effect of synchronization mismatch on modulation instability in passive fiber-ring cavity

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Abstract: we experimentally investigate the impact of the synchronization mismatch on modulation instability spectrum in coherently pumped passive fiber-ring cavities. We show that the position and the shape of the sidebands are surprisingly affected by the synchronization mismatch while related to even order terms.

In its simplest form, through continuous wave pumping conditions and in large dispersion regime, modulation instability in passive cavities is even order dispersion terms dependent only [1]. By coherently pumping cavities with optical pulses, the model has to be refined to accurately describe the dynamics of the process. It has been demonstrated that slight temporal drifts of pump pulses from round trip to round trip leads to a symmetry breaking of the MI spectrum [2] due to the contribution of the third order dispersion term in the low dispersion regime. In this work, we show that the contribution of odd dispersion terms is not limited to a second-order effect, may arise whatever the dispersion regime.

(a) (b)

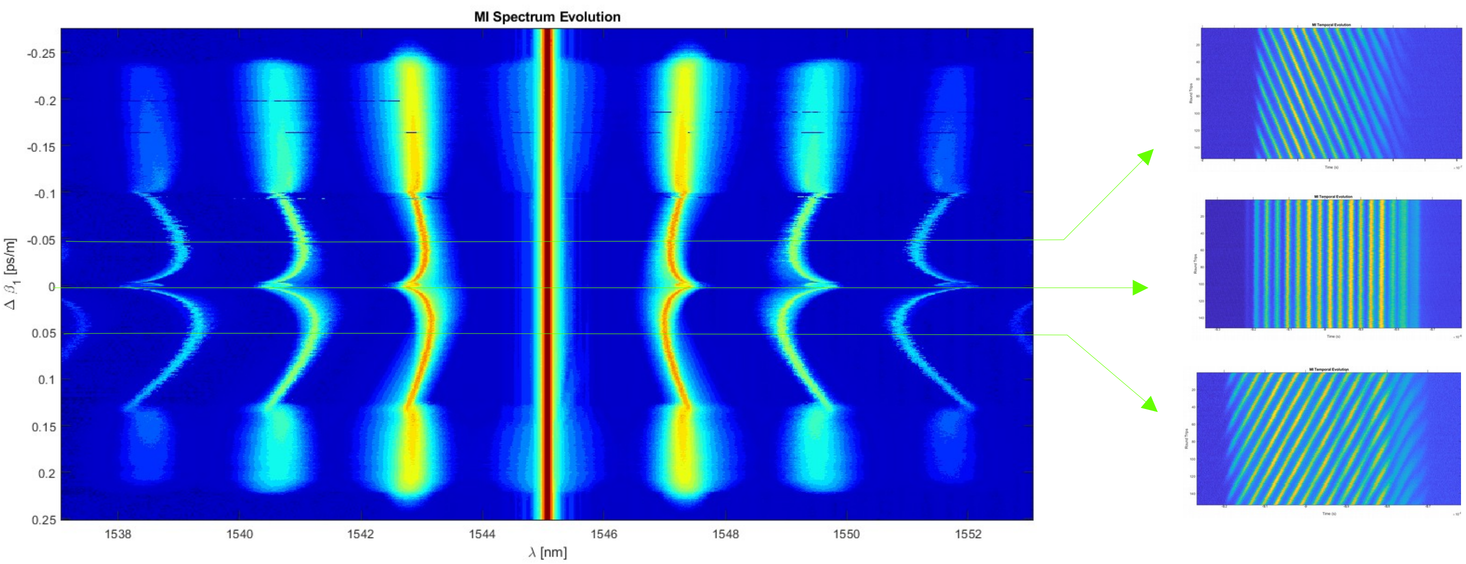

Figure 1 : (a) 2D plot of the output MI spectra as a function of the synchronization mismatch. Parameters : Pulse width = 5.6 ps, L=27.44 m, $\gamma \approx 2.5$ /W/Km, β_2 = -3.8ps^2/km. (b) Three typical temporal traces recorded with a time lens system.

More precisely, the synchronization mismatch is considered by accounting for the group velocity mismatch term β_1 and leads to a modification of the perfect phase matching relation. Consequently, the position of MI side bands is affected by this even order dispersion term. Figure 1(a) illustrates the evolution of the MI spectrum as a function of the synchronization mismatch. It is possible to observe two different behavior depending on the region of the mismatch: a sideband broadening and sideband shifting. Sideband broadening is characteristic in the extremes of the frequency interval, once the spectral components have emerged from the background noise. Closer to the perfect synchronization the sidebands become thinner and start to shift toward the pump, just to invert the motion before the perfect synchronization. At the central frequency, a sudden shift toward the pump is recorded and, once the perfect synchronization point is reached, the spectrum inverts its motion in a symmetric fashion. The correlation with the MI temporal pattern drift is illustrated in Fig. 1(b) for three typical mismatches to highlight the role of convection on the process.

To conclude we show that MI spectra, position of the sidebands and shapes, depends on the cavity synchronization mismatch under pulsed pumping configurations. Comparisons with theoretical investigation based on convective instability theory are ongoing to formally prove the contribution of even-order terms.

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Experimental and numerical demonstration of fiber optical parametric chirped-pulse oscillator at 1220 nm

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Wavelength-flexible fiber sources based on nonlinear frequency conversion are attractive for many applications such as nonlinear imaging, spectroscopy or microscopy. Several nonlinear processes can be used to efficiently perform the necessary wavelength shift (e.g. soliton self-frequency shift) but they are however limited in peak-power scalability due to intensity-related damages. Another solution then consists in exploiting the broad tunability offered by degenerate four-wave mixing in optical fibers. The implementation of this concept in chirped-pulse amplification (CPA) scheme has allowed to reach high-energy levels with fs dechirped pulses in different wavelength windows [1-4]. Moreover, its exploitation in fiber parametric oscillators with normal dispersion has allowed for record performances in terms of pulse energy [5]. The combination of both concepts to build a fiber optical parametric chirped-pulse oscillator (FOPCPO) could then be attractive to enable a full control of the output wavelength and bandwidth [6]. We here demonstrate for the first time a high-energy FOPCPO, allowing to reach hundreds of nJ over broad tuning ranges and our numerical simulations highlight the strong potential of such sources for further energy scaling.

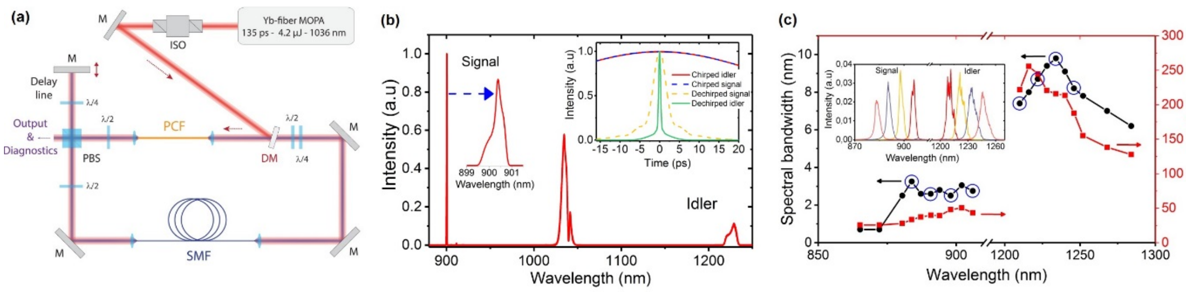

Fig. 1. (a) Experimental setup. (b) Numerical simulated full-field spectrum of the FOPCPO (*inset: chirped and dechirped signal and idler autocorrelation traces*). (c) Experimental tunability of the FOPCPO (*inset: selected idler and signal spectra*).

Highly-chirped pulses with 135 ps duration and up to 4.2 µJ energy, delivered by an ytterbium-doped fiber-based CPA system operating near 1036 nm at 1 MHz repetition rate are used to pump a photonic crystal fiber (PCF), Fig. 1(a). The PCF is inserted inside a singly-resonant cavity and is pumped in its normal dispersion regime. Numerical simulations show that our FOPCPO can generate idler and signal waves with energies as high as 250 nJ as shown in Fig.1(b). The linearly-chirped idler and signal pulses could be dechirped to their Fourier limit of 300 fs and 2.8 ps, respectively (inset in Fig. 1(b)). Moreover, the µJ energy level can be reached by increasing the pump pulse chirp along with increasing its energy. Using the system shown in Fig.1 (a) and guided by numerical results, we then obtained experimentally chirped output idler and signal pulses with energies higher than 250 nJ along with featuring a broad tunability of 75 nm and 45 nm, respectively (Fig.1(c)). These results then pave the way for the use of FOPCPOs as efficient high-energy tunable fiber sources.

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Acknowledgement

The authors acknowledge financial support from the Agence Nationale de la Recherche (LABEX-EMC3), Carnot ESP, the European Union with the European Regional Development Fund (ERDF) and the Regional Council of Normandie (SPIDER, IFROST, and TOFU projects).

Flexible lensless endoscope with a conformationally invariant multi-core fiber

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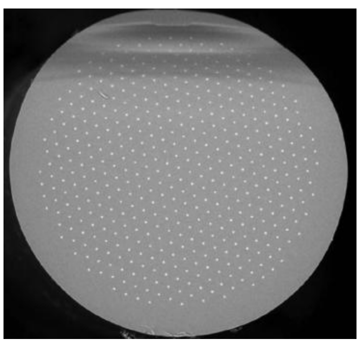
Abstract:

The lensless endoscope represents the ultimate limit in miniaturization of imaging tools: an image can be transmitted through a (multi-mode or multi-core) fiber by numerical or physical inversion of the fiber's pre-measured transmission matrix [1]. We have been developing the lensless endoscope technology using a multi-core fiber (MCF) to perform 2photon imaging [2] using aperiodic fiber core arrangement [3]. However, the transmission matrix changes completely with only minute conformational changes of the fiber, which has so far limited lensless endoscopes to fibers that must be kept static. We report in this presentation a lensless endoscope which is exempt from the requirement of static fiber by designing and employing a custom-designed conformationally invariant fiber. We give experimental and theoretical validations and determine the parameter space over which the invariance is maintained [4].



(A)

(B)

Figure 1 : (A) multicore fiber designed with a twist (B) during it fabrication process to enable conformationally invariant imaging

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Formation of Localized Structures in Doubly Resonant Cavity-Enhanced Second Harmonic Generation

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Abstract: We analyze the formation of localized structures in phase-matched cavity-enhanced second harmonic generation. We focus on the limit where the fundamental and generated waves are close to group velocity matching. The impact of a walk-off between waves is studied.

The formation of Localized Structures (LSs) in optical cavities with a quadratic nonlinearity is attracting a lot of attention. In the frequency domain, LSs correspond to a sequence of equally-spaced frequencies known as frequency combs. The formation of frequency combs in quadratic media has been lately studied because of its potential to reach new spectral bands and reduce the necessary pump power as compared to Kerr frequency combs[1].

We consider a resonator pumped in the anomalous dispersion regime, and the second harmonic to propagate in normal dispersion regime [2]. We impose that the temporal walk-off is small compared to the round-trip time. Fig. (a) shows the intensity of the continuous wave (cw) as a function of the cavity detuning (Δ) with a constant value of external forcing. Solid (dashed) lines show stable (unstable) solutions. The cw exhibits a region with bistability. Within this region, LSs can form due to the locking of the two different cw states, forming dark or bright states [see Fig. (i) and (ii)]. The bifurcation diagram associated with these solutions is shown in Fig. (a). This structure is known as *collapsed snaking* [3] and forms both in the upper and lower part of the diagram, and corresponds to dark and bright LSs respectively.

The effect of a small walk-off is twofold: on the one hand, due to the broken symmetry x → -x, LSs are not symmetric [see Fig. (c)]. On the other hand, the walk-off produces a drift of the LS [see Fig. (b)].

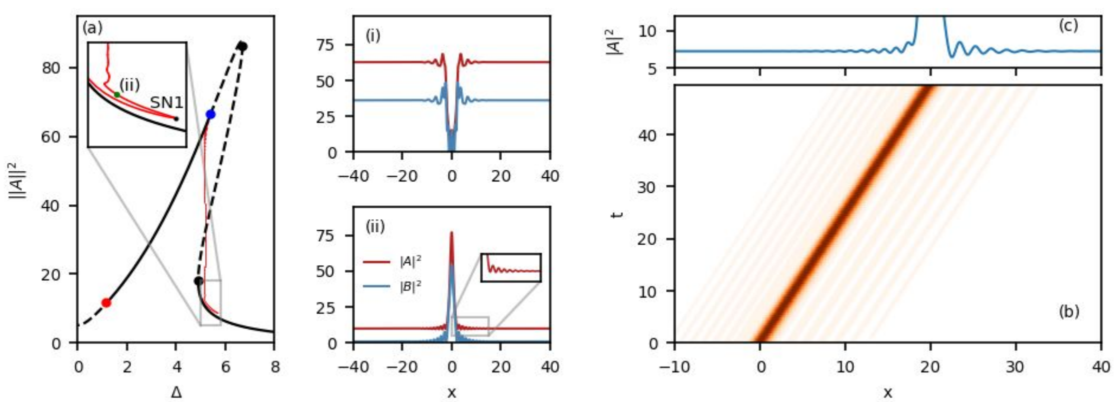

Figure : (a) Stationary solutions as a function of the cavity detuning. Black (red) lines stand for cw (localized) solutions. (i) Dark localized state. (ii) Bright localized state. (b) Evolution of a bright LS in presence of walk-off. (c) Fundamental wave intensity profile.

These results provide a better understanding of the bifurcation structure of the LSs in cavity-enhanced second harmonic generation. We prove that these LSs persist under small values of walk-off[4].

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High-power amplified spontaneous emission pulses with tunable temporal coherence for efficient non-linear processes

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Extreme wave phenomena in optics, often qualified as extreme amplitude rare events, have been particularly studied for many years for understanding hydrodynamic *rogue waves* observed on the surface of the ocean [1]. Starting from quantum noise, experiments based on the nonlinear propagation of short pulses using modulation instability in optical fibers [2] allowed to generate extreme events associated with the complex statistical behavior of *rogue waves* dynamics [3]. In this work, with the same concept we studied the statistical behavior of high-intensity chaotic temporal events occurring in amplified spontaneous emission (ASE) in the linear propagation regime. According to Einstein's theory [4], the physical properties of light sources based on ASE are characterized by electric field (or intensity) temporal fluctuations around a mean value. Indeed, a typical characteristic of these stochastic sources is the low temporal coherence with a photon distribution following the Bose-Einstein statistics **(Figure 1, left)**.

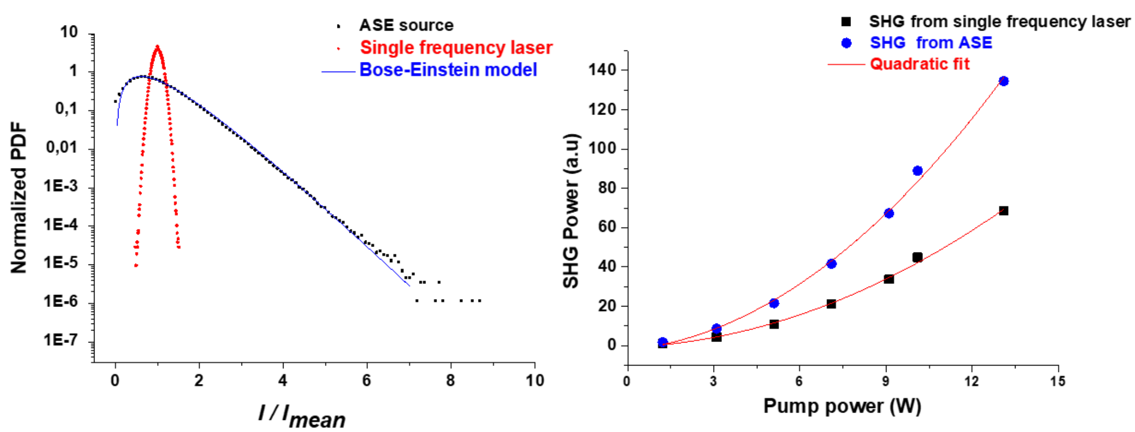

Figure 1: Statically behavior of light sources represented by normalized probability density function (PDF) with the Bose-Einstein distribution model *(left side).* SHG of the pulsed partially coherent sour *(right side)***.**

In this contribution, for the first time to the best of our knowledge, we report on a study of an ASE source operated in a picosecond pulsed regime and focusing on the influence of high intensity random events on the generation of nonlinear processes. To this aim, we have developed a monolithic high-power fiber system delivering partially coherent pulses of ASE. The system includes a Continuous Wave (CW) ASE seeder, spectral filtering stages, amplifiers and an electro-optical pulse shaper module. This approach provides a versatile tool where many parameters can be adjusted by the user: central frequency, pulse repetition rate, pulse energy, pulse duration and most importantly the coherence time. We have also developed a non-linear method to characterize the stochastic properties of the source. The source is then fully characterized for various configurations. An enhanced classical model has been established to reproduce the statistical properties of the source and predict the behavior when exciting non-linear processes. Finally, a non-linear process of second harmonic generation (SHG) is investigated comparing the efficiency when pumped by a pulsed beam with a maximal and a low coherence **(Figure 1, right)**.

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Investigation of the spectro-temporal dynamics in a fiber optical parametric oscillator

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In recent years, the characterization of ultrafast and non-repetitive events became possible with the rise of real time temporal and spectral measurement techniques, such as time lenses [1] and dispersive Fourier transform (DFT) [2]. For instance, the ability of DFT to record large numbers of consecutive optical spectra allows for the use of statistical matrices to unveil complex dynamical behaviors in various optical systems. Spectral correlations have proven effective in the study of complex processes involved in four-wave mixing, modulation instability, supercontinuum generation or random lasing. Also, it has been recently demonstrated that various shaping of these spectral correlations can be achieved in fibered systems [3,4]. Such a tailoring could be useful in the building of specific sources for quantum optics applications. In this frame, the spectral correlations within fiber optical parametric oscillators (FOPO) have never been studied experimentally and only the spectro-temporal properties of bulk OPOs have been recently investigated [5,6].

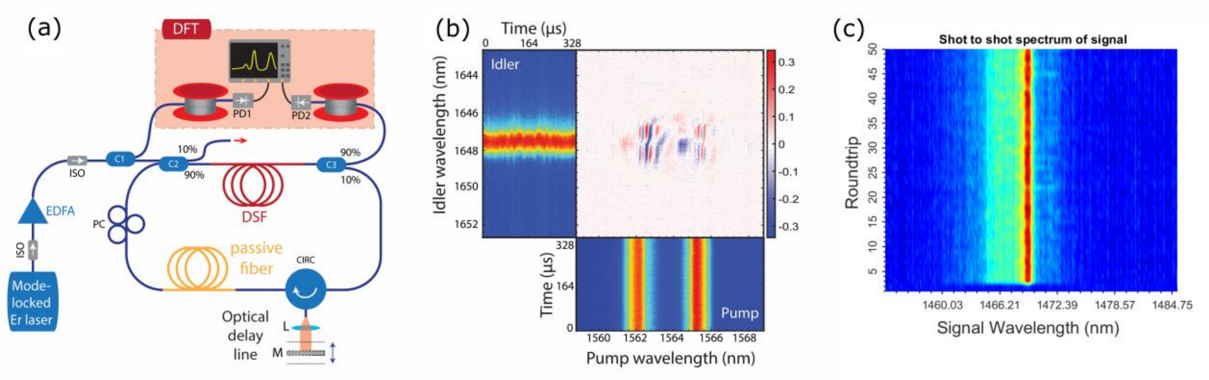

Fig. 1 (a) Experimental setup for recording the dynamics of the FOPO. (b) Typical correlation map built using mutual information analysis and least square fitting, along with the shot-to-shot spectral dynamics of idler and pump waves. (c) Signal wave build-up showing a direct generation of the parametric waves.

Here, we therefore experimentally investigate the dynamics of a synchronously-pumped picosecond fiber optical parametric oscillator (FOPO), shown in Fig. 1(a). We used DFT for recording its real time spectral evolution. Then, particular spectro-temporal dynamics both in the steady state and build-up regimes of the oscillator were revealed using a combination of statistical tools including mutual information analysis, which has proved relevant for investigating the dynamics of laser sources [7]. We show that the FOPO build-up (first few roundtrips) exhibits particular dynamics with the direct generation of parametric waves. In the steady state, we then show that spectral correlations – of which a typical example is shown in Fig. 1(b) - could be shaped to a certain extent. This study then demonstrates the potential of FOPOs for on-demand spectral correlation shaping but also that the use of simple statistical tools can prove insightful in comprehending their intrinsic dynamics.

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Acknowledgement

The authors acknowledge financial support from the Agence Nationale de la Recherche (LABEX-EMC3), Carnot ESP, the European Union with the European Regional Development Fund (ERDF) and the Regional Council of Normandie (SPIDER, IFROST, and TOFU projects).

Isotopic ratio measurements with mid-infrared electro-optic dual-comb spectrometer

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Abstract: We present an electro-optic dual-comb spectrometer operating in the mid-infrared designed for carbon dioxide analyses and especially isotopic ratio measurements.

Spectroscopic measurements based on mutually coherent frequency combs is a powerful technique for gas sensing [1]. Moreover, dual-comb spectroscopy can be really straightforward when the combs are generated by the electro-optic modulation of a continuous wave laser, which drastically simplifies the experimental setup [2]. Here, we present a dual-comb spectrometer operating in the mid-infrared based on intensity modulators and frequency conversion in a PPLN crystal [3,4]. The setup, designed for gas sensing between 4.2µm and 4.85µm, is able to monitor the ν_3 rotational-vibrational band of carbon dioxide. Around 4,36µm, absorption lines of $^{13}CO_2$ are as intense as lines of $^{12}CO_2$, enabling isotopic ratio measurements which show potential applications towards medical diagnoses [5]. Figure 1 shows an example of carbon dioxide absorption spectrum in the exhaled air of the experimentalist over an absorption length of 2.5cm. The associated fitted ratio, in a confidence interval of 95%, is r = (0.0103 ± 0.0001), which has to be compared to the expected natural ratio of r = 0.0112. Further studies have to be performed to investigate the impact of systematic deviations on the results.

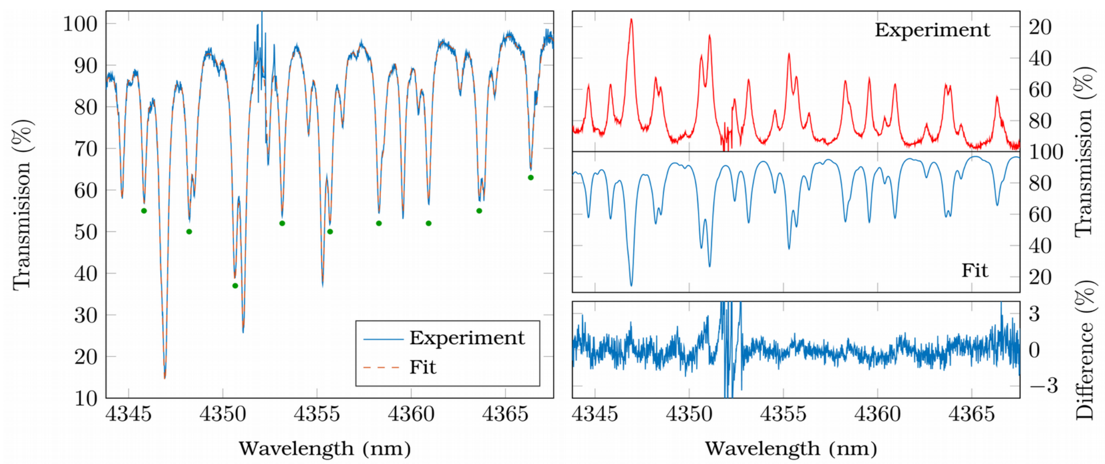

Figure 1 : Example of carbon dioxide absorption spectrum obtained in the exhaled air of the experimentalist and compared with a fitted spectrum based on the HITRAN database. The green dots point $^{13}CO_2$ absorption lines.

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Loss induced multiple symmetry breaking in the Fermi Pasta Ulam recurrence process

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Abstract: We report a complete experimental description of the optical fiber losses effect in the nonlinear stage of MI and FPU process. The tuning of those losses highlights multiple critical values for which symmetry breakings occur.

Fermi Pasta Ulam (FPU) recurrence process describes the ability of a nonlinear system to excite multiple modes and then to return to its initial state. In fiber optics, such process has been investigated within the framework of modulation instability (MI), corresponding to growth of weak perturbations at the expense of a strong pump. Nonlinear stage of MI and FPU recurrences in optical fibers have been widely investigated and many results have been obtained with an efficient compensation of the losses [1]. Some investigations in optics [2] and water waves [3] showed, for their part, the influence of dissipation on MI and on breathers respectively. However, to the best of our knowledge, dissipation and the understanding of its impact on FPU remains an unaddressed problem. Using a setup similar to the one in [1]and based on a multiple HOTDR system, we managed to record FPU recurrences in power and phase along the fiber length as a function of the loss, Fig. 1. The dissipation is controlled thanks to a counter-propagating Raman pump whose power is tuned to get an effective loss coefficient. A direct relation between the Raman pump power and effective loss coefficient is obtained, allowing a direct comparison between experiments (left panel) and simulations (right panel).

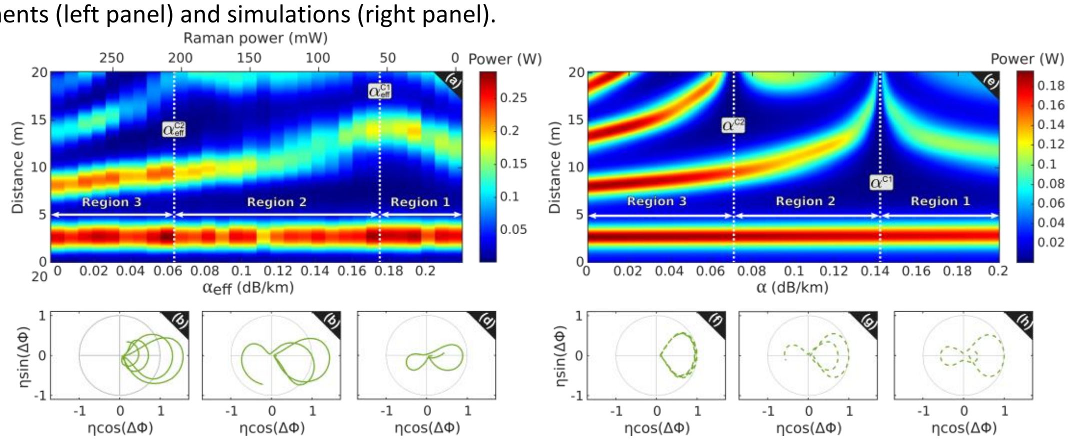

FIG. 1. 2D-plot of the signal power evolution along the fiber length as a function of loss (a) in experiments and (e) in numerics. An example of phase-plane evolution is plotted for each region; (b), (c) and (d) for experiments, and (f), (g) and (h) for numerics.

Three different regions are discernible. In the 3rd one (quasi-compensation of the losses), the recurrences are in phase according to the phase-plane (high power compression points, appearing due to the growth of the perturbation, remain at the same temporal location at each recurrence) [1]. In the 2nd region (partial compensation), the first two recurrences are in phase and the 3rd one is shifted. In the first region (the loss is close to the fiber intrinsic value), all consecutive recurrences are phase-shifted. Each region is separated by a critical value α^{CN} for which signal maxima with an order k>N are located beyond the fiber length limit. Experiments are in good agreement with numerics. To conclude, we present a detailed study on dissipation impact on FPU dynamics in optical fibers thanks to a controlled compensation of loss and non destructive distributed measurement setup [1].

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Möbius fibre cavity: early experimental works

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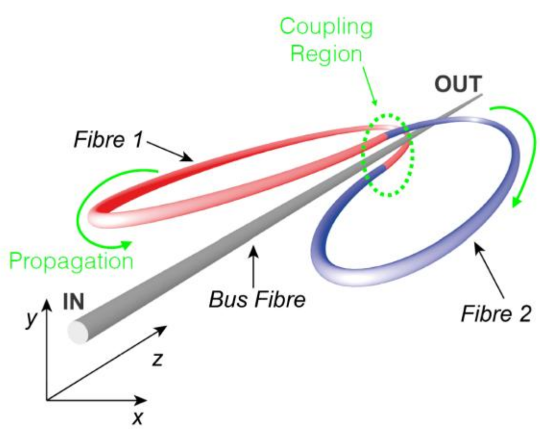
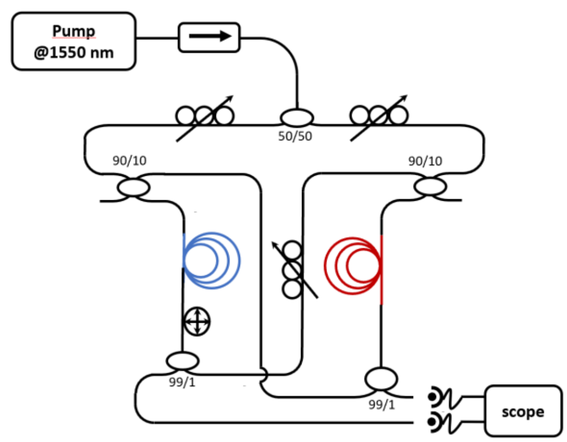
Abstract: We investigate theoretically and experimentally a novel optical resonator architecture based on two interlinked passive cavities in the form of a Möbius strip. We present early experimental investigations of this resonator.

Optical resonators play a ubiquitous role in modern optics. They are suitable devices for laser studies, optical filtering and nonlinear optics experiments [1]. A Möbius resonator is a double fibre resonator in which the output of each loop is fed into the other one, as depicted on Fig. 1(a). The length of each loop and its relative dispersion are the main physical parameters that can lead to non-linear regime such as modulation instabilities [2]. The presence of two fibers with different dispersion properties add one degree of freedom in contrast with a single loop resonator, leading to a richer variety of phenomenon such exotic cavity solitons and extended modulation instability, as we recently predicted theoretically [3]. We present here the preliminary work of such a resonator in linear regime. The experimental setup is depicted on Fig. 1 (b).



a)



b)

Figure 1 : (a) Schematic of the Möbius fibre loop cavity, (b) experimental setup.

We used two optical fibers owing normal dispersion values ($\beta_2^{(1)} = \beta_2^{(2)} = 6.21$ ps^2/km) pumped by a common laser source. Linear cavity resonances are shown on Fig. 2 (a,d) from the linear stability analysis [3] as a function of the cavity detuning of each loop (ϕ_1 and ϕ_2). The specific feature of Möbius resonators is that loop detuning are inter-linked and linear resonances characterizing the cavity has two dimensions. Early experimental recordings of the linear behavior are shown on Fig. 2 (c) and (f) by tuning either both cavity detuning of loop 1 and loop 2 simultaneously with the laser frequency (diagonal shift on Fig. 2(a)) or only the cavity detuning of loop 1 with a piezo actuator (horizontal shift on Fig. 2(d)). These are in pretty good agreement with theoretical predictions, as shown on Fig. 2 (b) and (e).

To conclude, experimental investigations are under progress and we do hope getting additional experimental results to show during the conference that highlight specific features of Möbius resonators in the context of modulation instability or frequency comb generation.

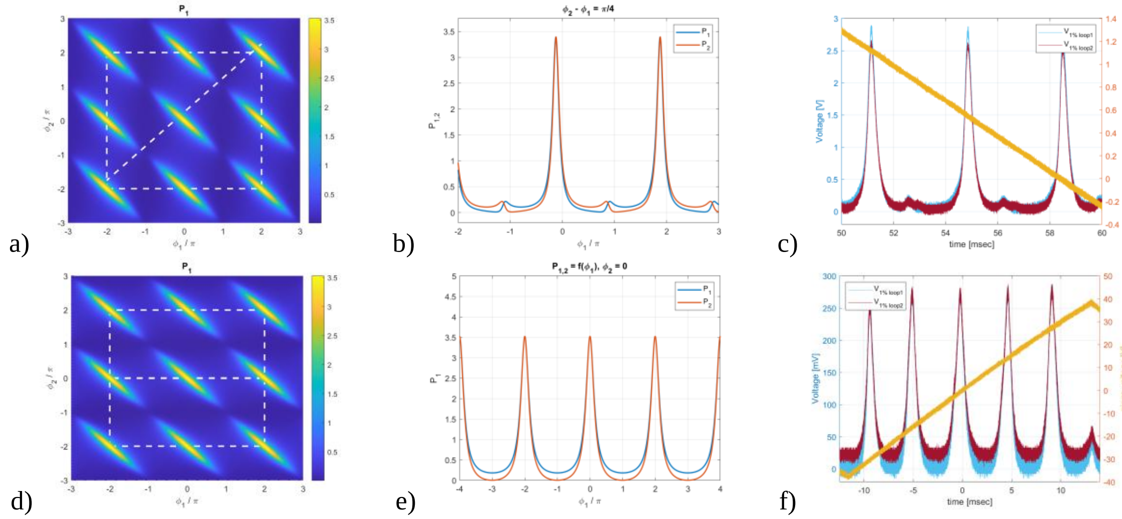


Figure 2 : (a, d) 2D-plot of the cavity resonances in the (ϕ_1, ϕ_2) plane in the case of linear sweep of ϕ_1 and ϕ_2 simultaneously (a) and ϕ_1 only (d), (b, c, e, f) theoretical and experimental cavity transfer functions sweeping ϕ_1 and ϕ_2 with the laser frequency (b, c) and ϕ_1 only with a piezo actuator (e, f). Parameters: $L_1 = L_2 = 30$ m, $P_L = 800$ uW

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Modified conformationally invariant MCFs for lensless endoscopy

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Abstract:

For deep tissue imaging, multi-photon imaging techniques benefits from intrinsic optical sectioning, cellular resolution, high sensitivity, and high imaging rate compared to linear contrast imaging techniques. However, the imaging depth is in practice limited to 1 mm (for 2 photon fluorescence imaging) due to the exponential depletion of ballistic photons. One way of improving the imaging depth is by miniaturization of the imaging system to an extent that it can be inserted deep into the tissue without causing damage. In lensless endoscopy, a long flexible optical fiber is used for delivery of the excitation light and collection of the fluorescence signal. In such an approach the light source and detectors can be remote and the device inserted into the tissue can be as thin as the optical fiber (few 100µm) [1]. Any waveguide with spatial degrees of freedom can be used for lensless endoscopy, but for the scope of this study we deal with multi-core (single mode) fibers (MCFs). However, fields propagating in MCFs are subject to phase distortions due to bending of the fiber during its use [2]. A solution to this problem is to modify the geometry of the MCF in such a way that there is intrinsic compensation for bending distortions [3]. MCFs where the cores are twisted along the length of the fiber with a twist period P which is much smaller that the radius of curvature of the MCF bend has been shown to be independent of conformational changes to the MCF. However optimal coupling into such fibers requires calibration of individual cores of the MCF. In this work we report a modified twisted fiber where calibration of individual cores is not needed.

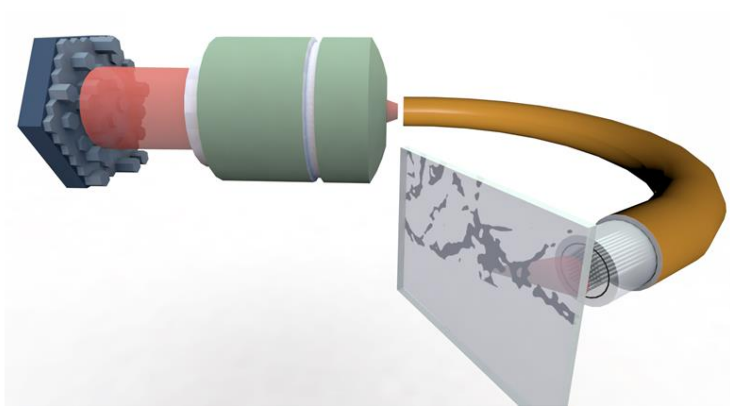

Figure 1 : Lensless Endoscopy Concept

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Multimodal imaging of biological tissues with help of a miniature flexible endoscope

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Abstract: Nonlinear microscopy has become one of the major optical instruments providing valuable information about the dynamic processes occurring in biological tissues on the cellular level. Providing the microscopist with such nonlinear contrasts as 2-photon excitation fluorescence (TPEF), second and third harmonic generation (SHG and THG) allows him to probe the sample tissue only in the focal volume due to the nature of these nonlinear processes. Moreover, the use of longer excitation wavelengths permits higher penetration depths due to reduced scattering. The emission light has a different wavelength - thus easily separated from the excitation - can be obtained in a purely non-labelled way thanks to endogenous NADH and NADPH (visualized in TPEF) or non-centrosymmetric structures like Collagen I (SHG). Furthermore, via nonlinear imaging, it is possible to probe the molecular vibrations using stimulated Raman and coherent anti-Stokes Raman scattering (SRS and CARS correspondingly). Hence, the whole Raman vibration spectrum can be targeted sequentially with high spectral resolution (<10 cm-1). Recently all these approaches have been actively applied for tissue imaging and diagnostics.

However, nonlinear microscopy has been restricted only to biopsy due to its bulkiness of the distal part used for imaging (microscope objective). To study the real dynamics of biological processes in a whole living organism, either human or animal model, a miniaturized version of the nonlinear microscope is very much needed. Many efforts have been made in this domain, however, up to now no miniature microscope or endoscope was able to combine in a simple way TPEF, SHG and CARS imaging modalities with high resolution, large FoV and high-speed image acquisition.

In this work, we will present our original miniature endoscope probe for nonlinear imaging together with a dedicated optoelectronics all in-house packed in a wheeled cart [1]. With only 2 mm outer diameter probe and a custom-made miniature objective, the endoscope can provide multimodal nonlinear imaging with sub-micron resolution across 350 um field-of-view (FoV) and at 10 frames/sec acquisition speed.

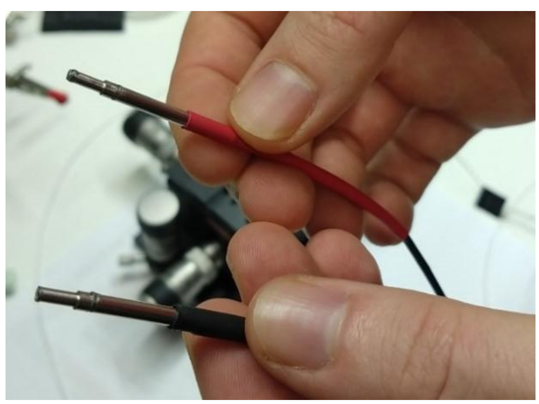

Figure 1 : A photograph of the miniaturized fibered probes

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Nonlinear fiber propagation of partially coherent fields exhibiting temporal correlations

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Abstract: Using photonic first-order differentiator applied on a partially coherent field, we generate two correlated temporal waveforms and experimentally study their correlation properties upon nonlinear propagation along the two orthogonal polarization axis of an optical fiber.

The powerful analogy between the spatial and temporal evolutions of optical waves has stimulated a large number of recent researches [1, 2]. Indeed, the temporal consequences of dispersion are formally identical to the spatial evolution of a 1D beam affected by diffraction. Given this powerful duality, numerous papers have reported the temporal analogs of well-known optical systems processing coherent signals such as lenses, dispersion grating, interference devices and recently the famous Arago spot formation.

Processing of partially coherent signals has also been explored [1]. However, at this stage, the number of studies remains rather limited with examples of temporal imaging or ghost imaging. On the contrary, the spatial domain has attracted much more interest regarding the diffraction of partially coherent fields, especially with the studies dealing with speckle and scattering in random media [3]. As a recent example, it has been shown that the statistical properties of the speckle could be easily manipulated taking advantage of singularities found in speckle fields [4]. This was done using spiral phase patterns imprinted on a wavefront prior to its propagation in a random medium. It was shown that spiral phases (� phase shifts between two opposite points in the pupil plane) of different handiness resulted in complementary speckle intensity patterns (where maxima and minima are exchanged).

In the present contribution, we propose to study a similar situation in the time domain by means of a Fourier processing that can generate two stochastics fields with complementary temporal properties (where maxima and minima are exchanged). We experimentally demonstrate that performing a temporal differentiation (through an all optical first-order differentiator) can efficiently transform a partially coherent field to generate complementary patterns in the time domain. Using a polarization multiplexing scheme, we experimentally confirm that such complementary features can be maintained over dispersive propagation in fiber. We also discuss experimentally and numerically the impact of Kerr non-linearity on the temporal complementary of partially coherent and incoherent fields and find that self- and cross-phase modulation may deeply affect the temporal field correlations [5].

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Mid-infrared supercontinuum generation in pure germanium waveguides

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Abstract: We report the experimental demonstration of mid-infrared supercontinuum generation (from 3.53 to 5.83 µm) in a pure germanium on silicon waveguide. With the aid of numerical simulations, we attribute the long wavelength extension limit mainly to free-carrier absorption.

In the last two decades, germanium has played a key role in group-IV photonics. In particular, germanium based platforms are ideal candidates for group IV mid-infrared photonics, owing to the transparency of germanium up to 14 µm [1]. Several germanium-based active and passive mid-infrared devices have been realized [2], but the demonstration of a broadband source afforded by the strong nonlinear response [3] of a pure germanium waveguide is still lacking. A broadband source, such as a supercontinuum, is a fundamental element for integrated sensing platforms since it allows for parallel detection of multiple gas species [4].
Here we report the first experimental demonstration of supercontinuum generation in a pure germanium waveguide. We pumped a 4.46 µm x 2.57 µm cross-section germanium-on-silicon air-clad waveguide close to the zero dispersion wavelength (fig 1a) with ≈200fs pulses at 4.6 µm, generating a supercontinuum extending from 3.53 to 5.83 µm (fig 1b). Owing to the transparency of the atmosphere between 3 and 5 µm and to the strong absorption of hazardous and greenhouse gases such as CO (≈4.5 µm), CO_2 (4.2, 4,3 µm) and CH_4 (3.45 µm) [5], our source has potential applications in free-space communications and environmental monitoring. With the aid of numerical simulations, we attribute the long wavelength extension limit mainly to free-carrier absorption, generated by three-photon absorption. We believe that improvements could be achieved if we could increase the pump wavelength to 5 µm. This should reduce the multiphoton absorption and therefore the generation of free-carriers [6].

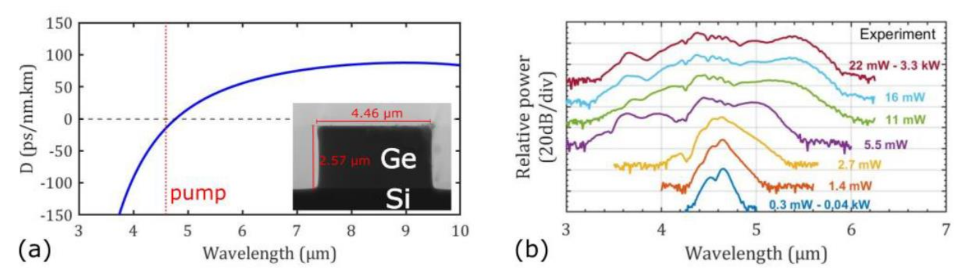

Figure 1 : (a) Dispersion parameter of the germanium on silicon waveguide with a 4.46 µm x 2.57 µm cross-section. A Scanning Electron Microscope image of the waveguide is shown in the inset. (b) Output spectra for different coupled average powers.

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Optimum setup of NOLM-driven mode-locked fiber lasers

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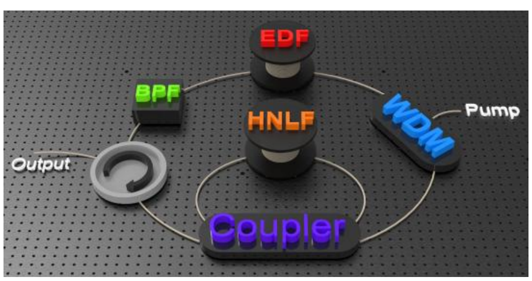
Abstract: We present a way to design NOLM-driven mode-locked fiber lasers, which minimizes intra-cavity pumping powers and does not affect the self-starting feature of the laser.

The simplest form of a nonlinear optical loop mirror (NOLM) consists of a coupler whose outputs are connected to a passive fiber so as to form a loop [1]. The NOLM is highly valued for its versatility, as it inherently has features that allow a variety of operations to be performed [2,3], such as time division multiplexing, frequency conversion, signal regeneration, suppression of a continuous background, or mode locking in laser cavities. However, in most of those applications the NOLM is not properly designed and therefore is not being used to the best advantage. This is in fact why in laser cavities where the NOLM is used to perform mode locking, the laser is generally not self-starting, thus making it necessary to use additional components (e.g. polarization controllers) to facilitate its start-up. Consequently, cavities equipped with NOLM are generally less efficient and less competitive than those using other mode locking elements [4,5]. Here we present an optimal NOLM configuration specifically dedicated to mode locking (figure 1 (a)), which minimizes intra-cavity pumping powers through proper adjustment of the NOLM's coupler ratio, while a band-pass filter is used to modify the curvature of the transfer function at the origin so as to preserve the self-starting feature of the laser. The NOLM loop is preferably made of a high non-linearity fiber (HNLF) so that a relatively short fiber length is sufficient to structure the transfer function by only self-phase modulation, i.e., without higher-order effects. When a NOLM operates in Transmission mode, an isolator must be placed just before the NOLM in order to suppress the reflected beam and impose a unidirectional propagation of light in the cavity. In our laser setup, this isolator is replaced by a circulator that simultaneously plays the role of isolator and output coupler. In addition, the circulator redirects the reflected beam to the laser output, rather than suppressing it, which helps to reduce intracavity losses.
Our experimental results (Figure 1 (b)) confirm the generation of pulse trains in the optimized setup of our NOLM-driven mode-locked fiber laser.



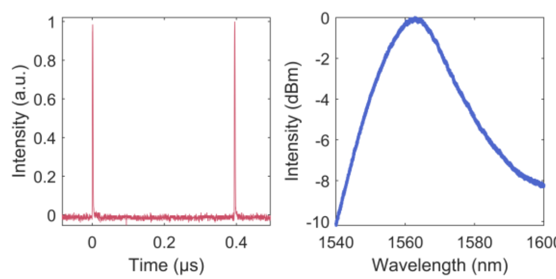


Figure 1 : (a) Optimum setup of our NOLM-driven mode-locked fiber. (b) Temporal and spectral profiles obtained with our laser setup. BPF : Band-pass filter, EDF : Erbium doped fiber, WDM : Wavelength division multiplexer, HNLF : Highly nonlinear fiber.

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Self-Pulsing in mutually coupled cavities

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Abstract: We show, theoretically and experimentally, that a light beam inside two mutually coupled Kerr fibre cavities could undergo self-pulsing. Additionally, we study in detail the dynamics, stability and bifurcation structure of this system.

Lately, there has been a growing interest in the study of the emergent behavior arising from two mutually coupled nonlinear cavities [1]. While one single cavity has been extensively studied in the last decades, the addition of a second cavity requires deeper study. It is the addition of this second cavity that enriches even more the complex nonlinear (NL) dynamics of the traditional single cavity. Distinct experimental architectures have been studied such as microresonators or micropillars [2,3] allowing the prediction and observation of phenomena ranging from super-efficient soliton generation to spontaneous symmetry breaking [1,4]. These advances have been applied, for example, to the demonstration of "photonic molecules" as shown by Zhang in [5].

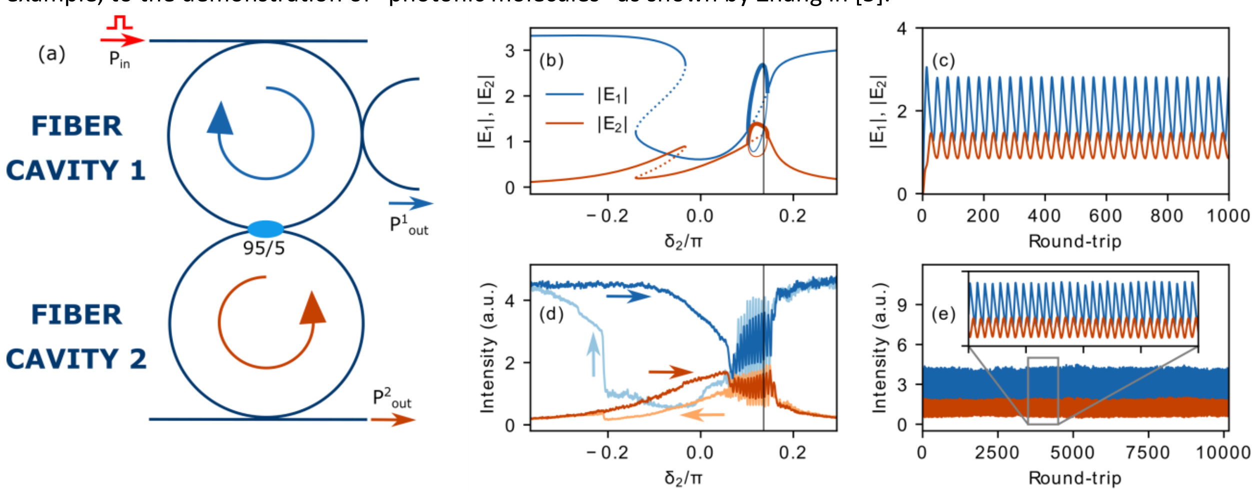

Figure 1 : (a) Schematic of the setup. (b-d) Theoretical and experimental nonlinear resonances for $\delta_1 = 0.18\pi$. (c-e) Self pulsing (SP). (c) Numerical simulation of SP for 1000 round trips. (e) Experimental SP for more than 10000 round trips, 1000 in inset.

Our system (Fig. 1, panel a) is composed of two fibre rings in the normal dispersion regime ($L_{1,2}$ = 250 m), coupled through a 95/5 coupler, the lower ring being synchronously pumped by a narrowband laser beam. We report the observation of NL resonances obtained when locking the detuning of the first ring to $\delta_1 = 0.18\pi$ and scanning the second one (see panels b and d) for P_{in} = 1W. It is here where the bistability (see arrows in panel d) and the self-pulsing (SP) appear. We obtain, both theoretically and experimentally a sustained SP (see panels c and e) when locking the second ring detuning to $\delta_2 = 0.14\pi$ in the SP region (black vertical lines in panels b and e). Moreover, through a numerical continuation, we performed a bifurcation analysis of this dual geometry (not shown).
To conclude, we showed a sustained SP behavior for millions of round trips in mutually coupled fibre cavities demonstrating its potential as a testbed for studying complex dynamics occurring in nonlinear coupled systems.

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Temporal analogue of the Fresnel diffraction by a phase plate in linear and nonlinear optical fibers

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Abstract: The analogy existing between spatial and temporal optics has motivated many studies to interpret spatial phenomena in the domain of ultrafast optics [1,2]. In the present work we would like to extend the knowledge of spatial Fresnel diffraction to the fiber-based propagation of a continuous wave affected by a localized phase jump. The imprinted phase profiles have a step-like shape with single or double transition with a depth of $\Delta\varphi$ (Figure 1, (a)). We numerically and analytically demonstrate that linear evolution is well described by the interference of two phase-shifted patterns typical of the diffraction by a sharp edge. We can therefore benefit from all the theoretical framework established for Fresnel diffraction that relies on the use of Fresnel integrals [3, 4]. In the presence of nonlinearity, depending on the regime of propagation, coherent bright and dark structures emerge (Figure 1, panels (b) and (c)).

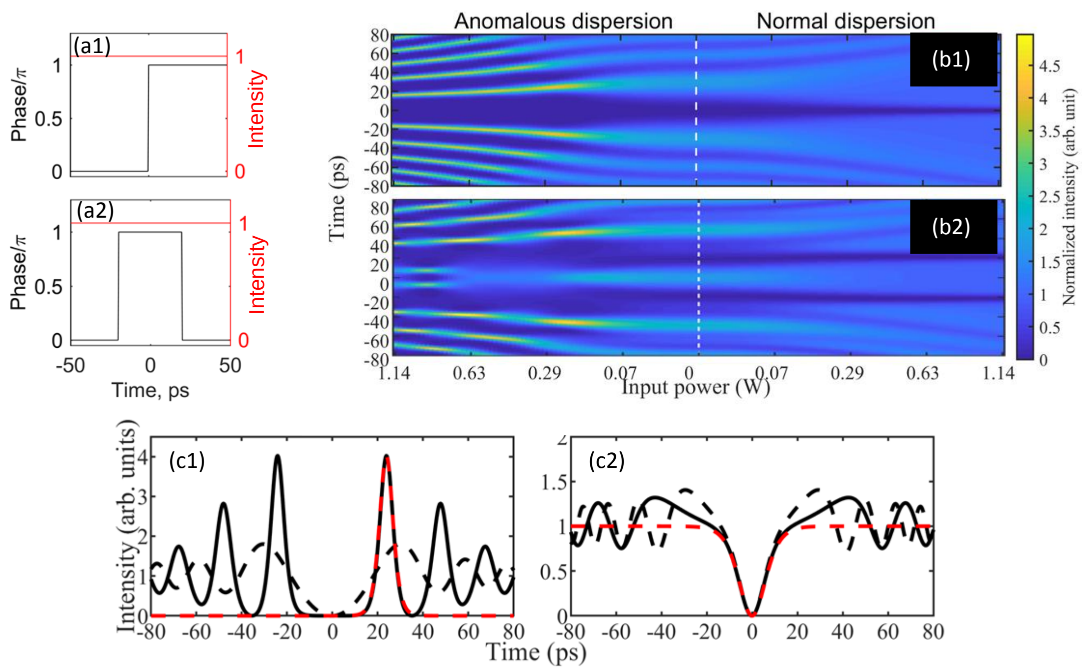

Figure 1 : Imprinted single-step and double-step phase profiles with a depth of π and the corresponding intensity profiles recorded after propagation in 10-km fiber with $\beta_2 = \pm 20$ ps^{2}km^{-1}, $\gamma = 1.1$ W^{-1}km^{-1} at different input power levels (panels (a1-2) and (b1-2), respectively). (c1) Profiles emerging during propagation in the anomalously dispersive fiber in the linear (dashed black) and nonlinear (solid black) regimes. The highest peak is well-filled by a bright soliton (dashed red). (c2) Comparison of profiles emerging from a 6 km and 10 km long normally dispersive fiber (dashed and solid black, respectively) with a black soliton (dashed red).

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Temporal Cavity Solitons in an Active Fiber Resonator

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The generation of solitons in passive optical resonators has attracted significant attention over the last decade [1,2]. Besides the interesting physics, a number of important applications of so-called temporal cavity solitons, including data transmission [3], atomic clocks [4] and microwave generation [5], have emerged. However, real life applications are still lagging behind, mostly because very little power can be injected in, or extracted from, a high finesse resonator. Even if solitons in mode-locked lasers can circumvent this problem, the noise coming from the gain medium causes timing jitter that may prevent their use. Here we show that incorporating an optical amplifier in a passive cavity but keeping the system below the lasing threshold allows to excite a new kind of temporal soliton that combines the advantages of laser solitons and passive cavity solitons. The experimental set-up depicted in Fig. 1(a) is a fiber resonator (50 m) incorporating a short erbium doped fiber (30 cm) pumped at 1480 nm and two couplers (99/1 and 90/10). The trough-port transmission when the driving laser (P_s =1 µW) is sent to the 99/1 coupler [Fig. 1(b)] shows an intracavity power of 215 µW and 2.5% of effective loss (Finesse of 248), much lower than the intrinsic roundtrip loss (>30%). Even if the effective loss increases with the intracavity power P_c to reach ~10% for P_c = 150 mW, this does not prevent the generation of a soliton as the intracavity power is mainly given by the continuous background on which it sits. To show it, we inject the driving laser (P_s = 110 mW) through the 90/10 coupler and stabilize the intracavity power at 60 mW (6.5% of effective loss). Then, we excite solitons with a single optical pulse [6] and record the output on a 10 GHz oscilloscope. A short pulse leaving the cavity at each roundtrip time (RTT) following the addressing pulse can be seen in Fig. 1(c). Detailed spectral, temporal and RF characterization (not shown) confirm that these pulses share similar properties with temporal cavity solitons of high finesse passive resonators despite the high intrinsic losses of our resonator. We envision many applications for the active cavities presented here, as they remove the important constraint of having to work with intrinsically low-loss resonator.

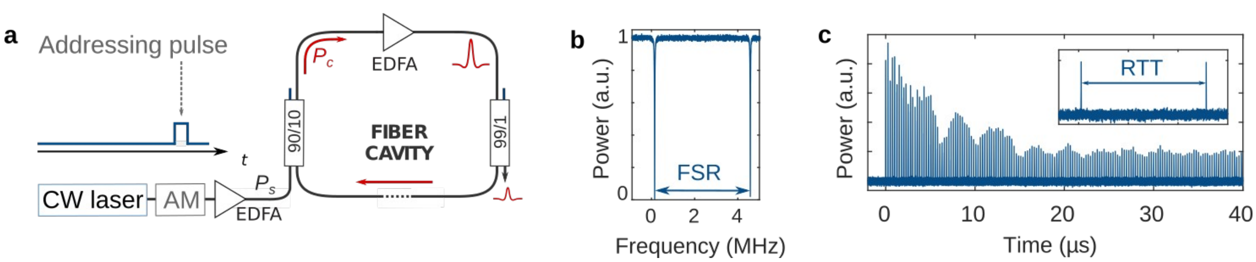

Fig. 1: **(a)** Experimental setup. Several components, such as a band pass filter and an isolator are not shown (dotted line). **(b)** Cavity resonances as the laser frequency is scanned over a free spectral range (FSR). **(c)** Oscilloscope recording showing a pattern of solitons leaving the cavity after each roundtrip.

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