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Noise-like pulse dynamics in passively mode-locked fiber lasers

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[4]*Instituto Nacional de Astrofísica, Óptica y Electrónica, Puebla, Pue., Mexico*

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We discuss:

- ✓ Presentation of noiselike pulses
- ✓ Single- or multiple-pulsing regimes (including harmonic mode locking)
- ✓ Challenge of characterizing precisely these pulses
- ✓ Observation of original noiselike pulse dynamics
- ✓ Applications

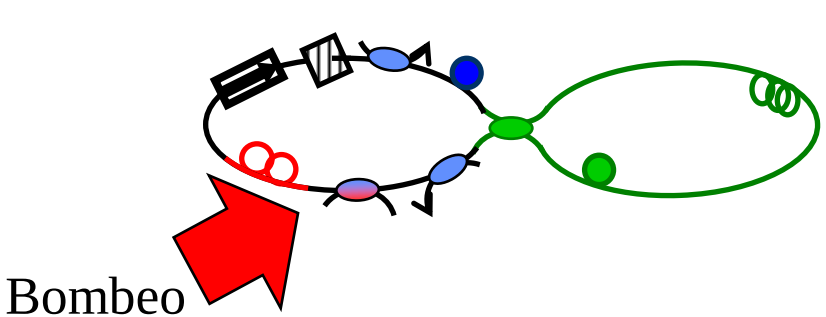
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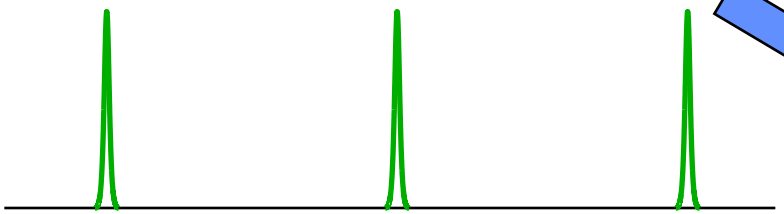
Most pulsed regimes of interest are stationary: solitons (conservative/dissipative)

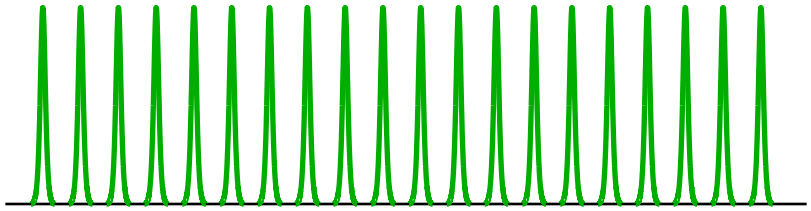
- ✓ High-power pump diodes and double-clad fiber technology (> W)
- ✓ New theoretical developments (dissipative soliton)

→

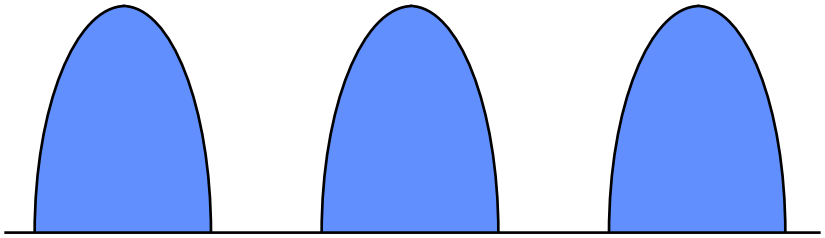
- ✓ High-rep-rate pulse trains (> GHz)
- ✓ High-energy pulses (→ μJ?)







Application: telecom

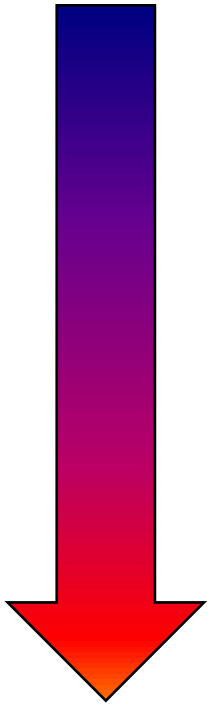


Application: industry, medicine

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Away from stationarity…

Stationarity



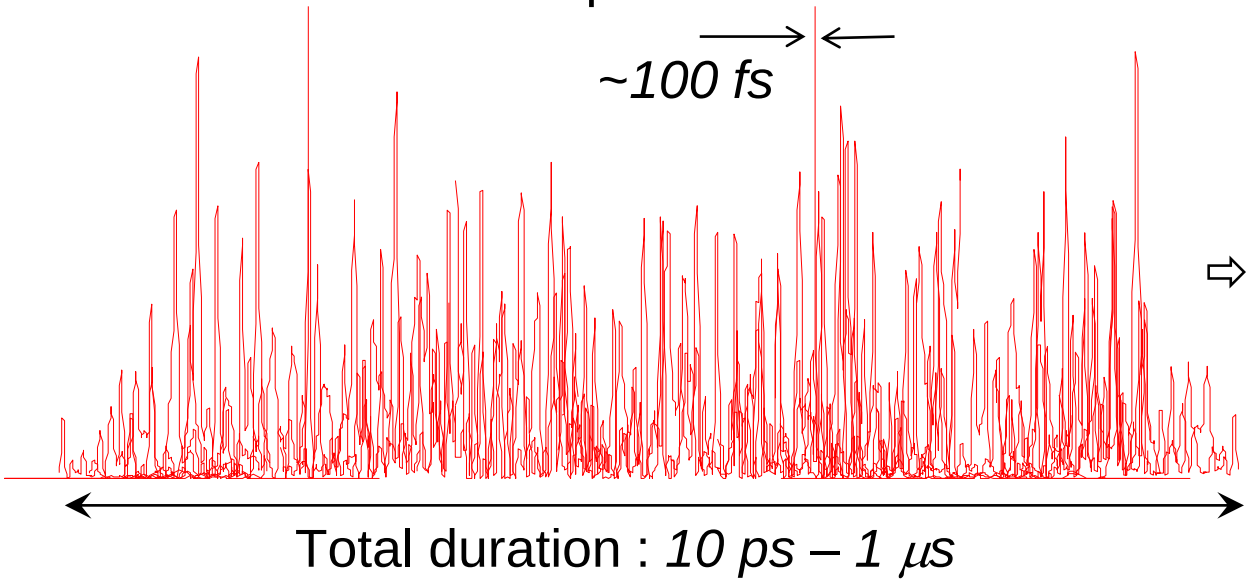
Chaos

- ✓Stable solitons
- ✓Multiple pulsing: interpulse interactions ⇨ different states (molecules, cristal, glass, rain etc.)
- ✓Soliton explosions, pulsating, creeping solitons, period-doubling…
- ✓Noiselike pulses (global stability, internal variability)
- ✓Rogue (freak) waves
- ✓…

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Noiselike pulses are radically different objects

Noiselike pulse = long, compact waveform with a very complex fine inner structure: large collection of sub-ps “pulses” suffering very fast, large variations in their amplitudes and durations.



⇨ Contains 10^3 – 10^7 sub-pulses!

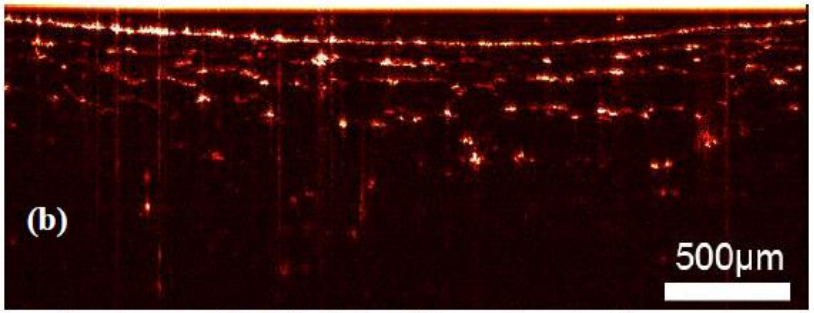
Global stability, **strong and fast variability of inner details** (changes completely after one round-tip)

⇨ Very complex objects (let alone phase and polarization aspects)

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Noiselike pulses are currently attracting attention

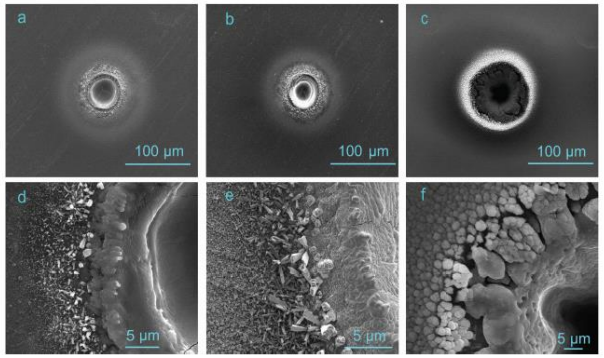
Applications:



📖 You et al., CLEO (2015) JW2A.94

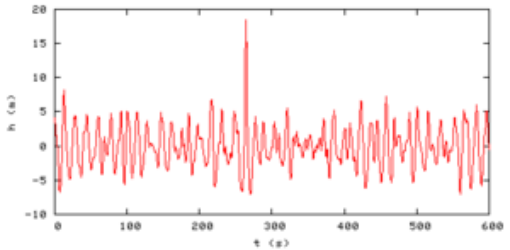
- Súperconinuum generation

  ⇨ spectroscopy, microscopy, sensing etc
- Nonlinear frequency conversion
- Micromachining
- …



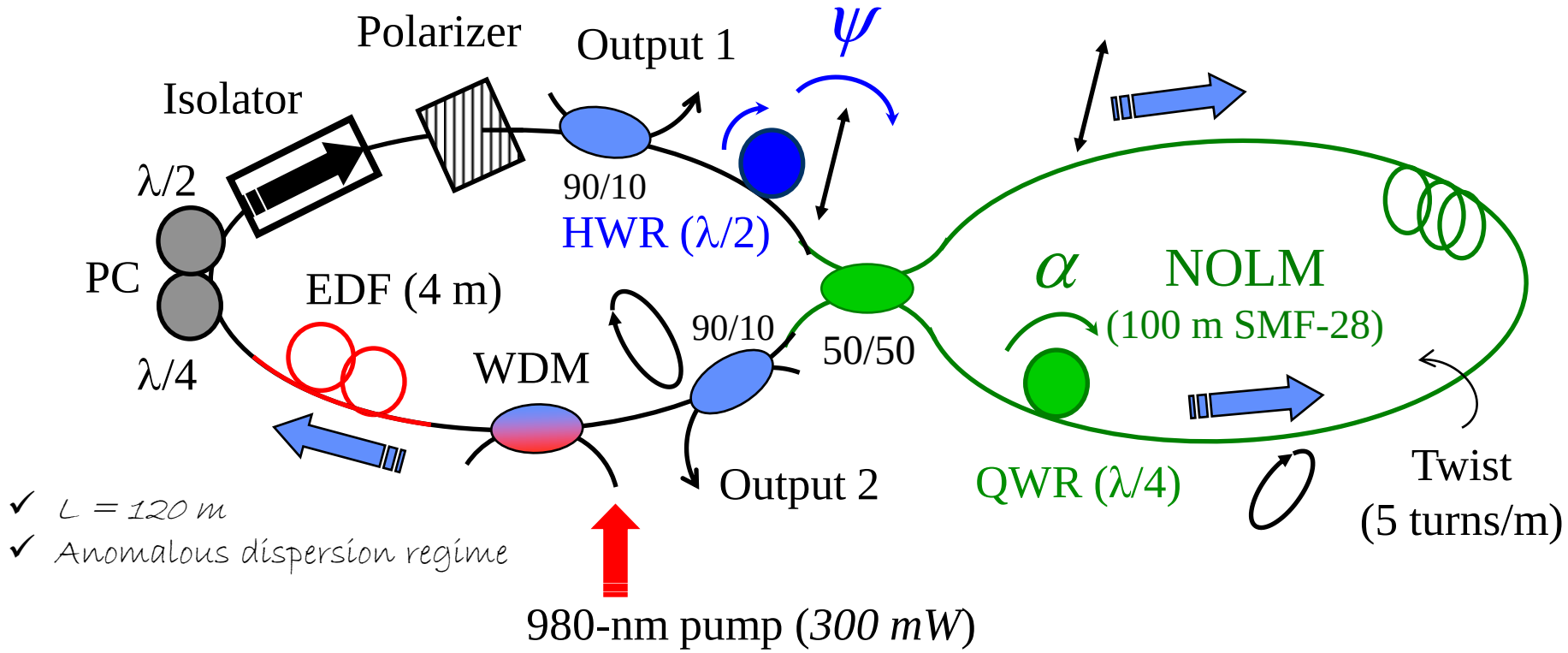
📖 Özgörenet al., Opt. Express. 24 (2011), 17647

Noise-like pulses are also attracting considerable interest in fundamental research (connection with optical rogue waves)



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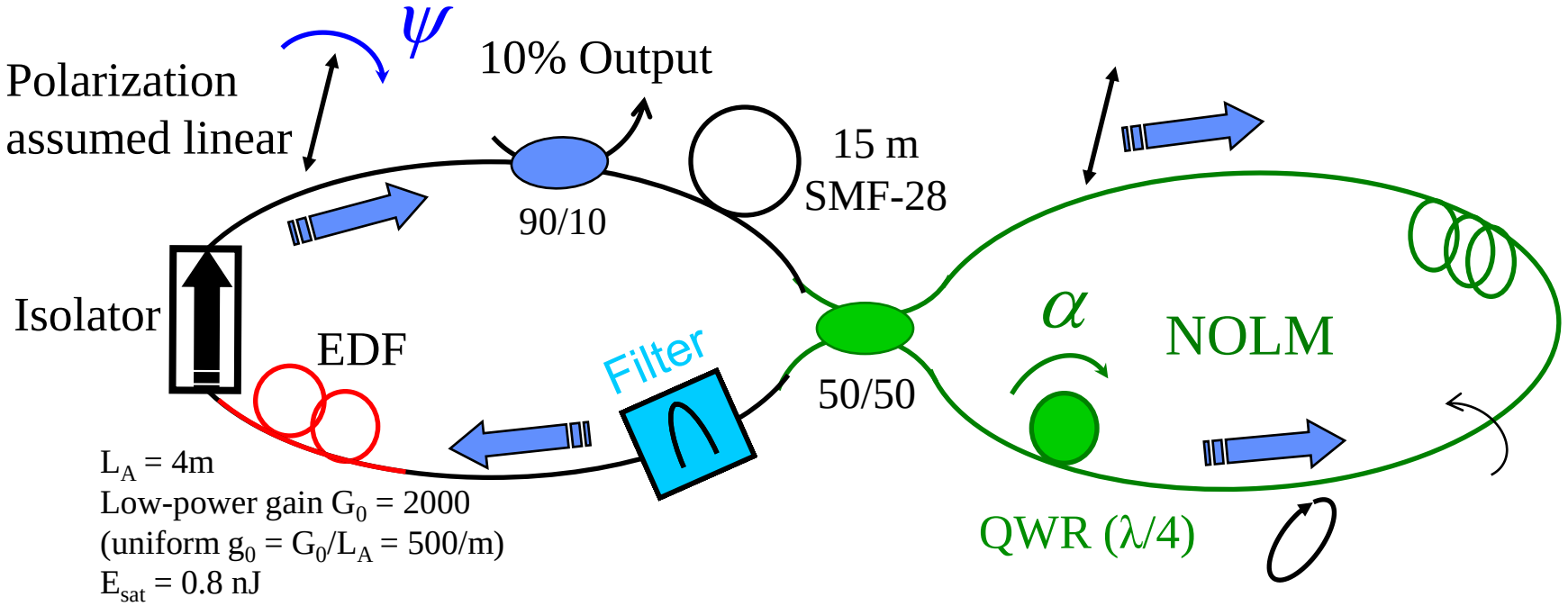
Figure-eight laser scheme



- ✓ A polarization-imbalanced NOLM is inserted in the laser (operates through nonlinear polarization rotation)
- ✓ Quarter-wave retarder (QWR) angle determines low-power NOLM transmission
- ✓ Input polarization to the NOLM is set linear
- ✓ Input polarization angle ψ, controlled through half-wave retarder (HWR), determines switching power

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Scheme used for numerical simulations



This scheme is **very similar to the experimental scheme**

- ✓ A 50-nm FWHM bandpass filter takes into account the bandwidth limitation of EDF gain
- ✓ Gain saturates on pulse energy
- ✓ QWR angle adjusted for small nonzero low-power NOLM transmission (≈ 0.1)

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Numerical model

Fiber sections: Propagation calculated using the coupled extended nonlinear Schrödinger equations:

$$\frac{\partial C^+}{\partial z} = -j\frac{\beta_2}{2}\frac{\partial^2 C^+}{\partial t^2} + \frac{2j\gamma}{3}\left(\left|C^+\right|^2 + 2\left|C^-\right|^2\right)C^+ + \frac{g}{2}C^+$$

$$\frac{\partial C^-}{\partial z} = -j\frac{\beta_2}{2}\frac{\partial^2 C^-}{\partial t^2} + \frac{2j\gamma}{3}\left(\left|C^-\right|^2 + 2\left|C^+\right|^2\right)C^- + \frac{g}{2}C^-$$

Dispersion — Kerr nonlinearity — Gain (for EDF only)

Pulse energy $\longleftarrow$ $g(E_p) = \dfrac{g_0}{1 + E_p / E_{sat}}$

Integrated using Split-Step Fourier method

Filter: $F(\lambda) = \exp\left[-\left(\dfrac{\lambda - \lambda_0}{\Delta\lambda_{FWHM}/1.66}\right)^2\right]$

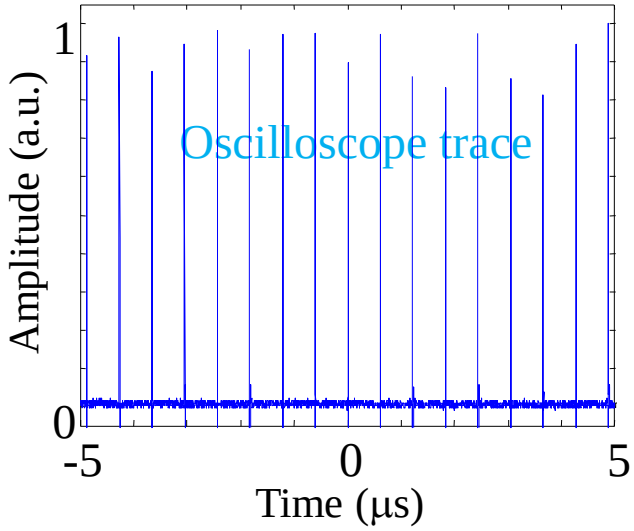
- ✓ Small-amplitude gaussian white noise is used as initial signal
- ✓ Integration is performed over several cycles until convergence is reached

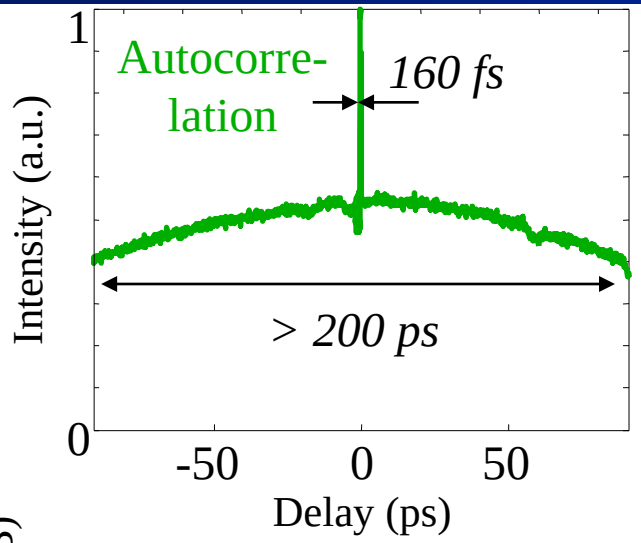
In order to keep computational time within reasonable limits:

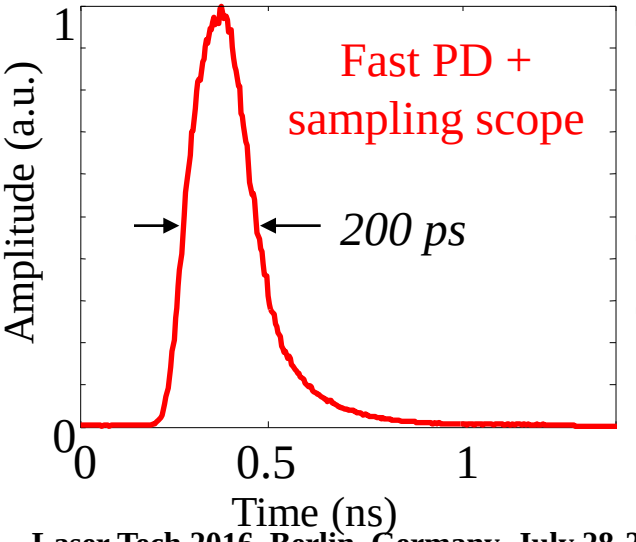
- ✓ **Laser length no longer** than a few tens of m
- ✓ **Noiselike pulse duration** ~100 ps (1-2 orders of magnitude **shorter than in experiment**)

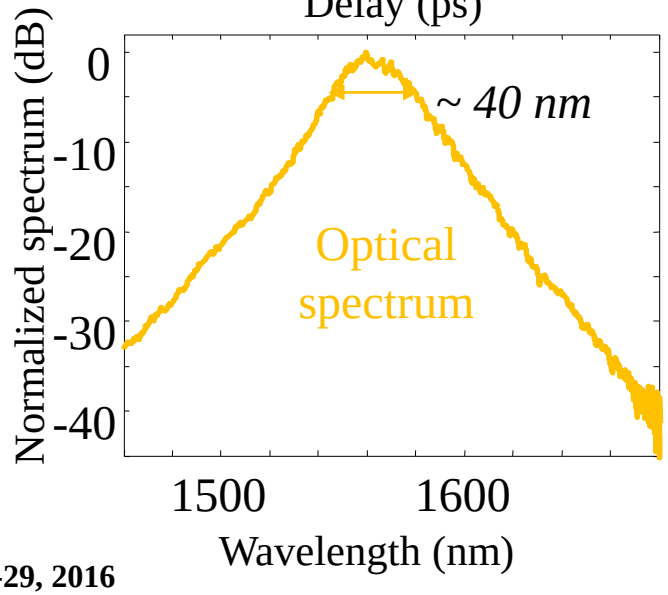
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Fundamental mode-locking was observed experimentally







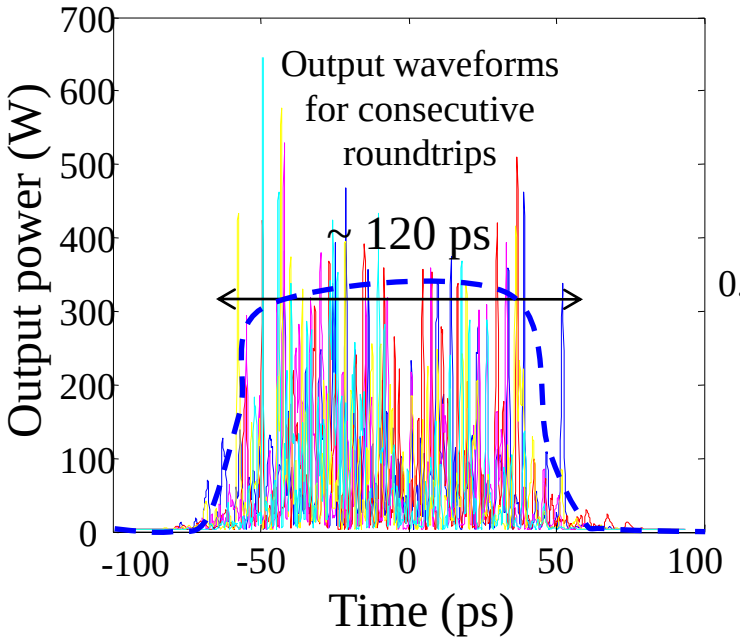


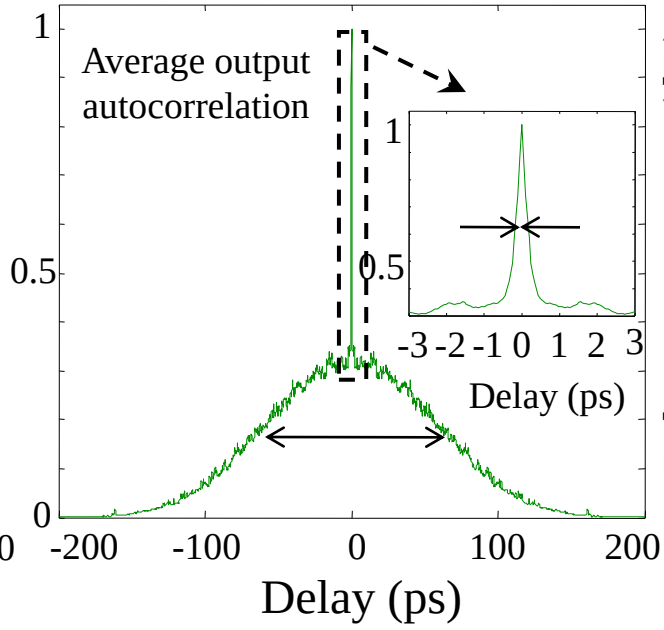
- ✓ For some adjustments, non-self-starting mode locking was observed at 1.6 MHz (fundamental mode locking)
- ✓ Typical features of noise-like pulses :

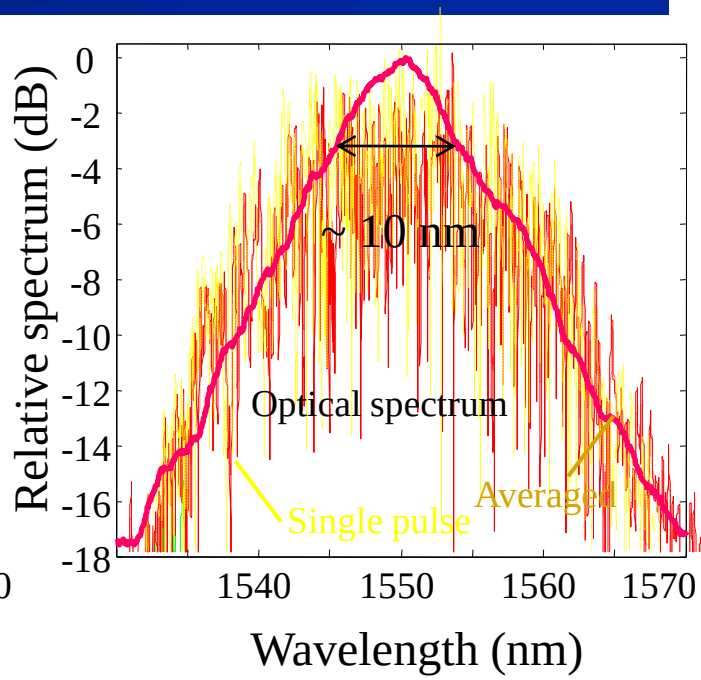
  - Double-scale (*ns/fs*) temporal structure
  - *Low coherence time*
  - Wide, smooth spectrum (*10-100 nm*)
- ✓ Large pulse energy (*nJ-μJ*)

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Numerical results are consistent with experiment





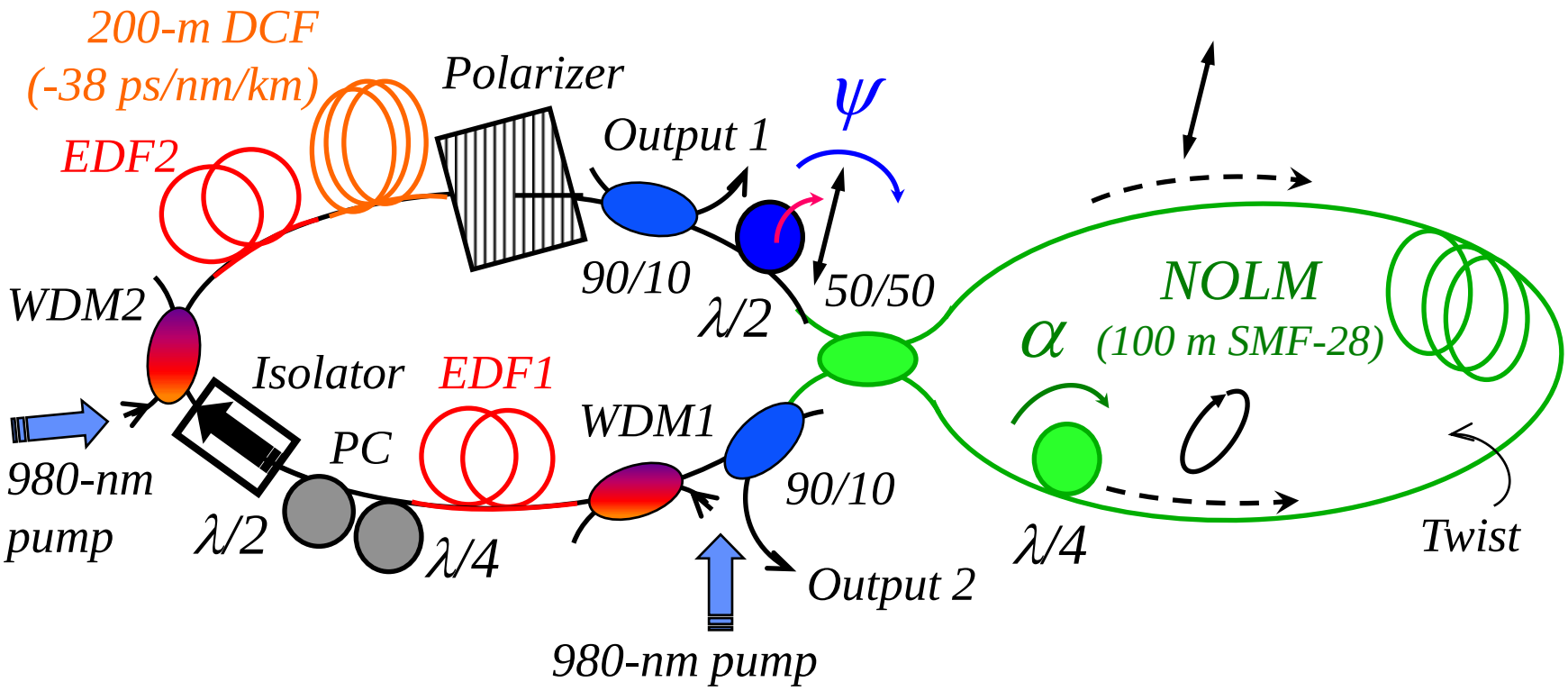


- ✓ Although there is no convergence to a constant pulse shape, a variable sub-ns packet of sub-ps pulses with stable caracteristics (peak power, duration) is maintained. Pulse energy = *1.4 nJ*
- ✓ Autocorrelation trace (averaged over many cycles) presents a sub-ps central peak riding a sub-ns pedestal (the ratio however is > 2, and may vary with simulation parameters)
- ✓ After averaging over many cycles, a smooth and relatively wide (10-nm FWHM) output spectrum is obtained

📖 Pottiez et al., Appl. Opt. 50 (2011), E24-E31

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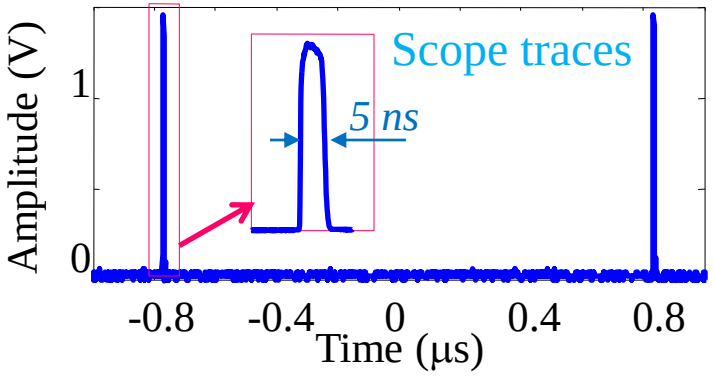
Multiple pulsing was observed in the normal dispersion regime

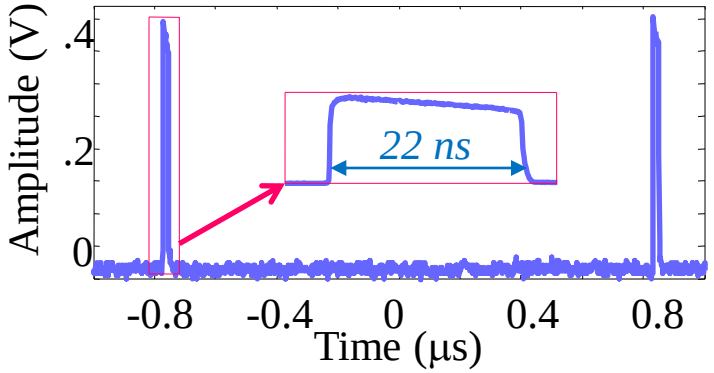


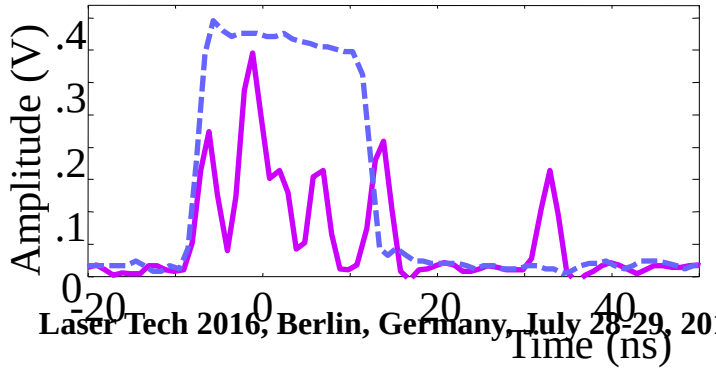
- ✓ L = 200 m
- ✓ Normal Dispersion

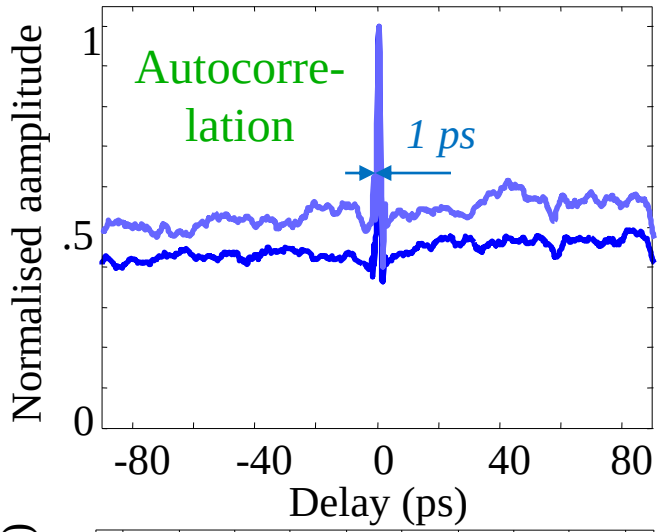
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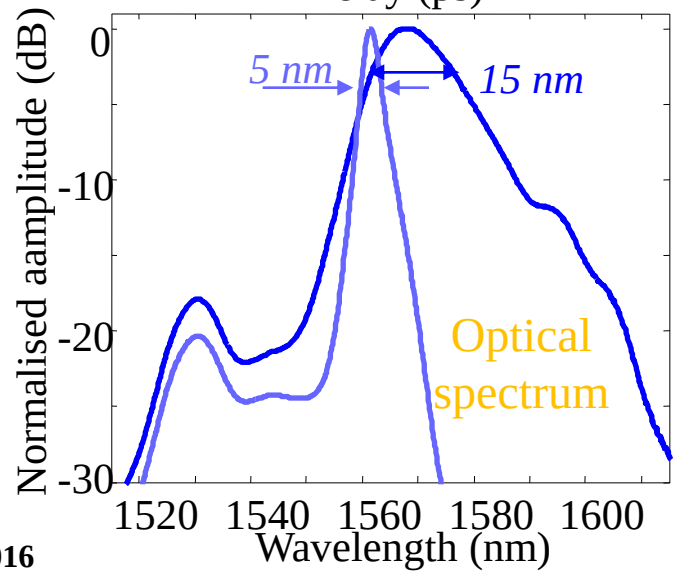
Fundamental mode locking was observed, followed by pulse breakup







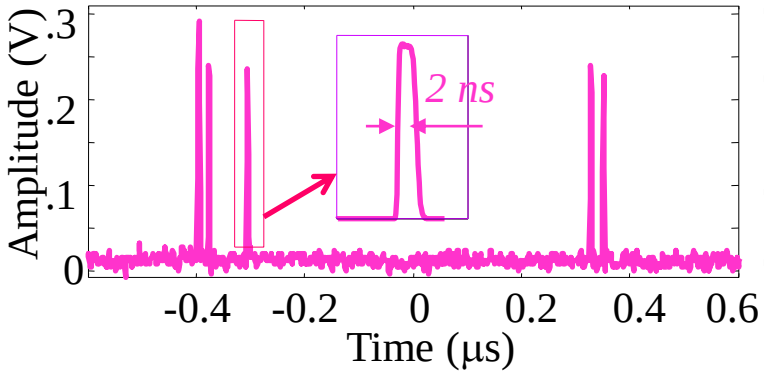


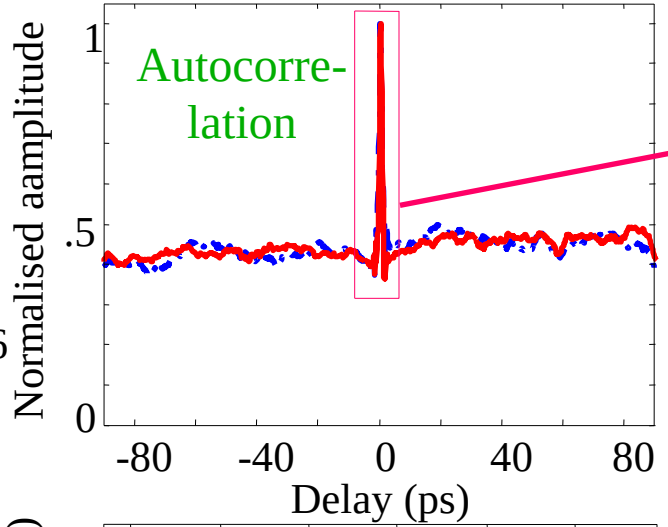


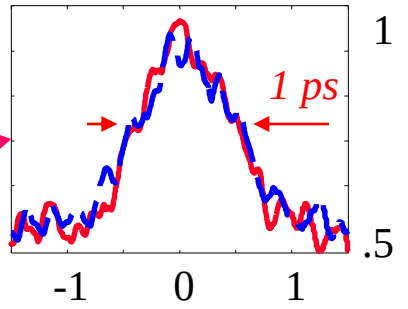
- ✓ For some adjustments, **mode locking** (sometimes self-starting) is observed, with one pulse per *1.6 μs* period (fundamental mode locking)
- ✓ Measurements confirm that pulses are **noise-like pulses**
- ✓ **Pulse properties** (peak power, duration) **adjustable** through HWR rotation
- ✓ Low-peak-power, **long pulse eventually splits into multiple pulses**

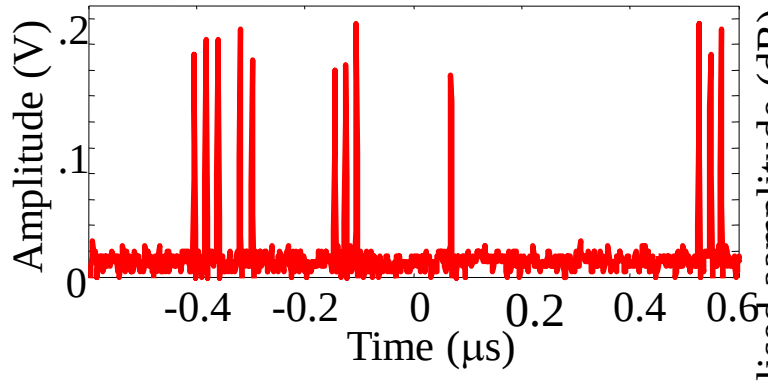
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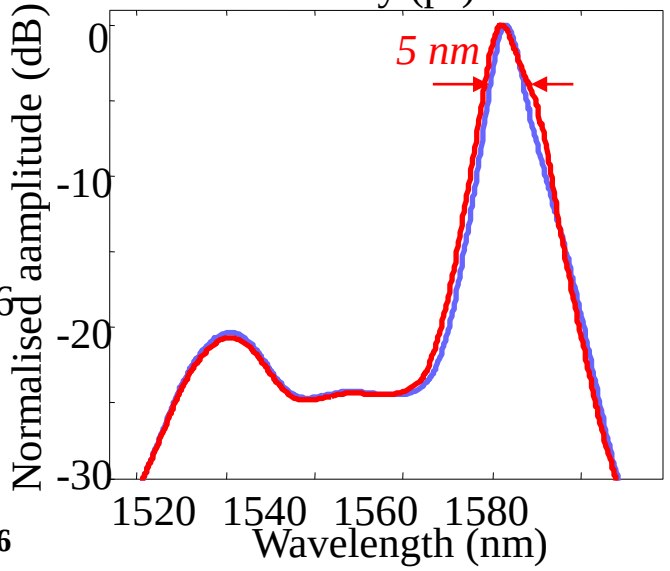
Up to 12 pulses were observed









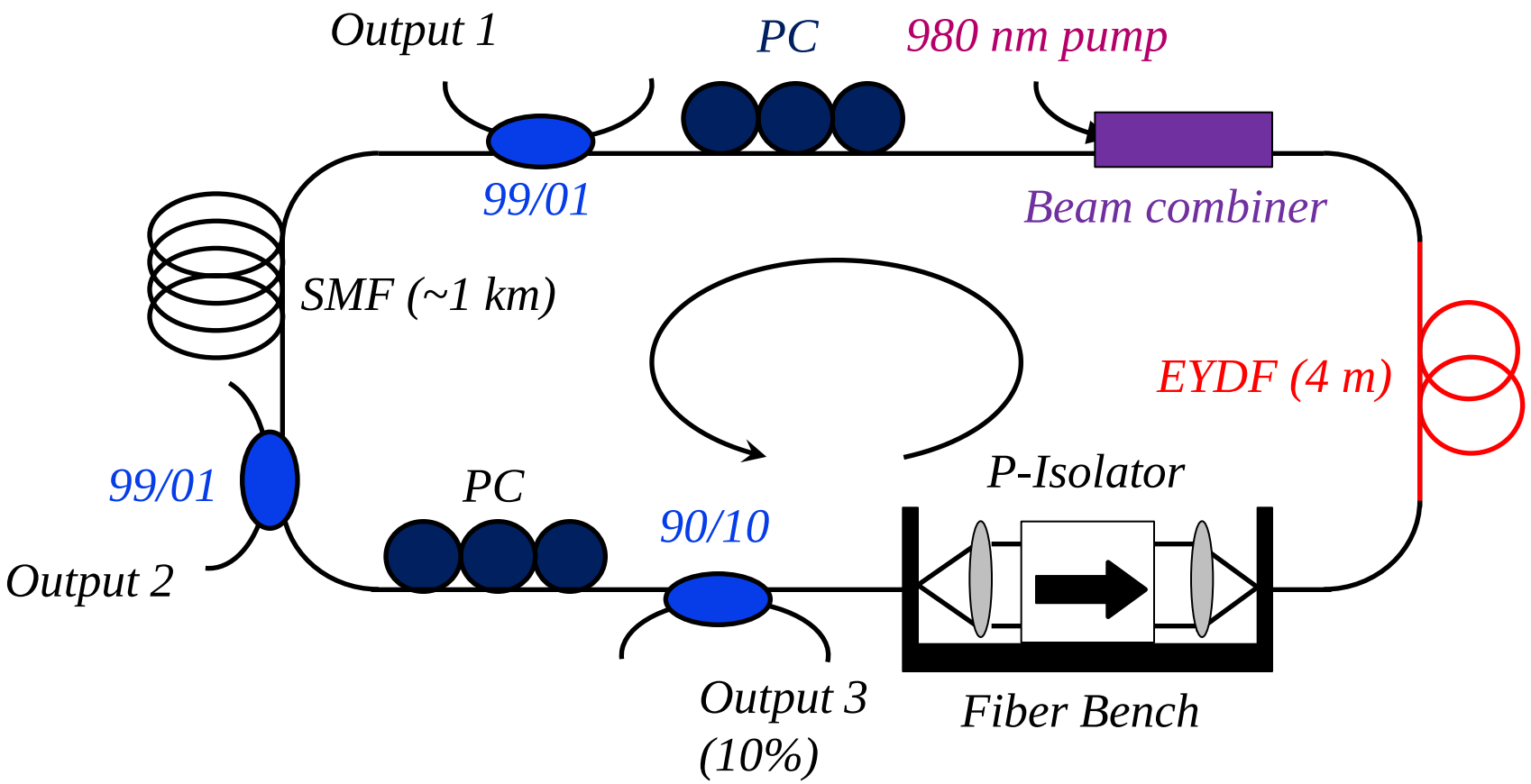


- ✓ For some adjustments, the **pulses synchronize**, although their **separation is not uniform**
- ✓ Some sub-groups with uniform separation of *~20 ns*
- ✓ Pulse autocorrelation and spectrum are unchanged
- ✓ **Same energy/round-trip as before**, but distributed among the multiple pulses

📖 Pottiez et al., Laser Phys. 24 (2014), 15103

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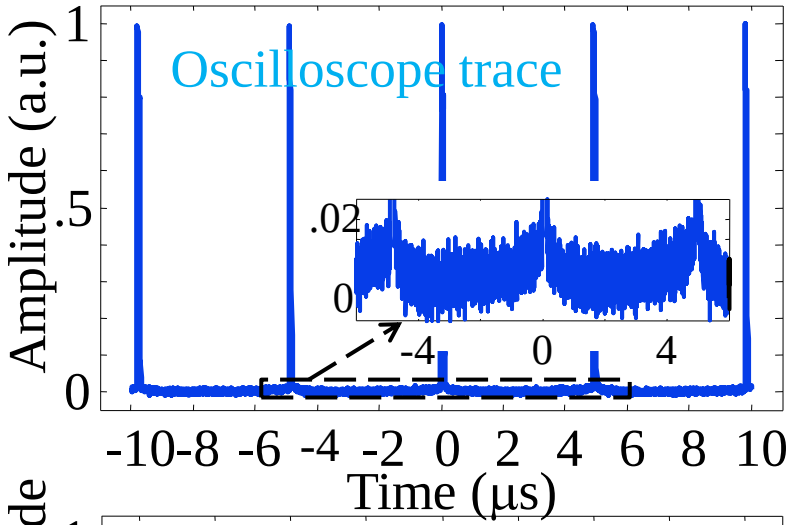
Noiselike pulse generation with a long fiber ring laser

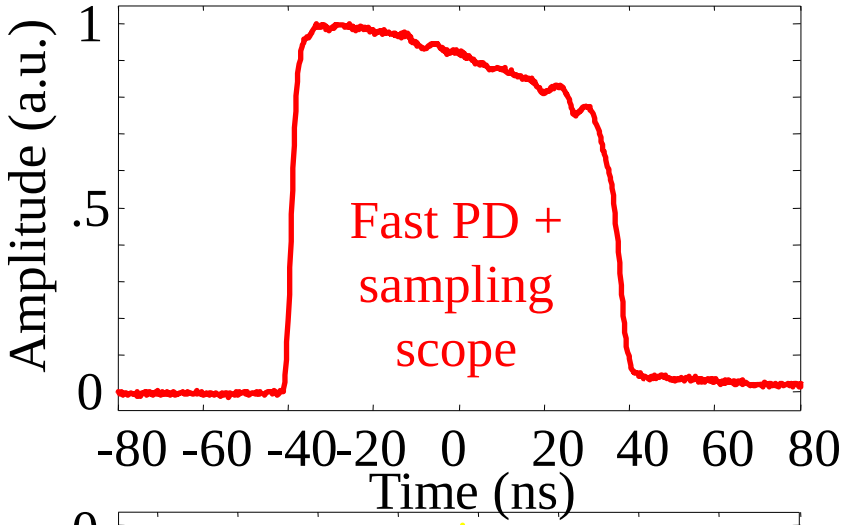


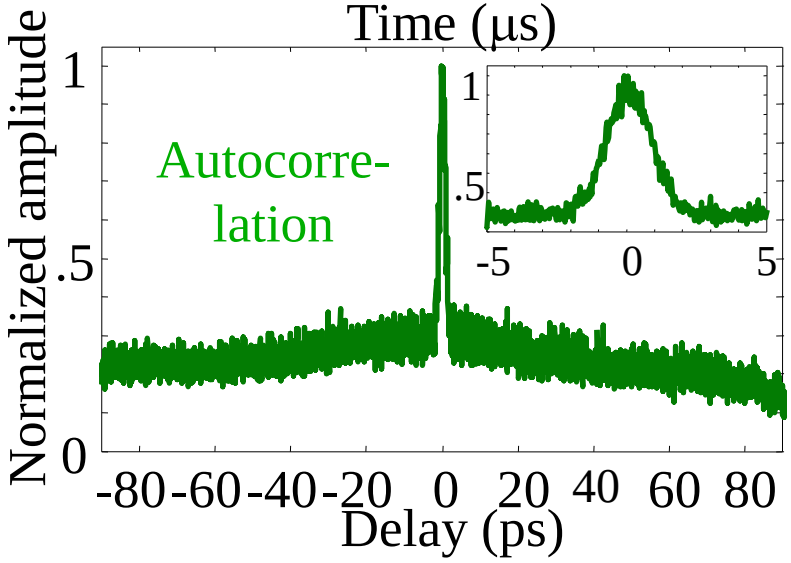
Pottiez et al., Laser Phys. 24 (2014), 115103

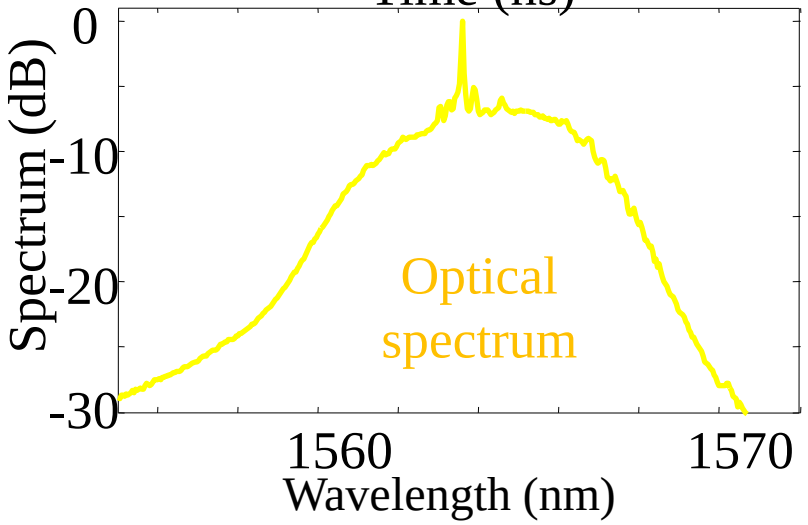
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Single-pulse energy up to 120 nJ was obtained









Fundamental ML

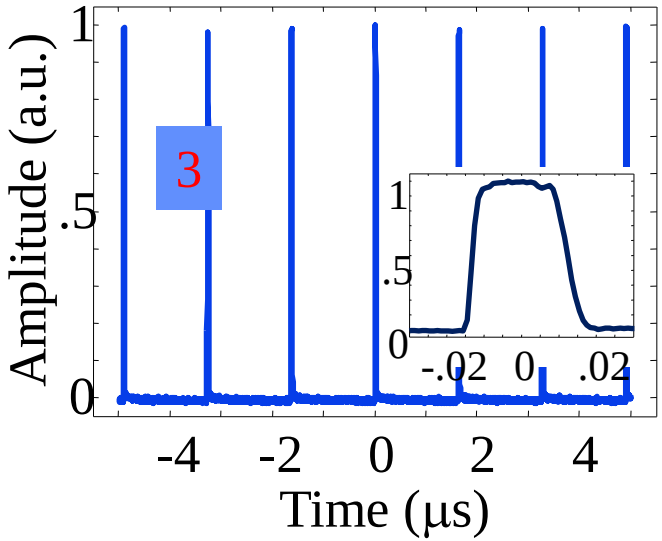
Rep. rate = 200 kHz

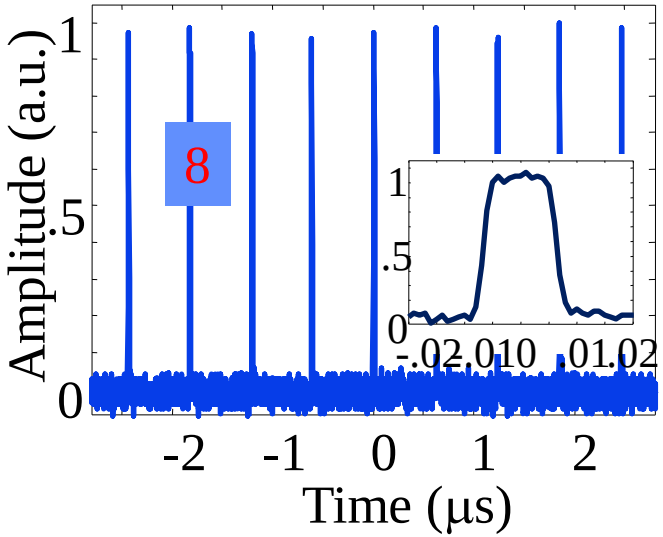
Pulse energy = 120 nJ

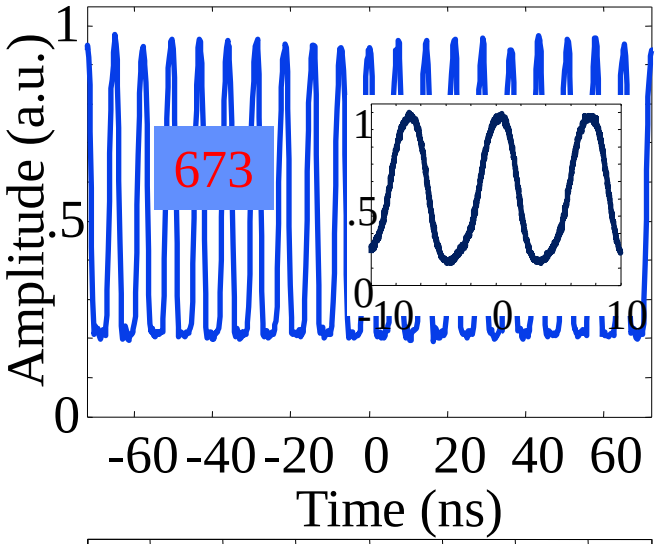
Single-pulse operation could not be maintained beyond some moderate value of pump power

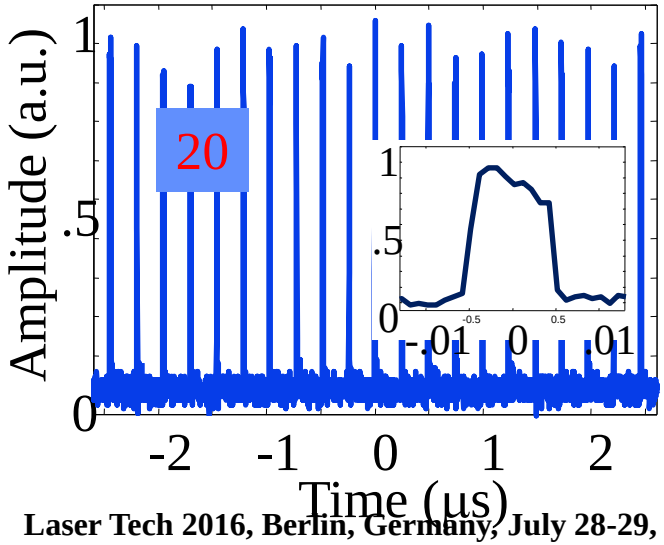
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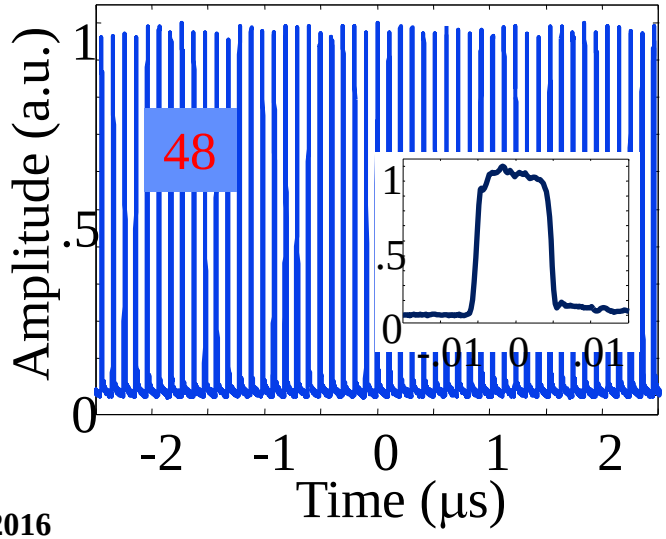
Harmonic regimes of orders 2-48, 673 and 1270 were observed

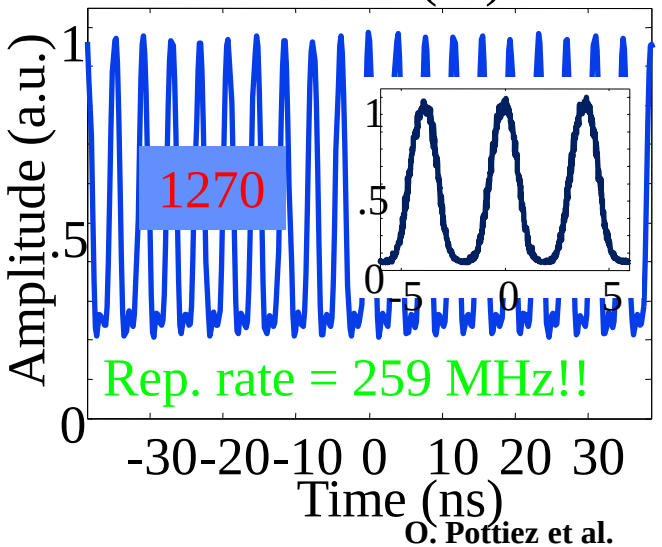






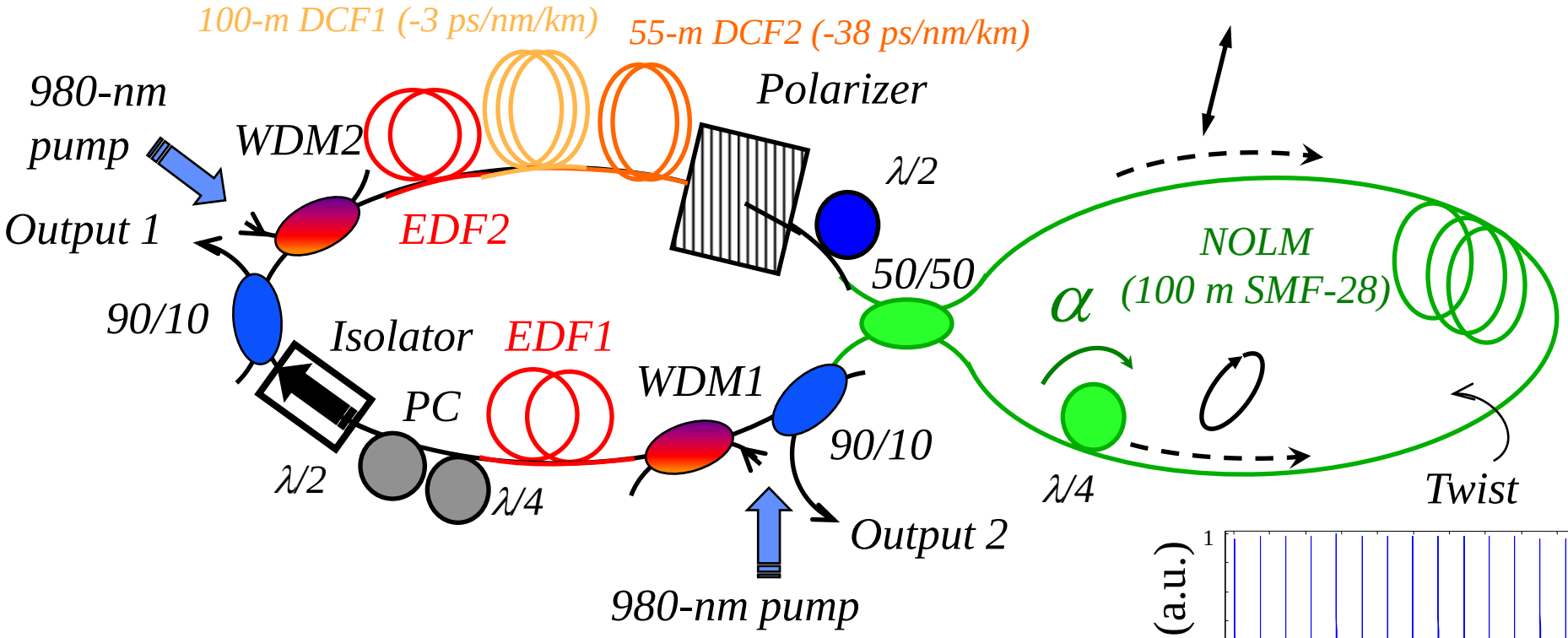


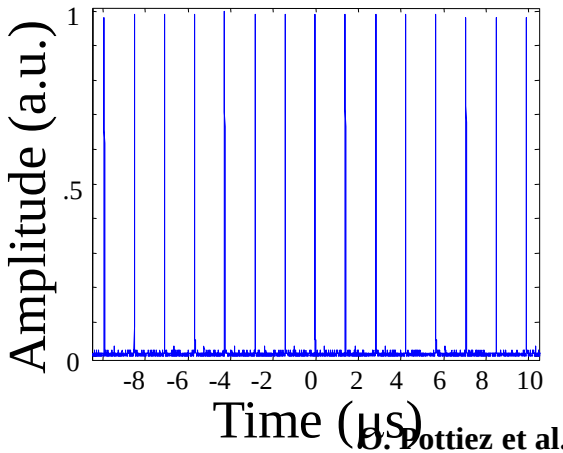




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Figure-eight laser with 100-m near-zero-dispersion fiber

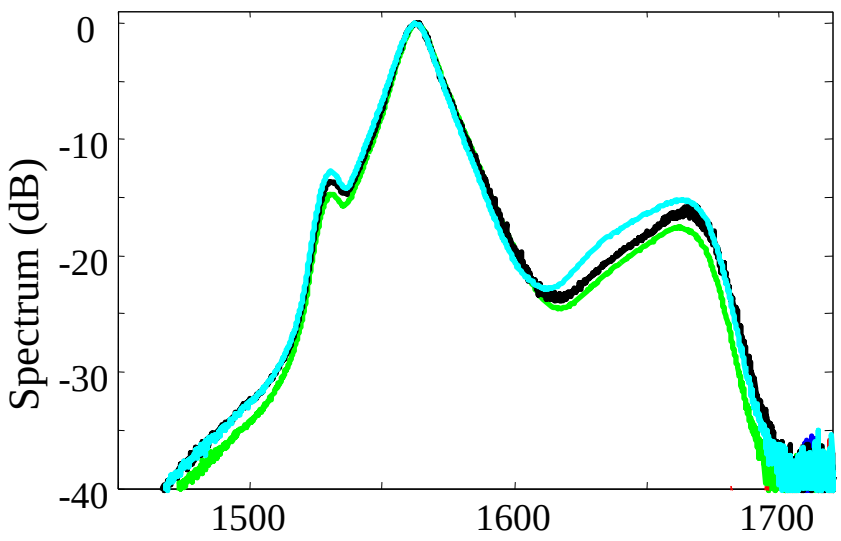


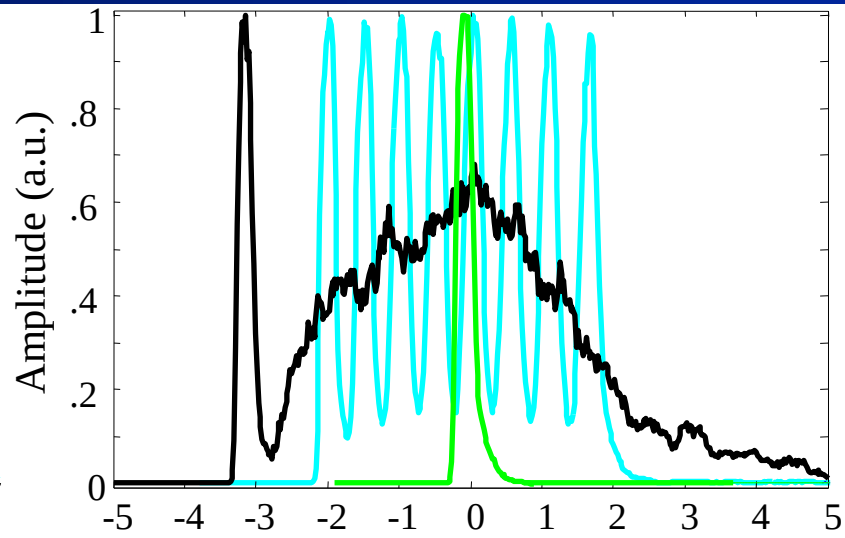


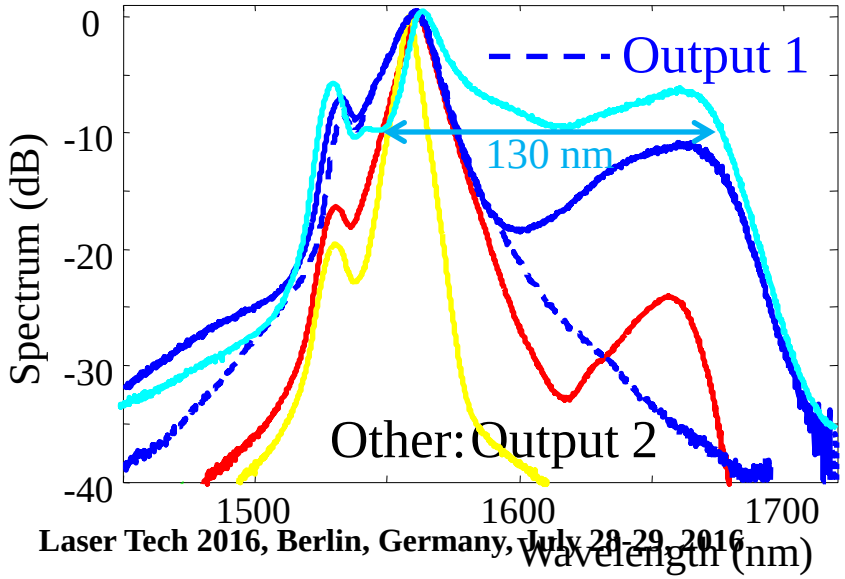
- ✓ A long piece of DCF with slightly normal dispersion is added ($D \approx -0.58$ ps/nm) to boost NL effects
- ✓ $L = 300$ m

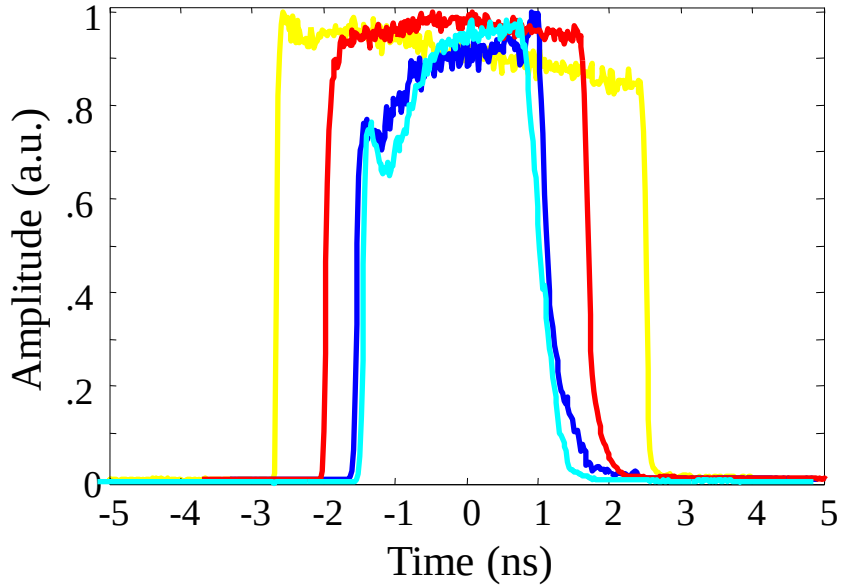
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Raman scattering enhanced the spectrum up to 130 nm





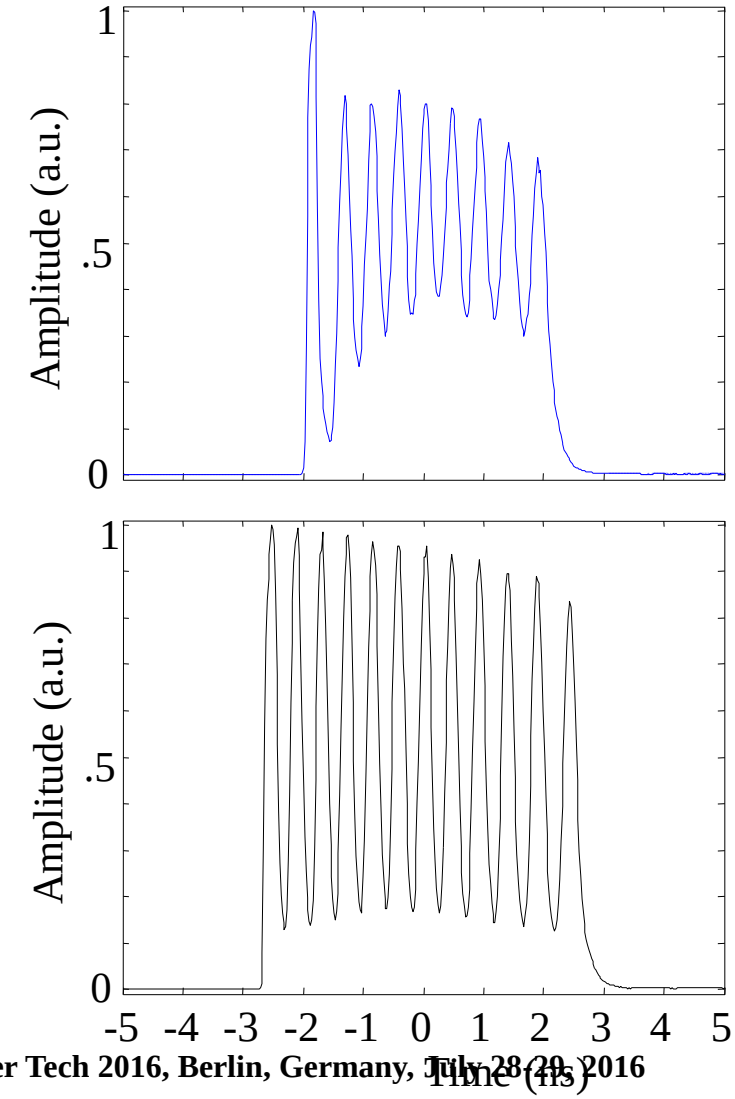


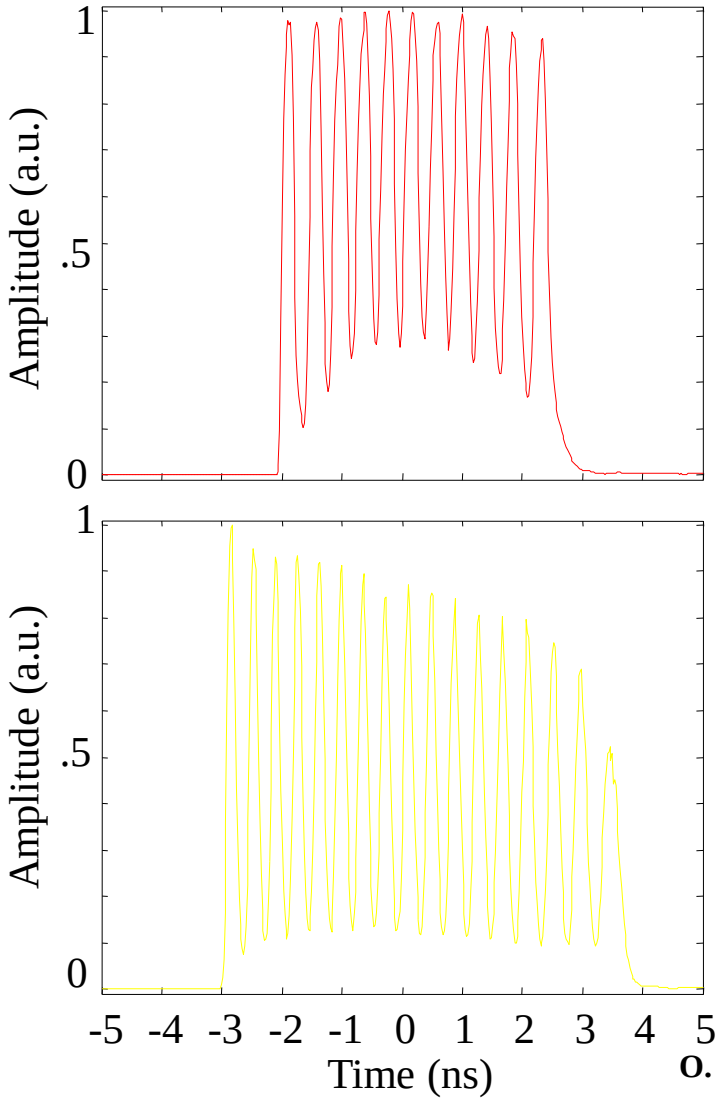


No clear correspon-dence between pulse temporal and spectral shapes

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Enigmatic “comb-like” noise-like pulses





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The measurement problem

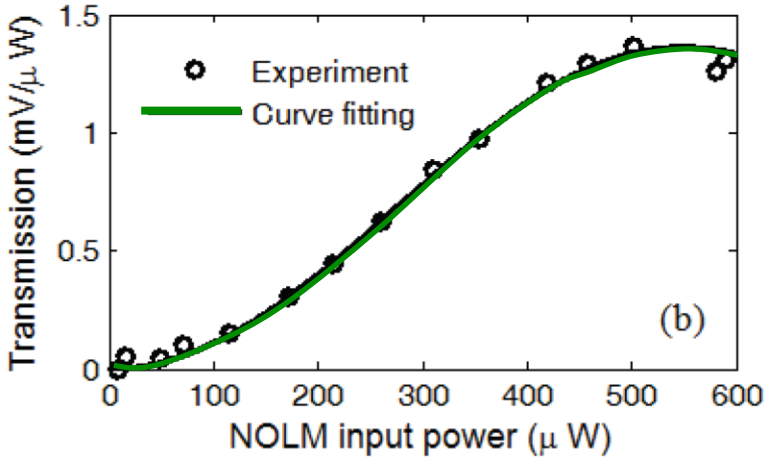
Noiselike pulse measurement is very challenging:

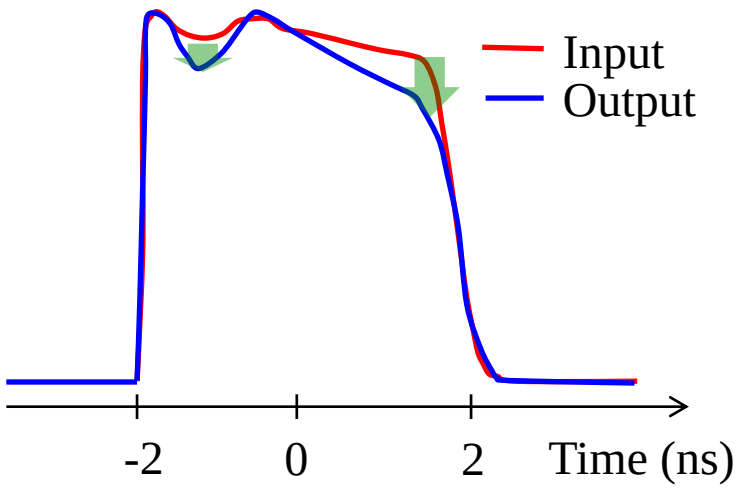
- ✓ ~100-fs details ⇨ **need for *fs* resolution** (orders of magnitude below the resolution of the fastest optoelectronics)
- ✓ ~ ns waveform with sub-ps details ⇨ **large number** (10^5-10^6) **of data points**
- ✓ **Cycle-to-cycle variability**
- ⇨ Average measurements give very poor information
- ⇨ **Single-shot measurements**

- ⇨ *Novel measurement techniques should be developed:*
- ✓ Single-shot optical spectrum 🕮 Runge et al., Opt. Lett. 38 (2013) 4327
- ✓ In our work, **we rely on the ultrafast response of** the optical Kerr effect in a **NOLM** (~fs) and focus on the statistics of the inner pulses
- ✓ Sequence analysis using fast oscilloscope

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Pulse characterization using a NOLM

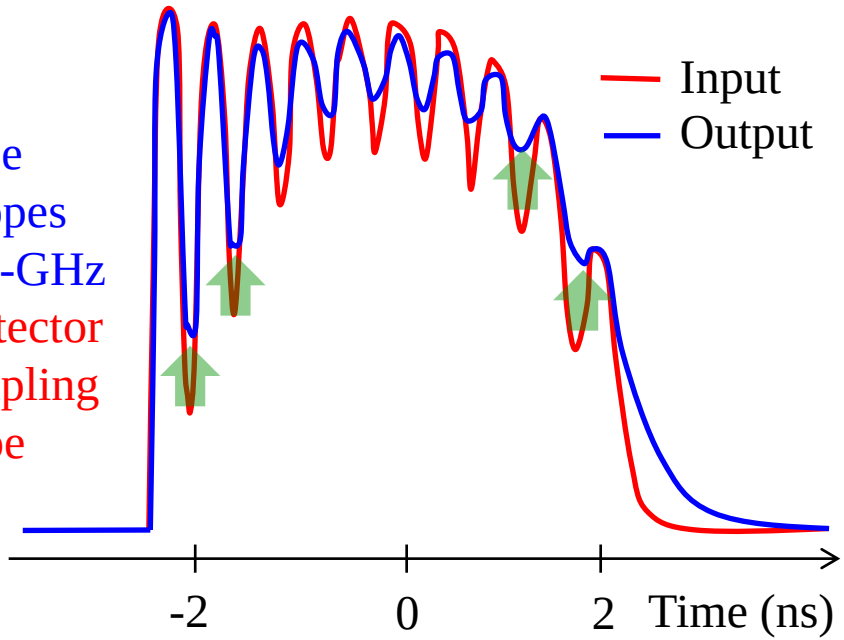




Lower amplitude yields lower transmission

⇨ **Envelope maps amplitudes** of sub-pulses

Pulse envelopes using 25-GHz photodetector and sampling scope



Valleys undergo higher transmission

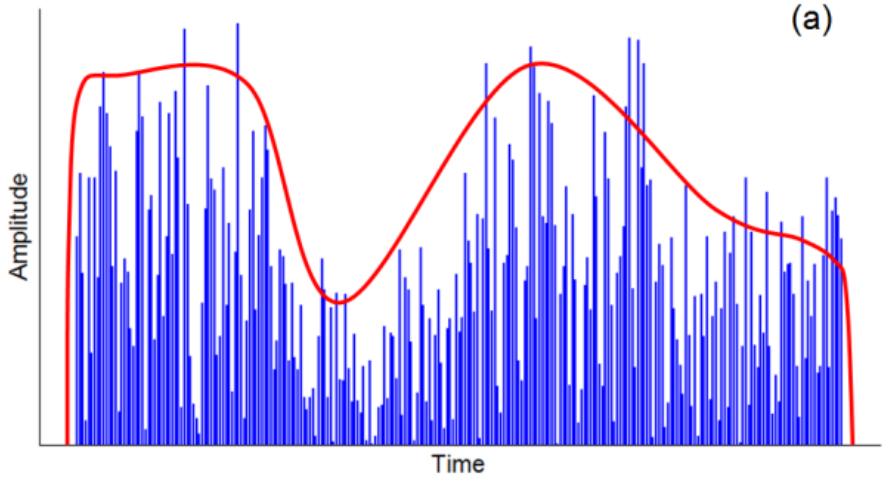
⇨ Sub-pulses in the valleys are not smaller than at the peaks

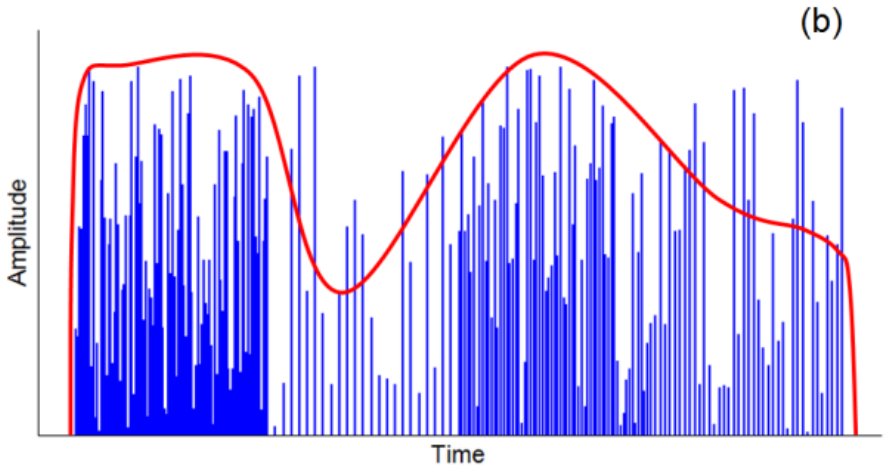
⇨ Probably **sub-ns sub-packets jittering around** their mean positions

⇨ **Intermediate level of organization** of noiselike pulse: **~100 ps** (between ~100 fs of inner pulses and ns of total waveform)

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Either the intensity OR the density of the sub-pulses vary

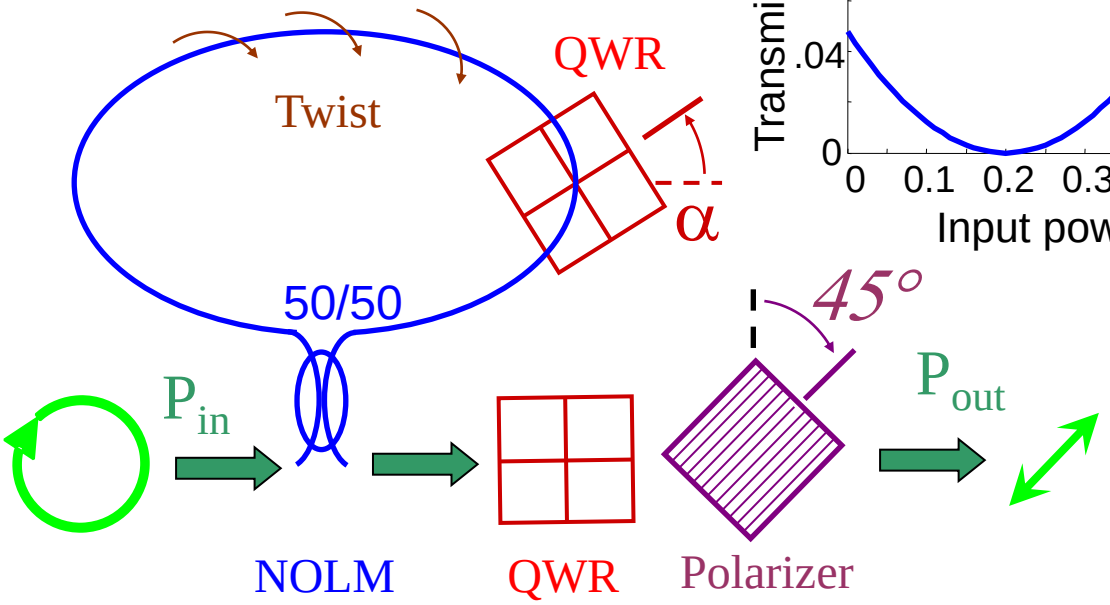


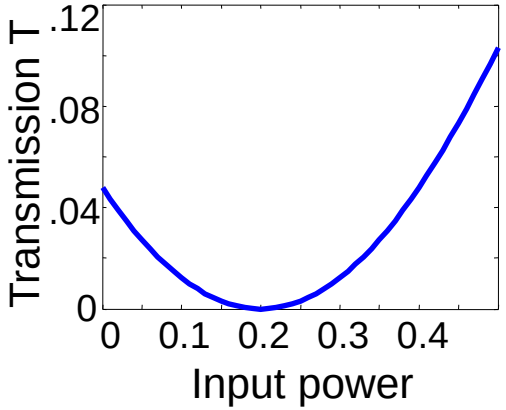


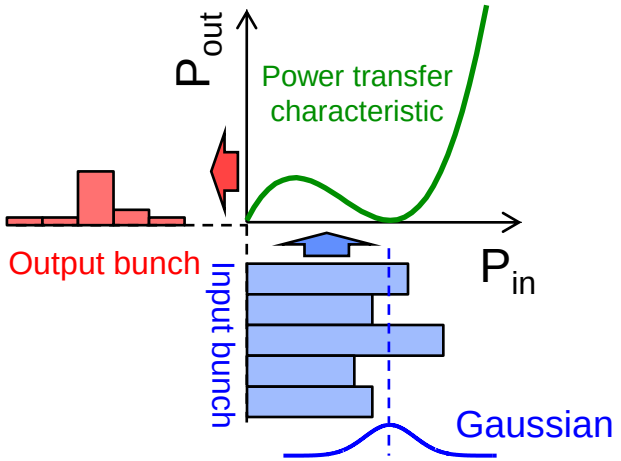
📖 Santiago-Hernandez et al., Laser Phys. 25 (2015), 45106

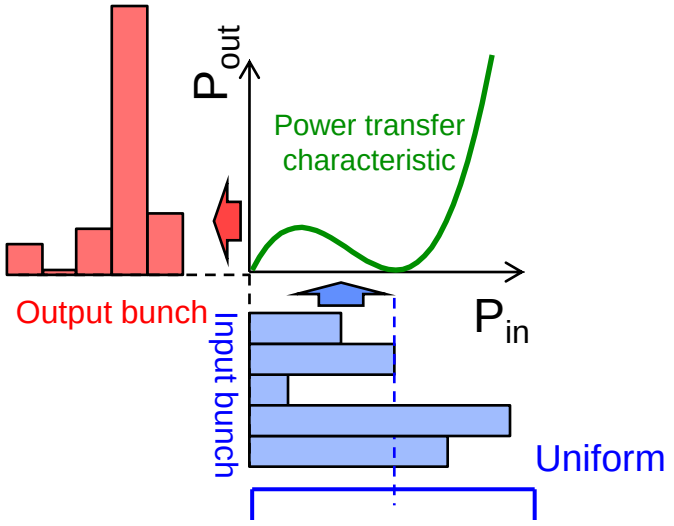
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Measurement of the statistics of a bunch of pulses using a NOLM





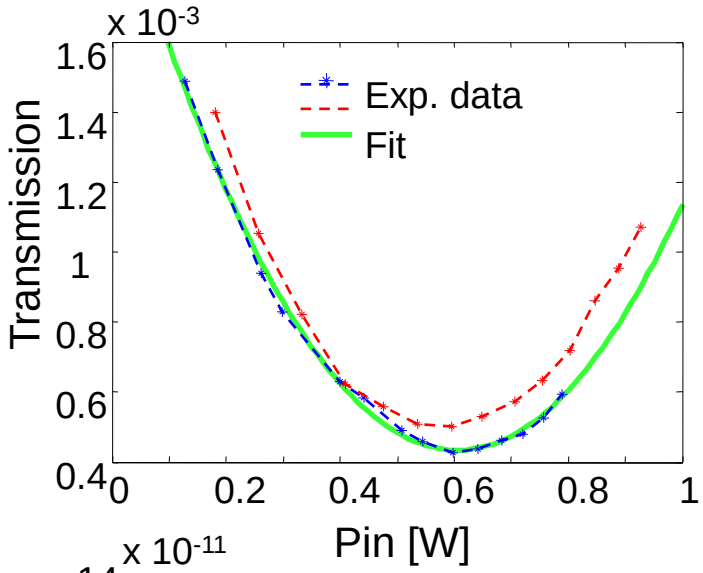


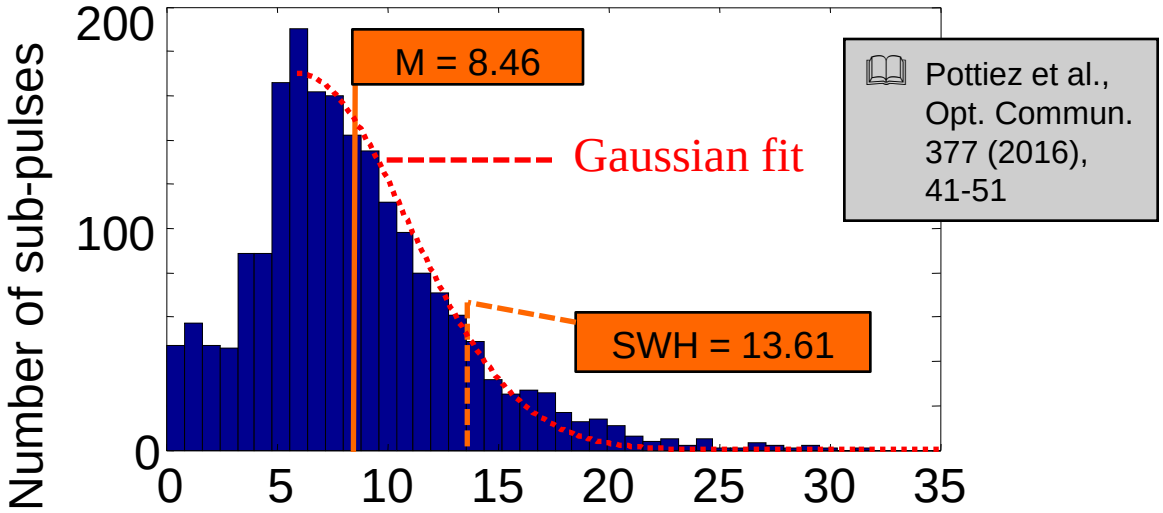


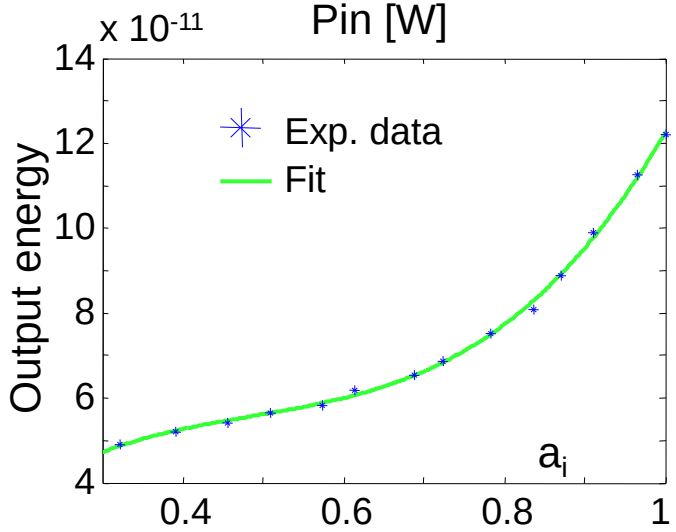
If the NOLM power transmission is known, output energy measurements allow reconstructing the statistics of a bunch of pulses

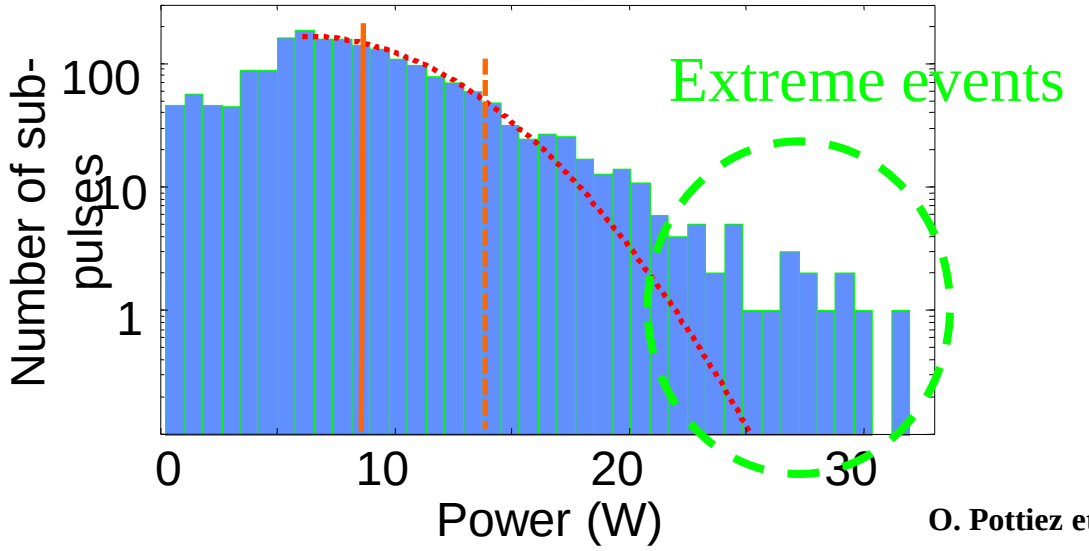
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The statistics of noiselike pulses was estimated



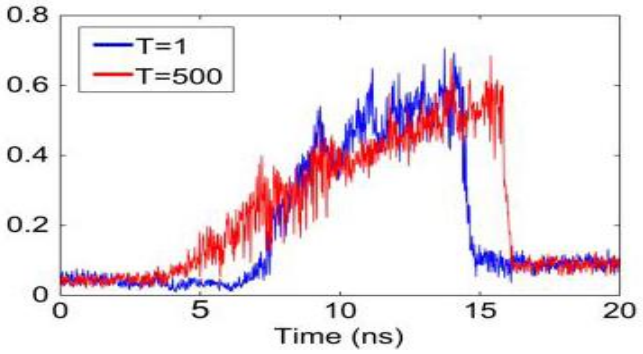


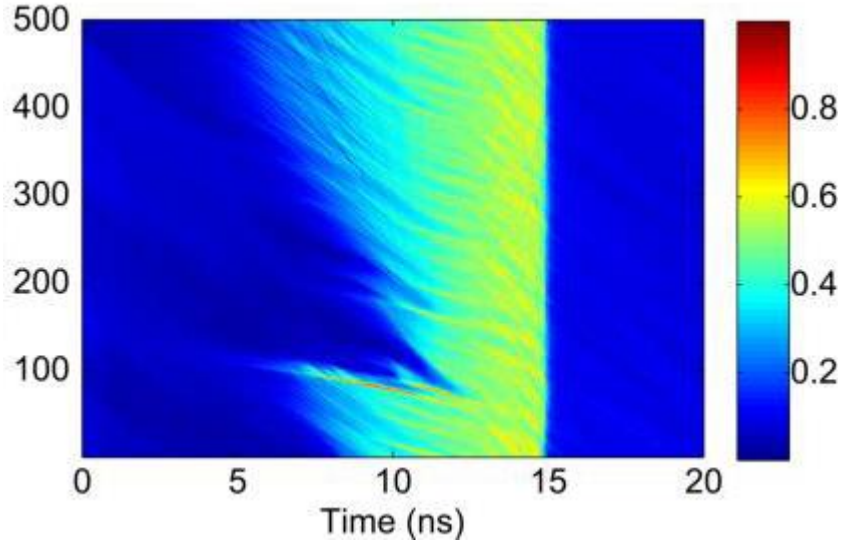


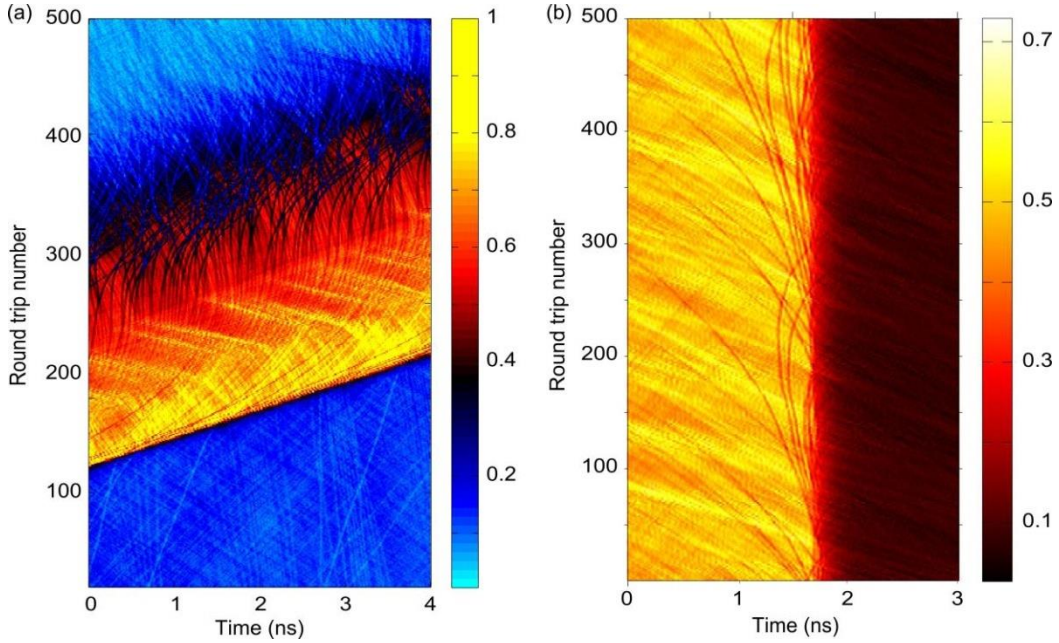


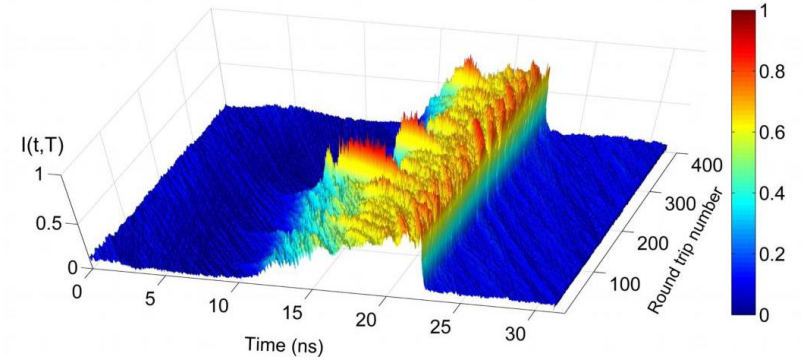
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Noise-like pulses: “noise” or deterministic?





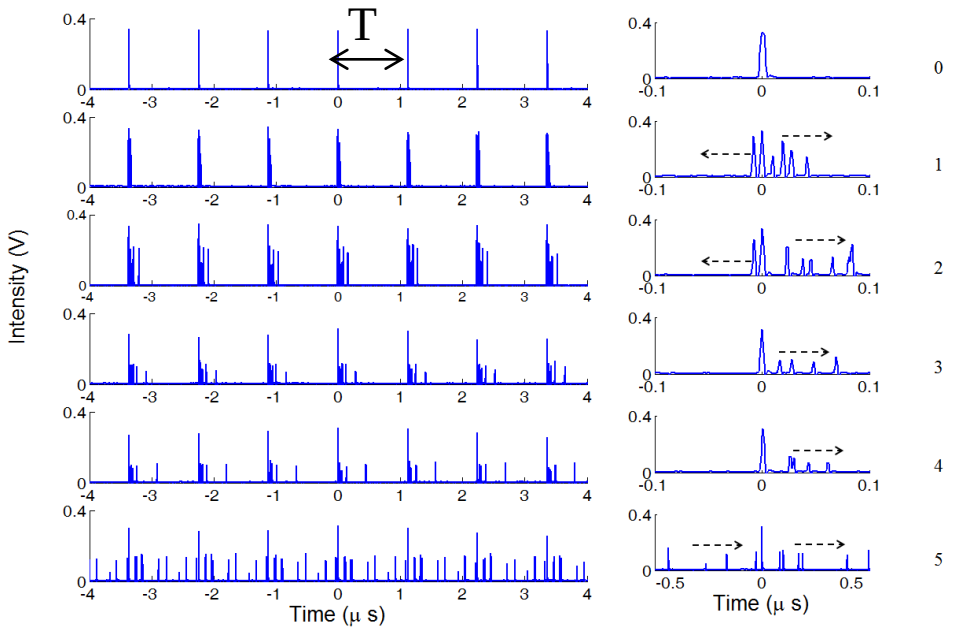


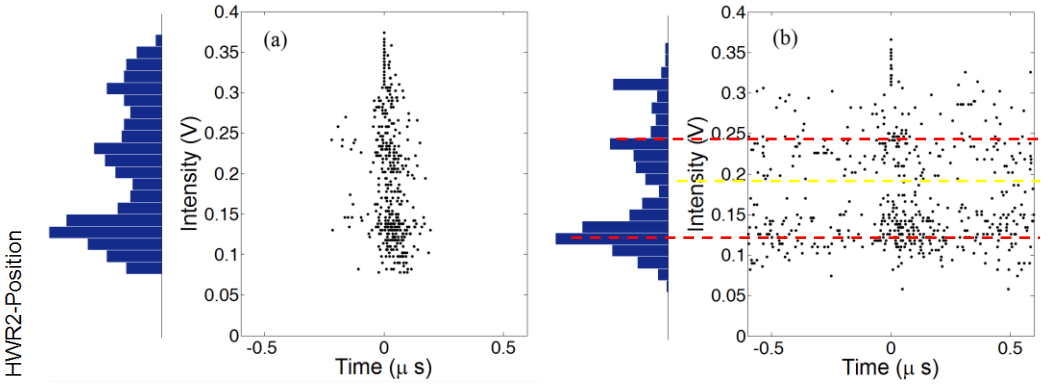


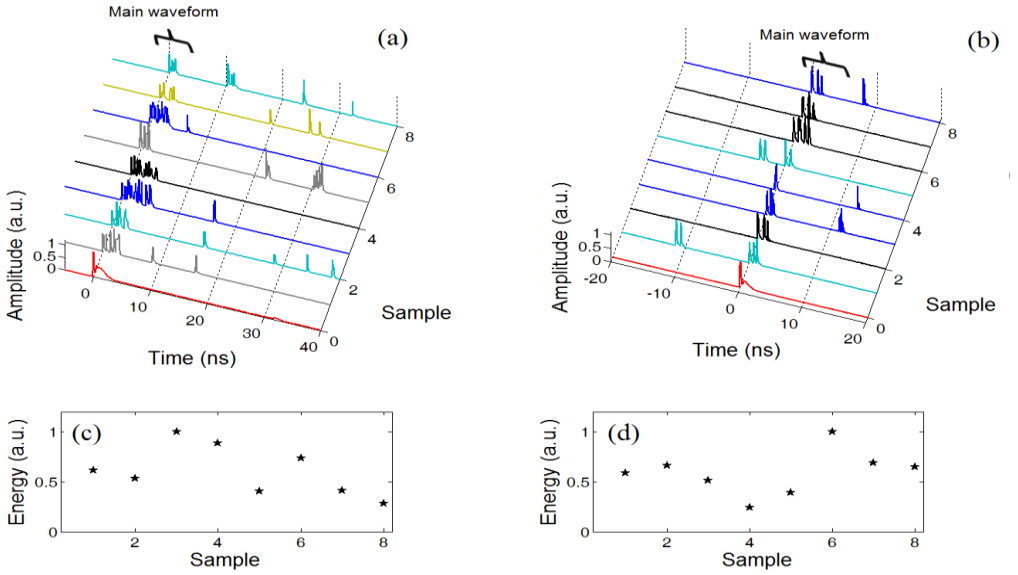
📖 Churkin et al, Nature Commun. 6 (2014), 7004

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An original dynamics at sub-ns scale has been evidenced







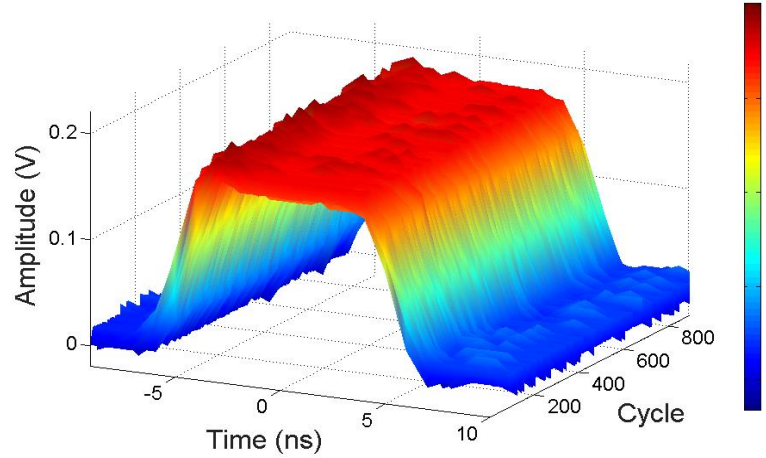
- ✓ Starting from stable fundamental ML, small WR adjustments initiate the dynamics
- ✓ **Sub-ns sub-pulses are released** from the main waveform and drift away from it, **decay and vanish**. Quasi-stationary regime.
- ✓ Their excursion increases and finally, they no longer decay, drift over an entire round-trip and are recaptured by the main waveform
- ✓ Sub-pulses are **units traveling alone or in pairs**
- ✓ **Analogy with** the **soliton rain/release of solitons** dynamics

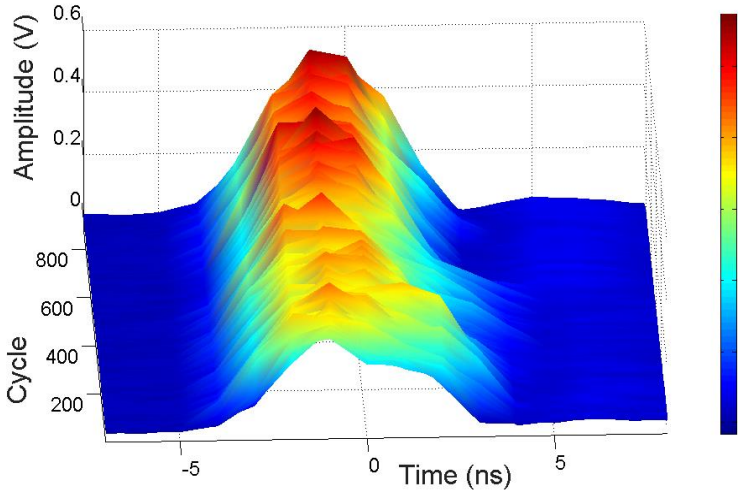
Santiago-Hernández et al., Opt. Express 23 (2015) 18840

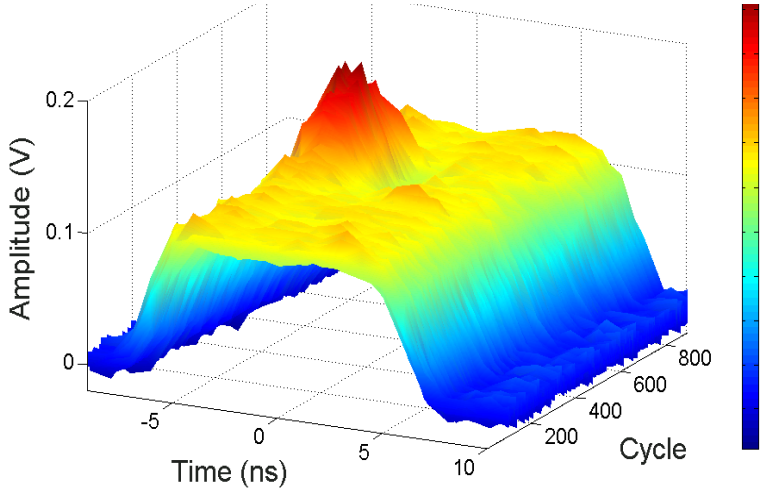
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Scope sequence measurement

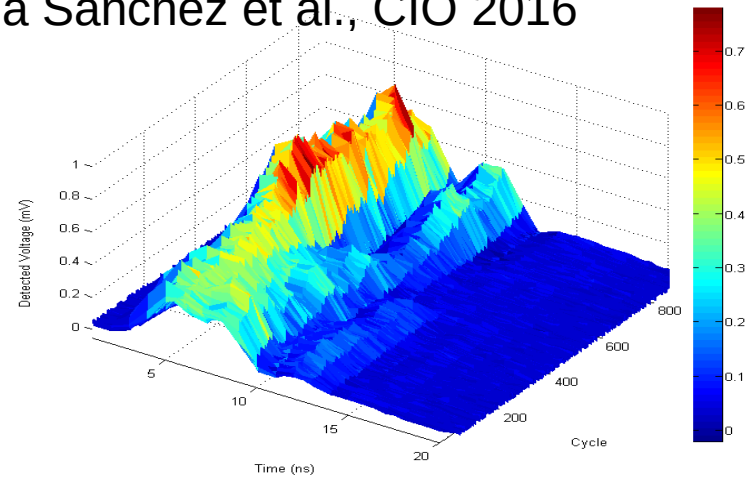
Sequences with 200-MHz scope (892 consecutice cycles)







Ernesto García Sánchez et al., CIO 2016

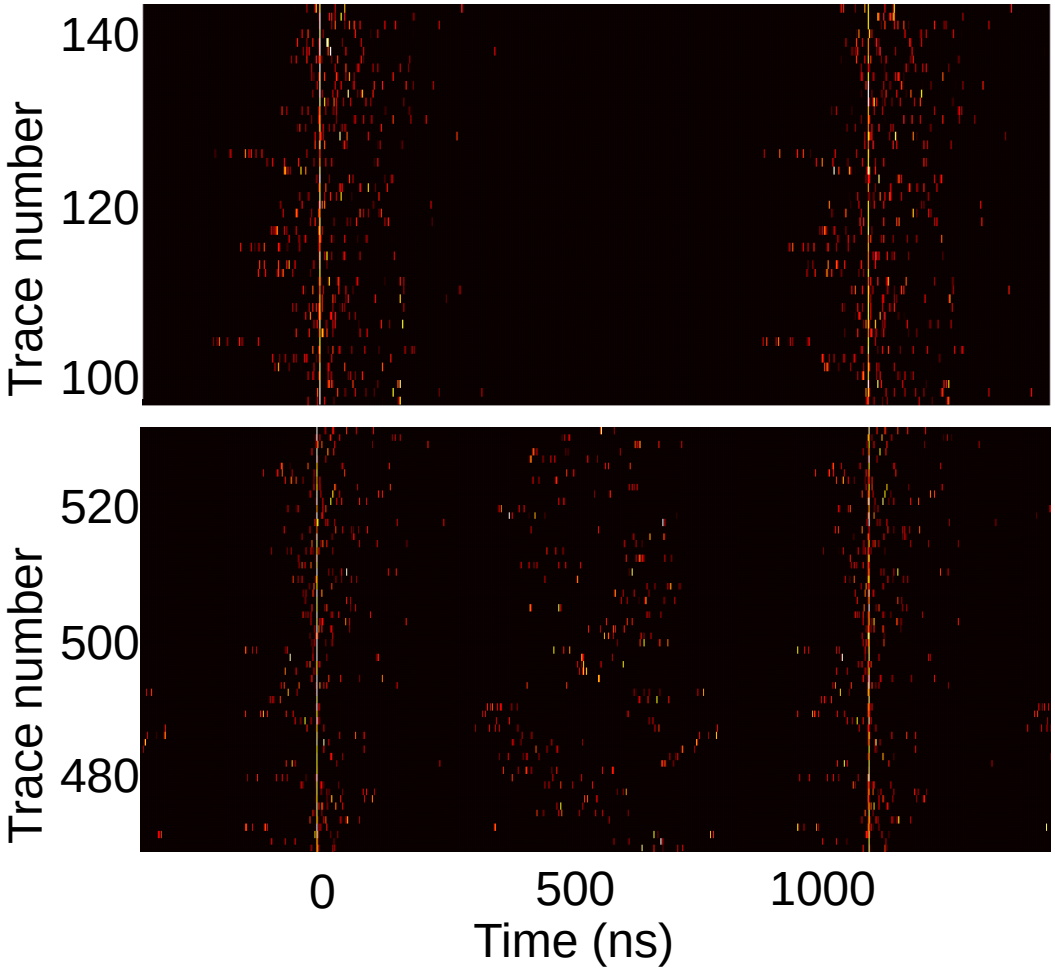


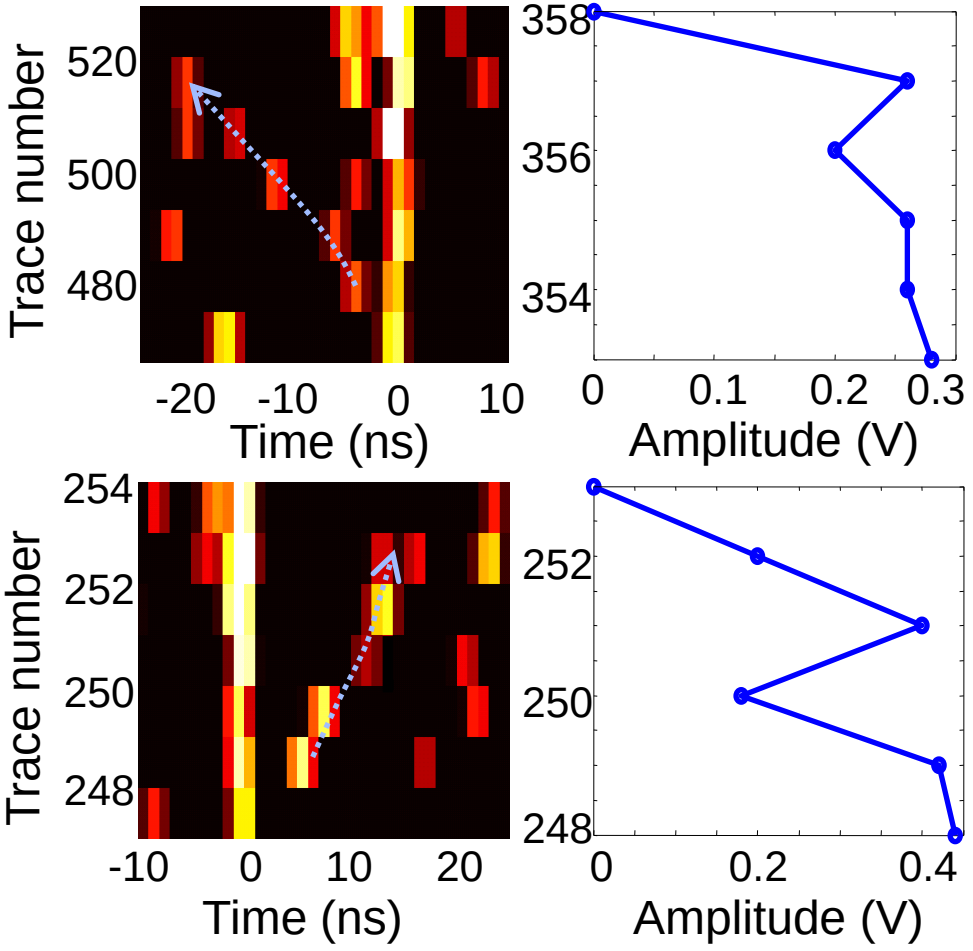
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Measuring sequences allows identifying peculiar dynamics

Measured with 200-MHz scope (every 230 ms)

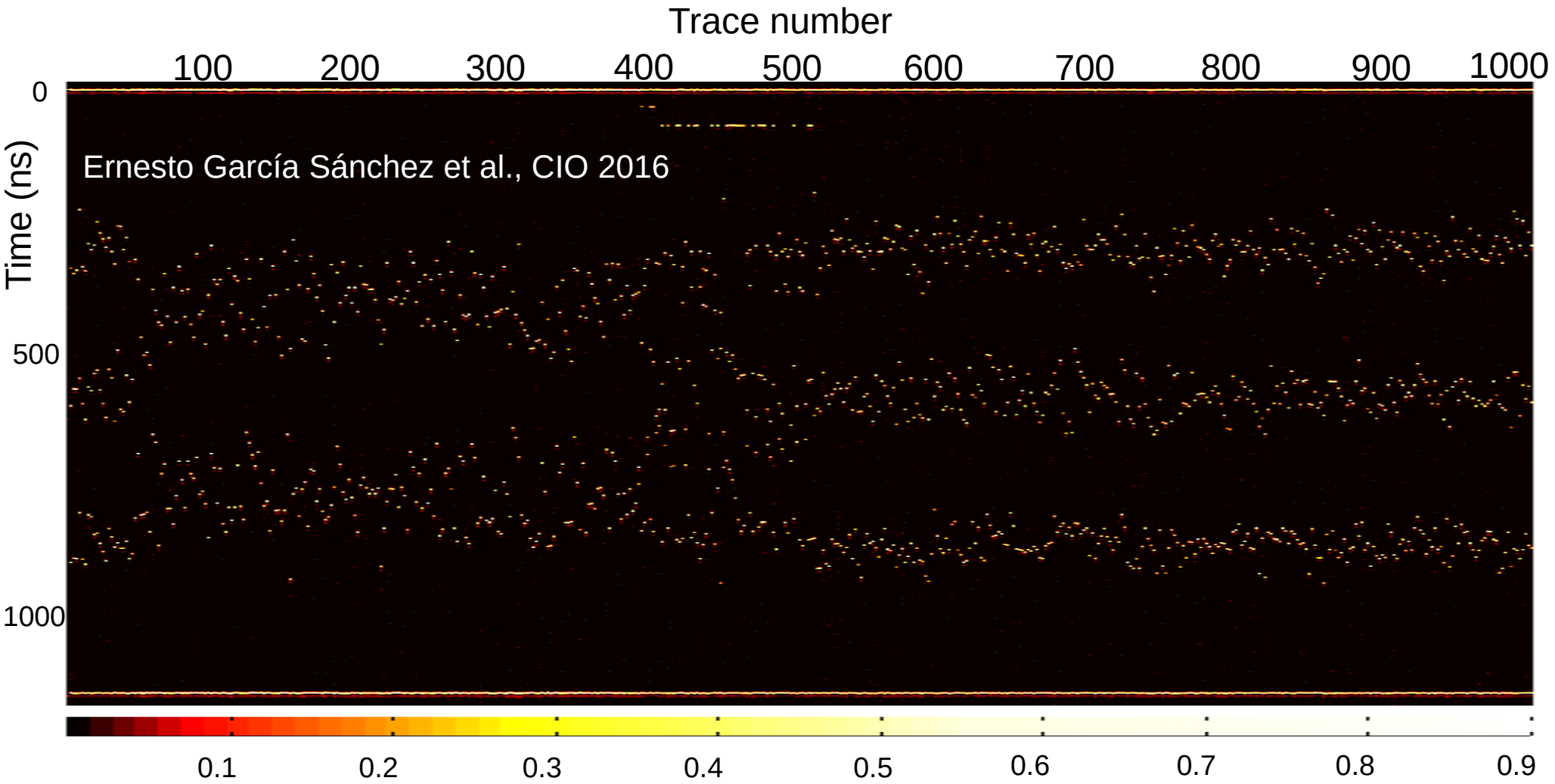
Ernesto García Sánchez et al., CIO 2016





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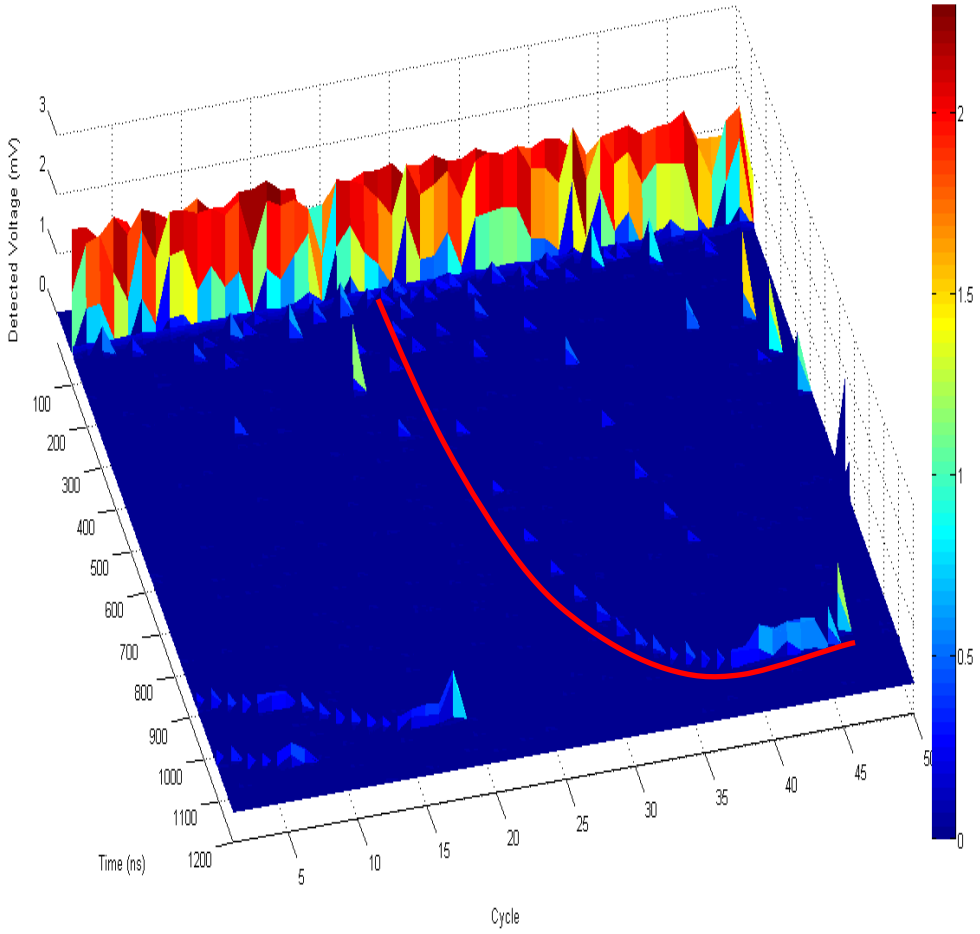
Measuring sequences allows identifying peculiar dynamics

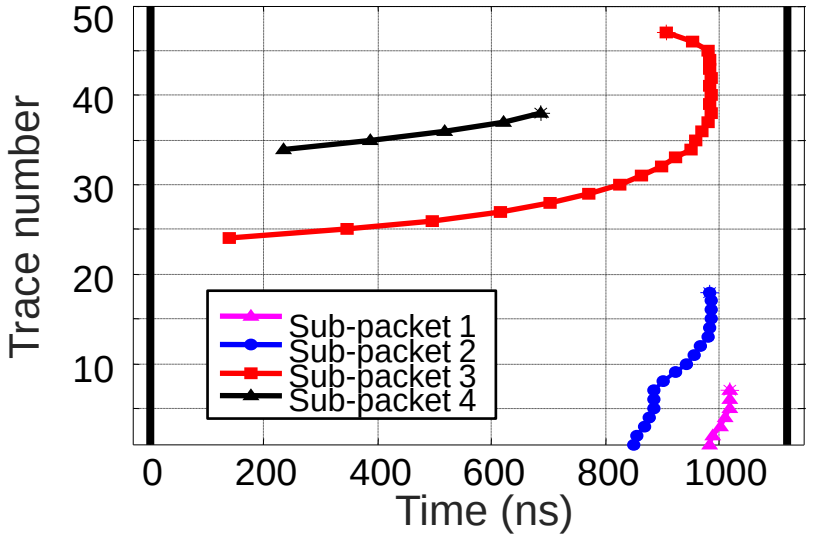


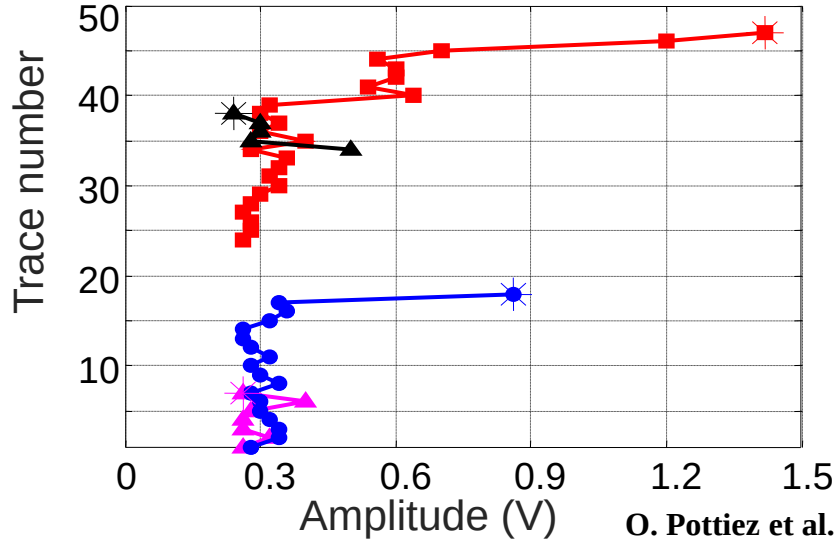
CENTRO DE INVESTIGACIONES EN OPTICA, A.C.

Measuring sequences allows identifying peculiar dynamics

Ernesto García Sánchez et al., CIO 2016

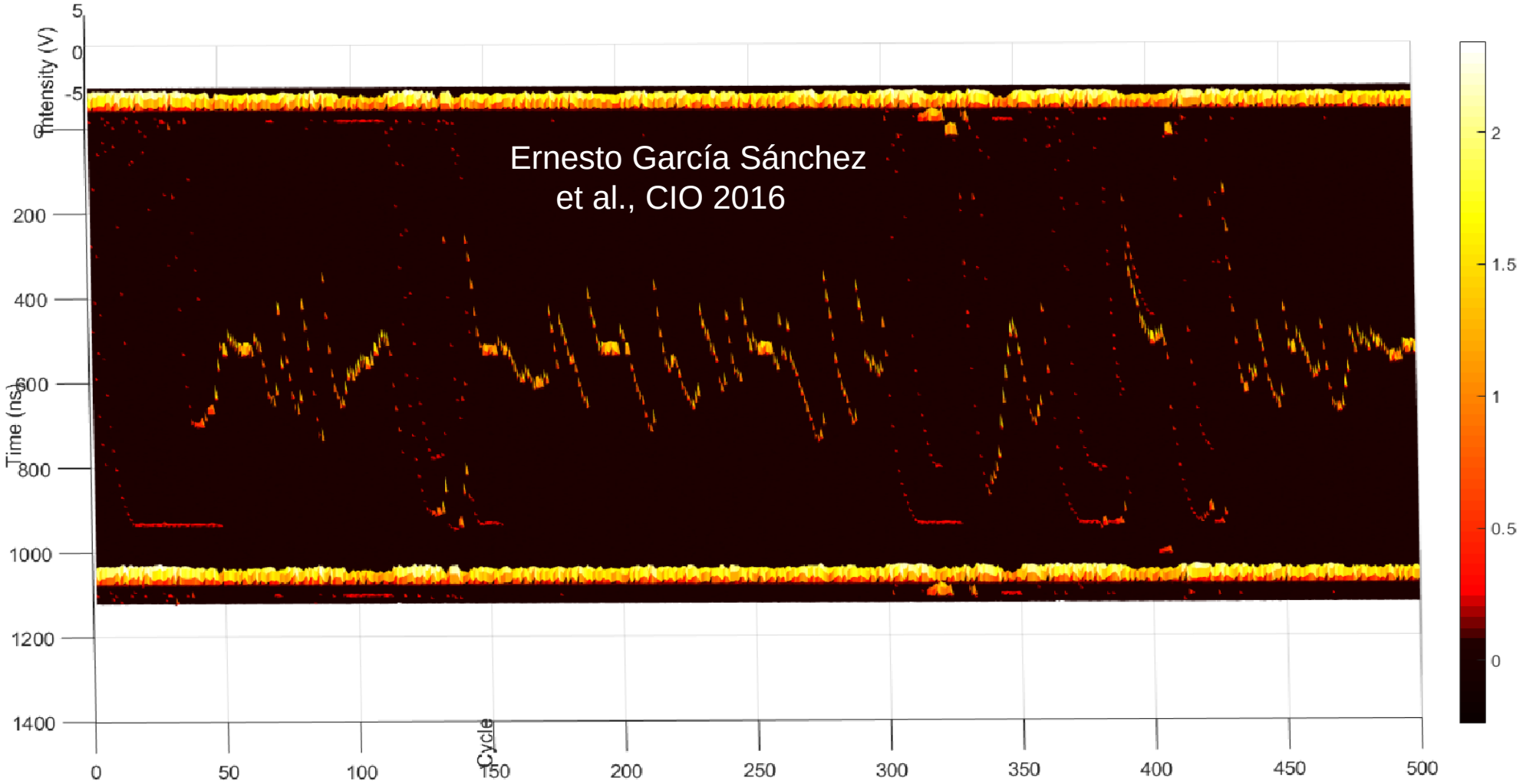






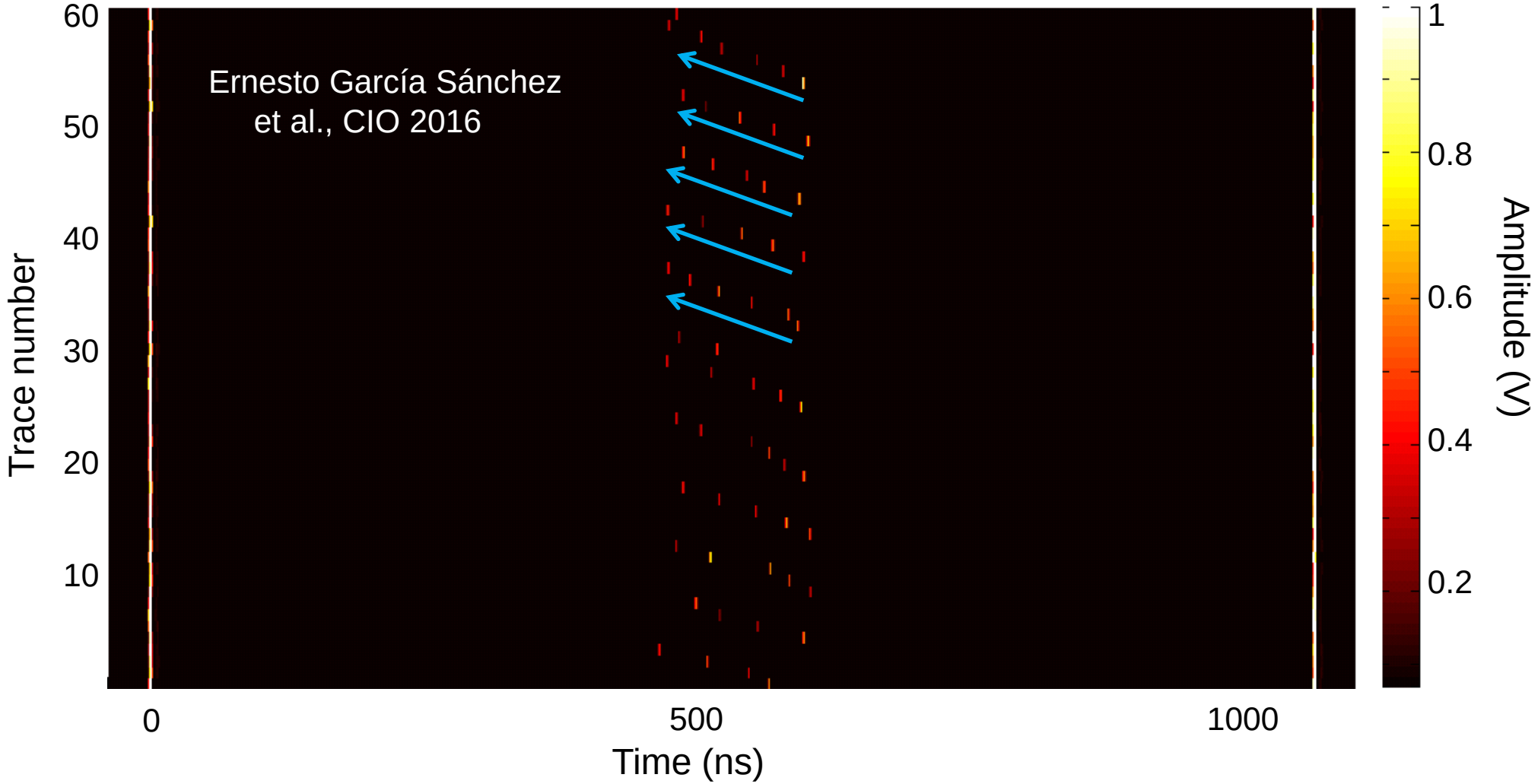
CENTRO DE INVESTIGACIONES EN OPTICA, A.C.

Measuring sequences allows identifying peculiar dynamics



CENTRO DE INVESTIGACIONES EN OPTICA, A.C.

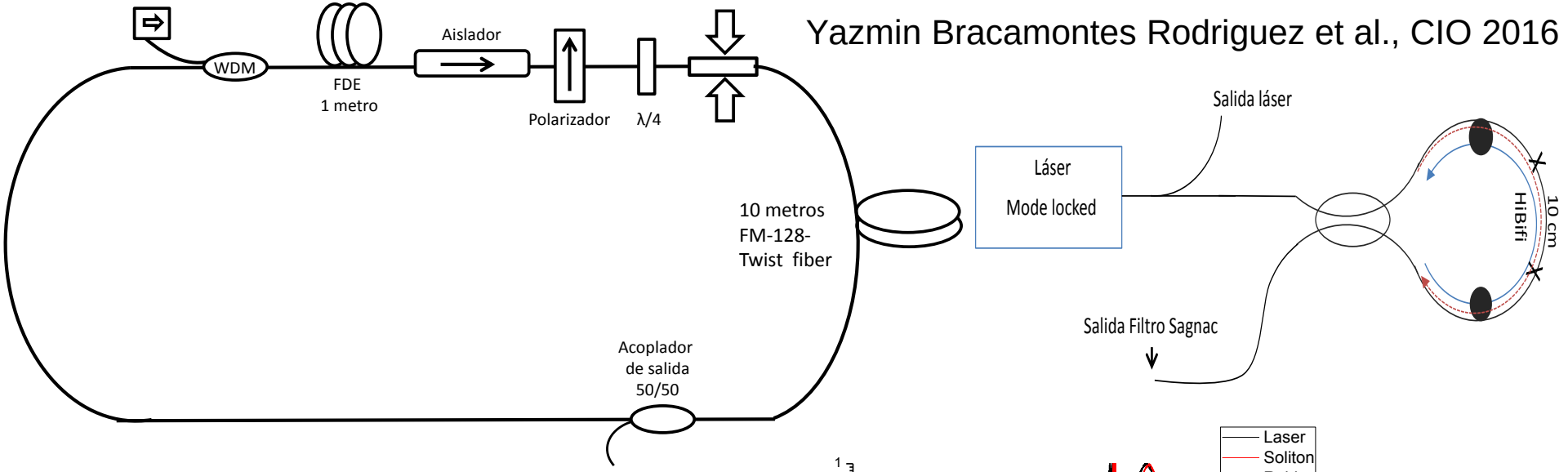
Measuring sequences allows identifying peculiar dynamics

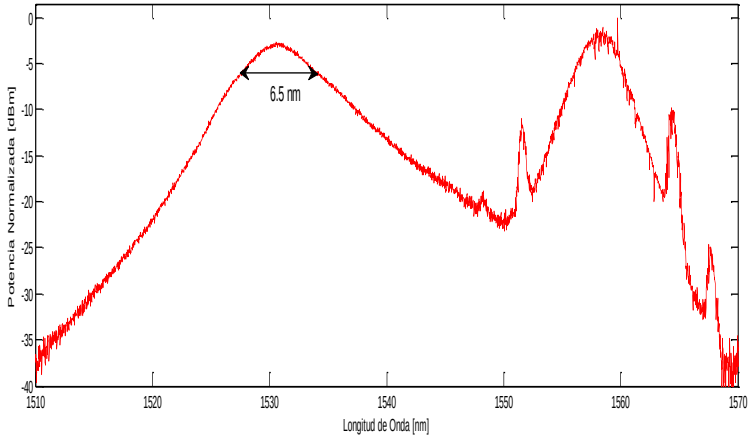


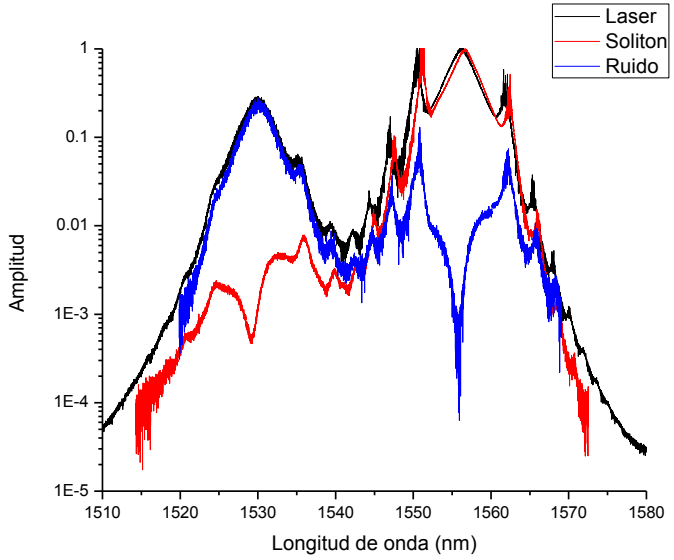
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Soliton-NLP fiber ring laser

Yazmin Bracamontes Rodriguez et al., CIO 2016

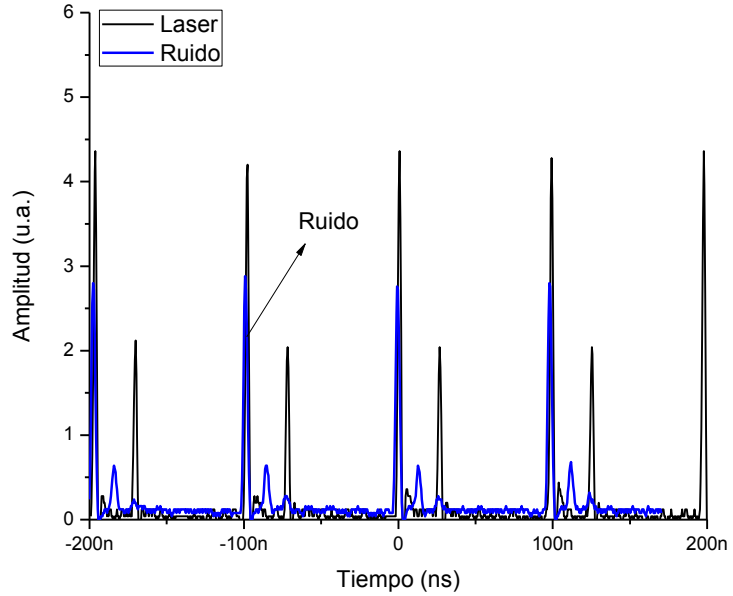


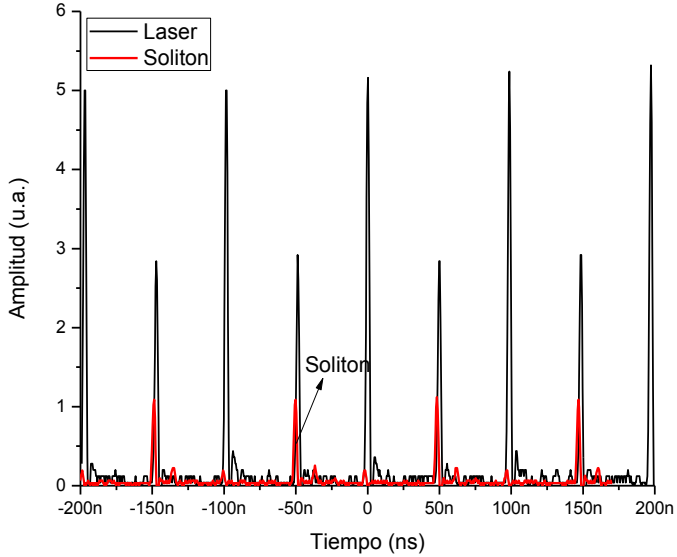


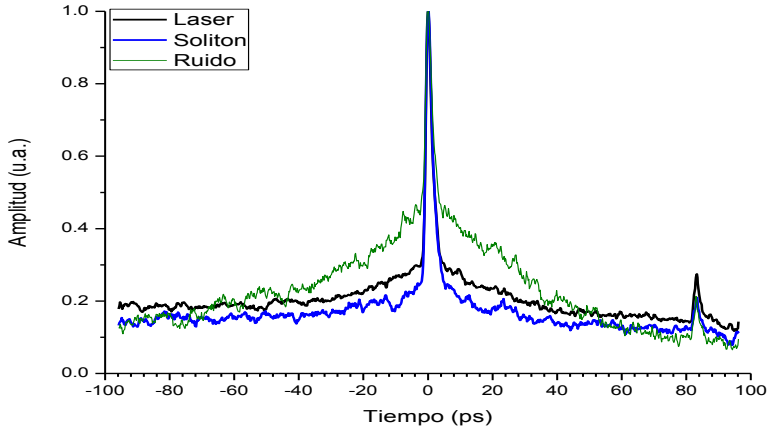


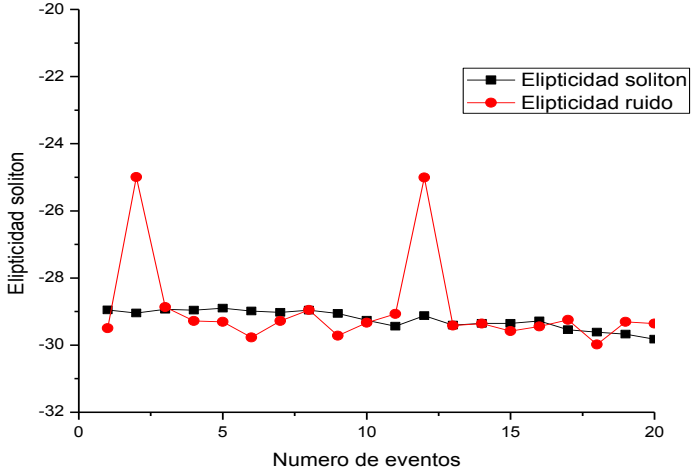
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Soliton-NLP fiber ring laser





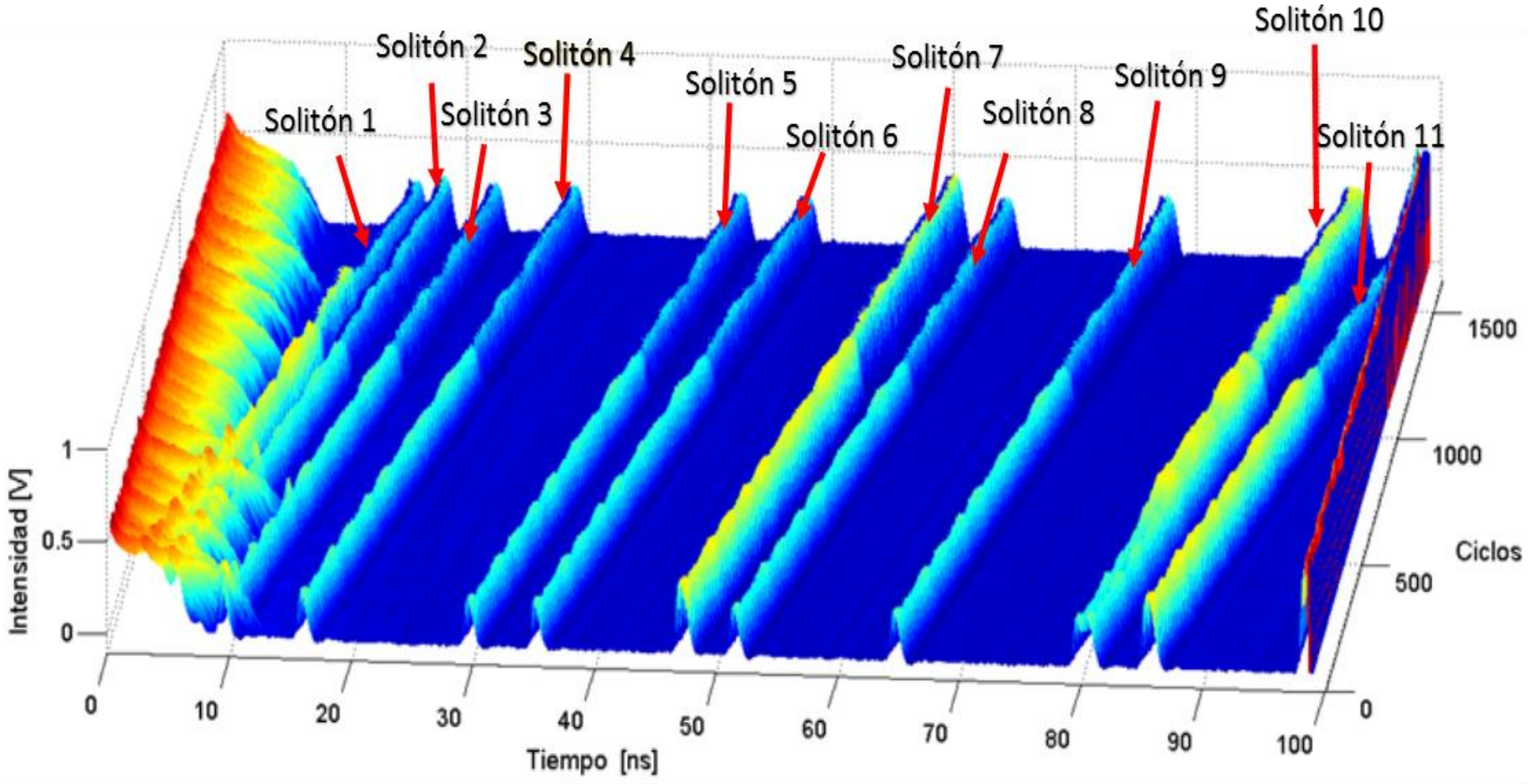




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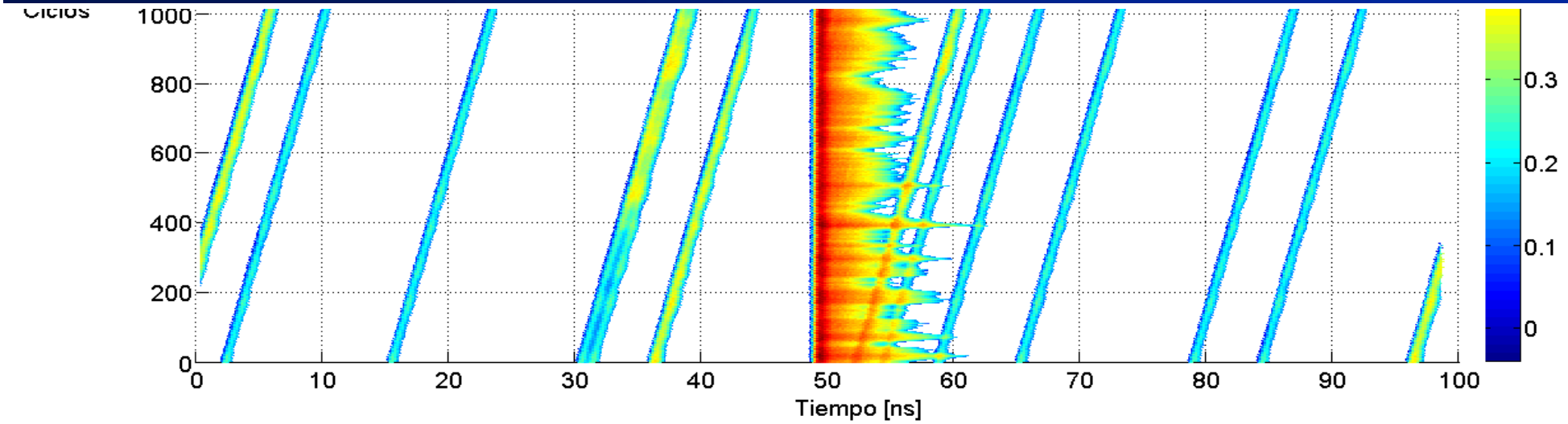
Soliton-NLP fiber ring laser

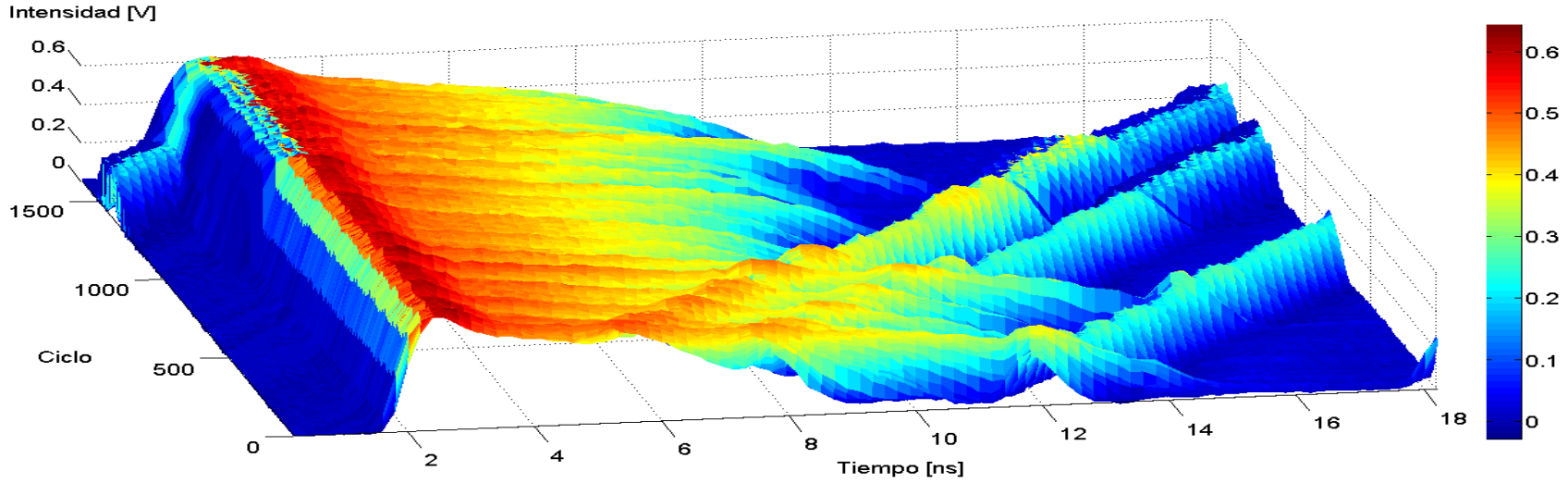
Yazmin Bracamontes Rodriguez, Hugo E. Ibarra Villalón et al., CIO 2016



CENTRO DE INVESTIGACIONES EN OPTICA, A.C.

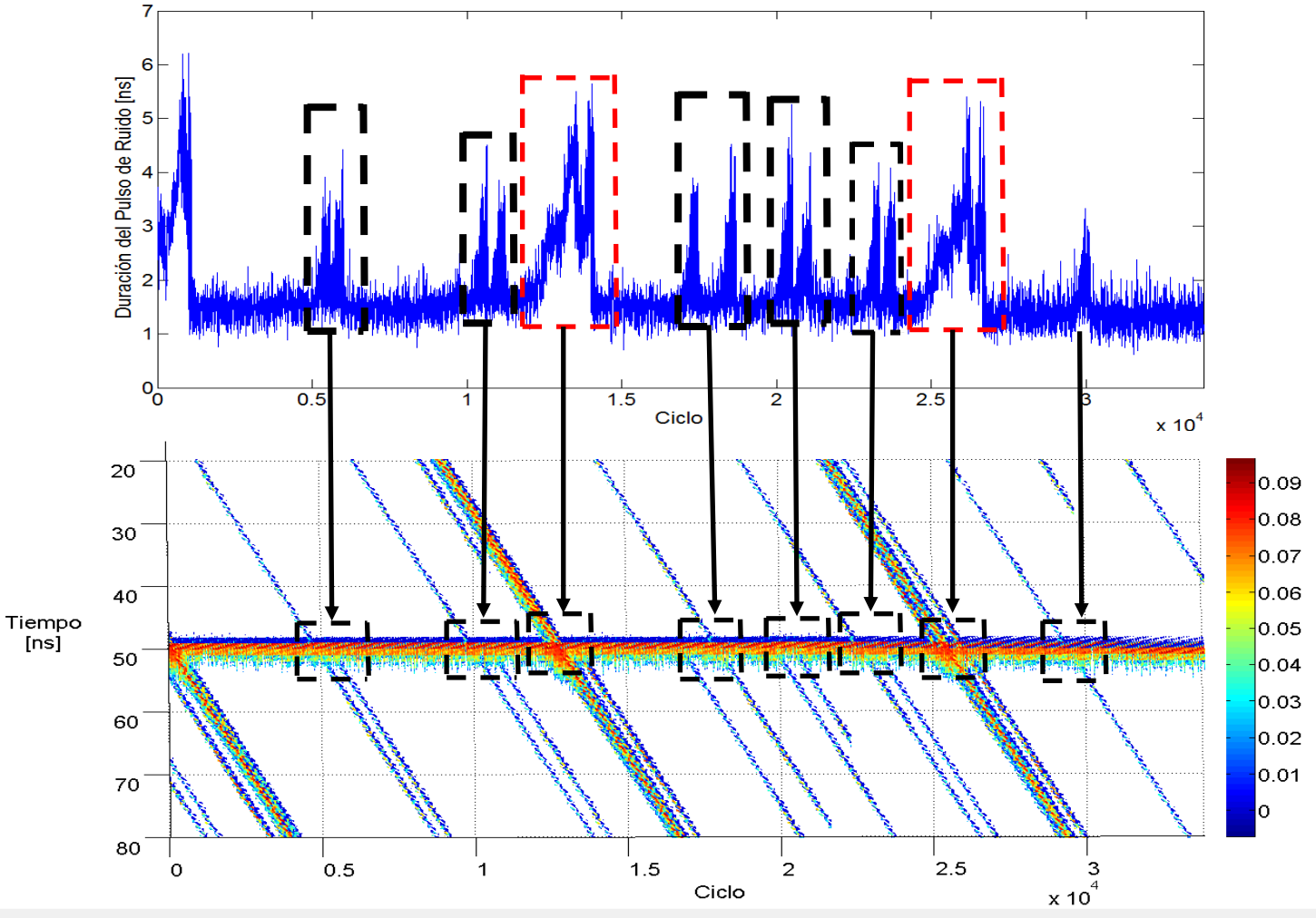
Soliton-NLP fiber ring laser





CENTRO DE INVESTIGACIONES EN OPTICA, A.C.

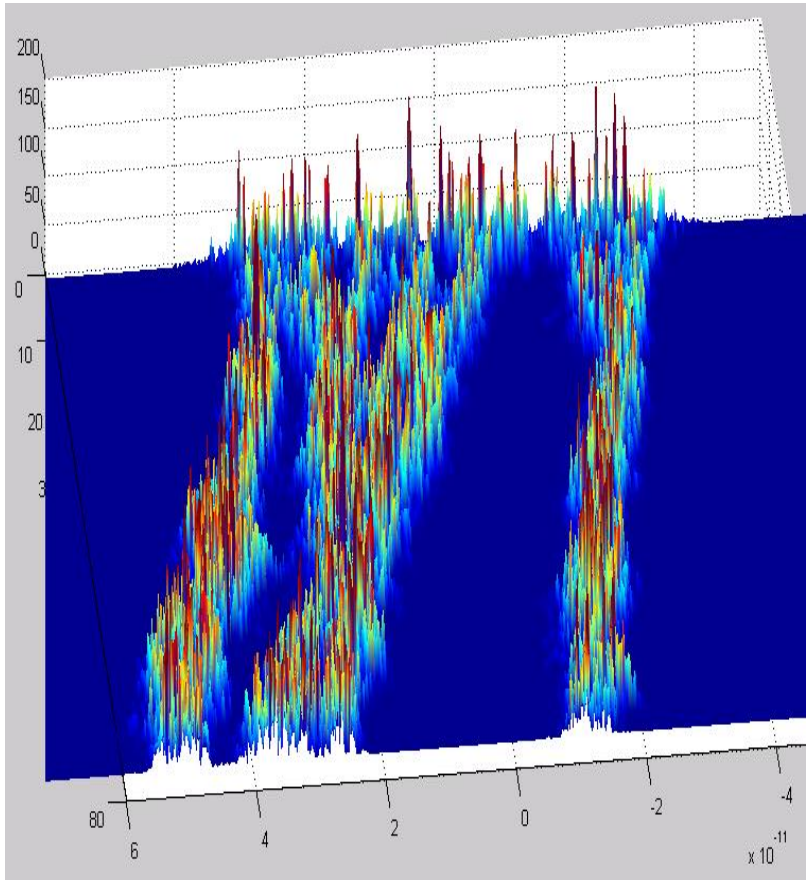
Soliton-NLP fiber ring laser



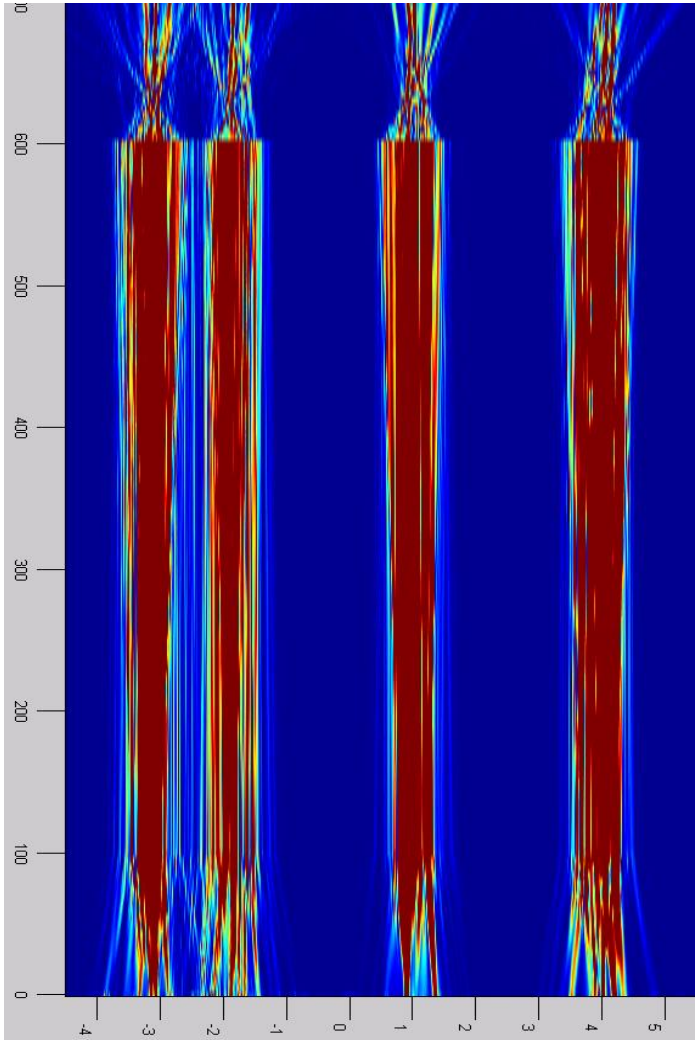
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Multiple pulsing behavior was reproduced numerically

Evolution of output bunch over successive cycles



Intrcavity evolution over 1 full cycle



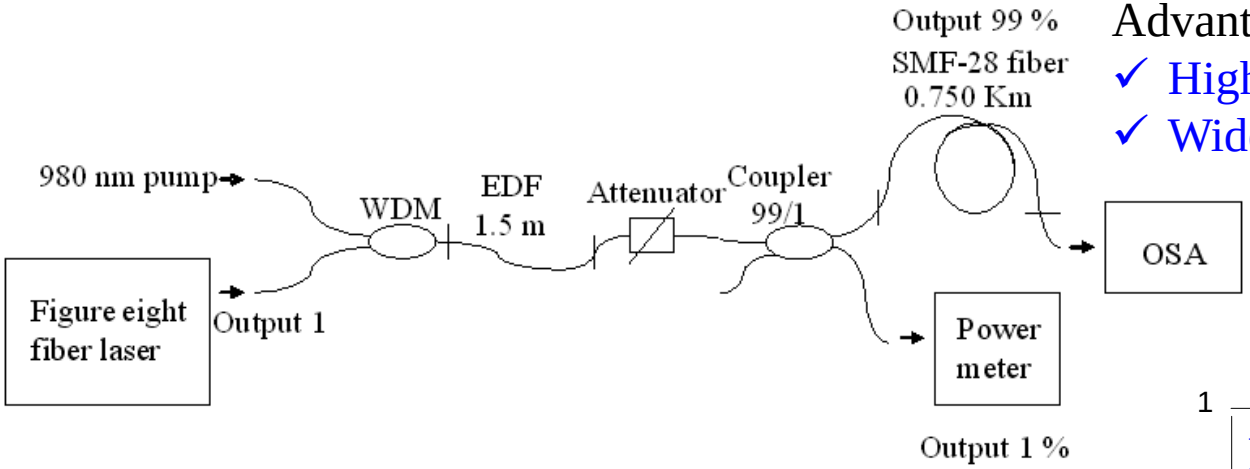
NOLM
D = 17 ps/nm/km

DCF
D = -3 ps/nm/km

Amplifier + filter
D = -70 ps/nm/km

CENTRO DE INVESTIGACIONES EN OPTICA, A.C.

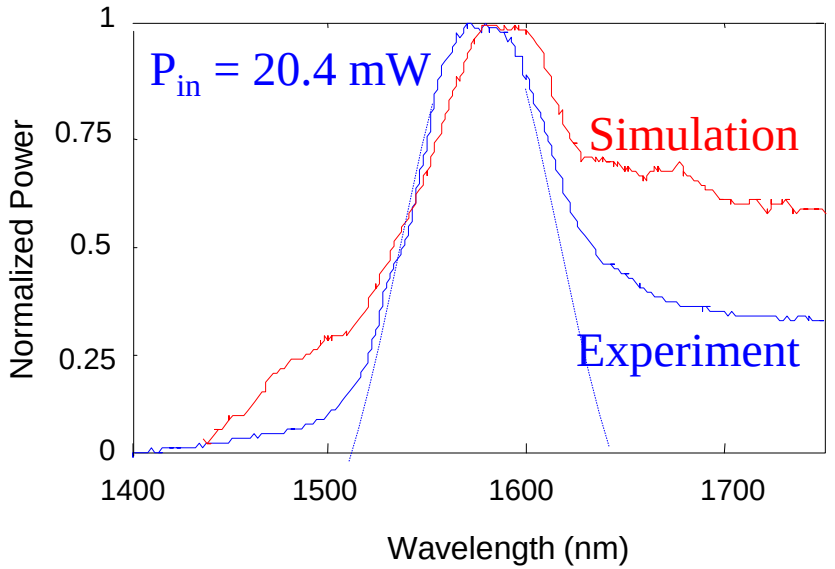
Noise-like pulses were used for supercontinuum generation in standard fiber



Advantages of noise-like pulses for SCG:

- ✓ High pulse energy
- ✓ Wide optical spectrum

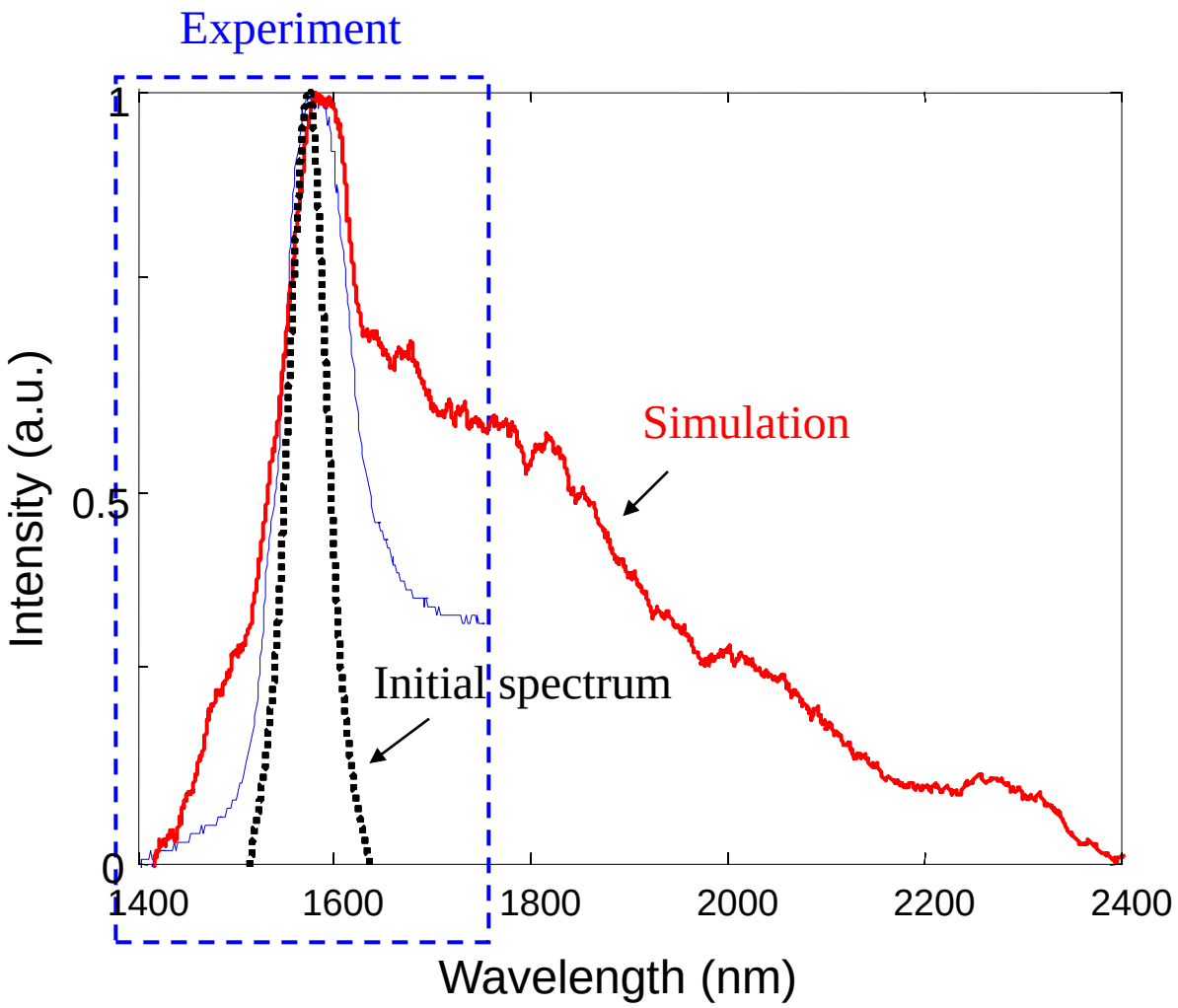
📖 Hernandez-Garcia et al., Laser Phys. 22 (2012), 221-227



- ✓ The spectrum widens towards longer wavelength due to Raman self-frequency shift (SFS)
- ✓ Random amplitudes of sub-pulses generate a relatively flat spectrum

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Numerical simulations predict further widening to the right

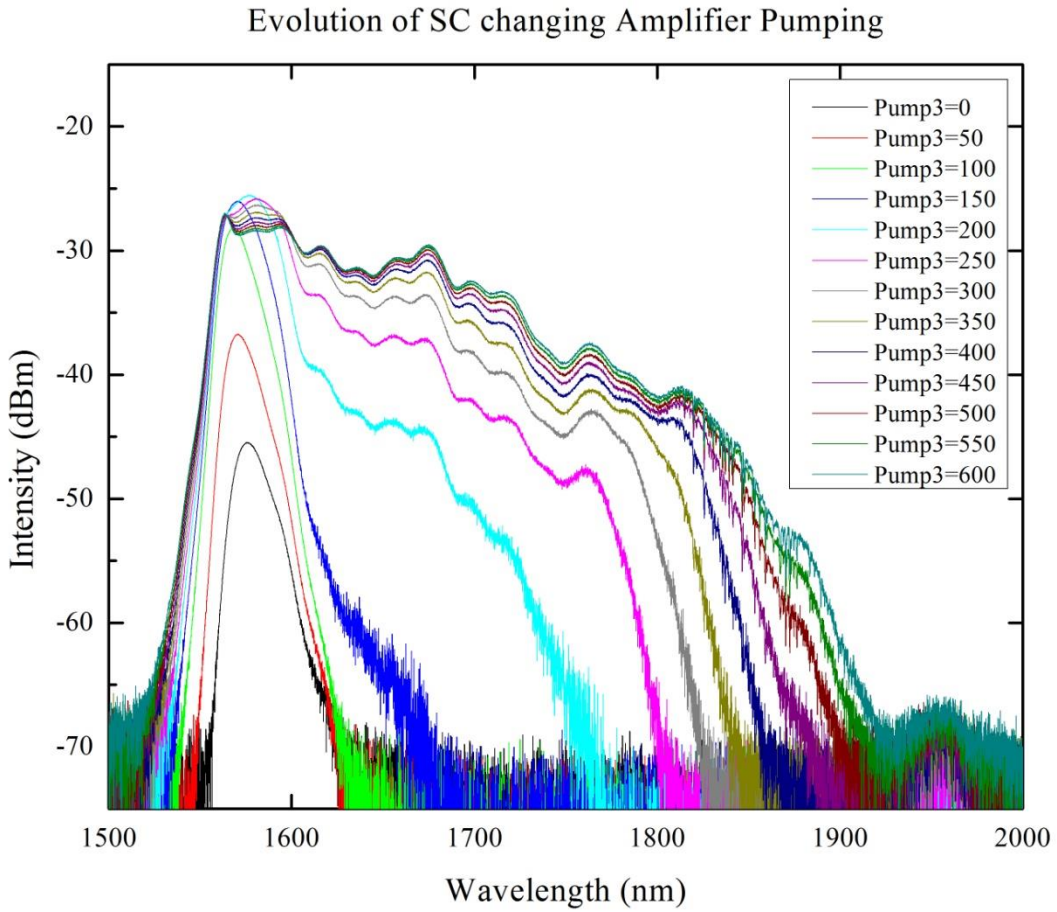


~70% of the total pulse energy moved towards other wavelengths

📖 Hernandez-Garcia et al., Opt. Comm. 285 (2012) 1915-1919

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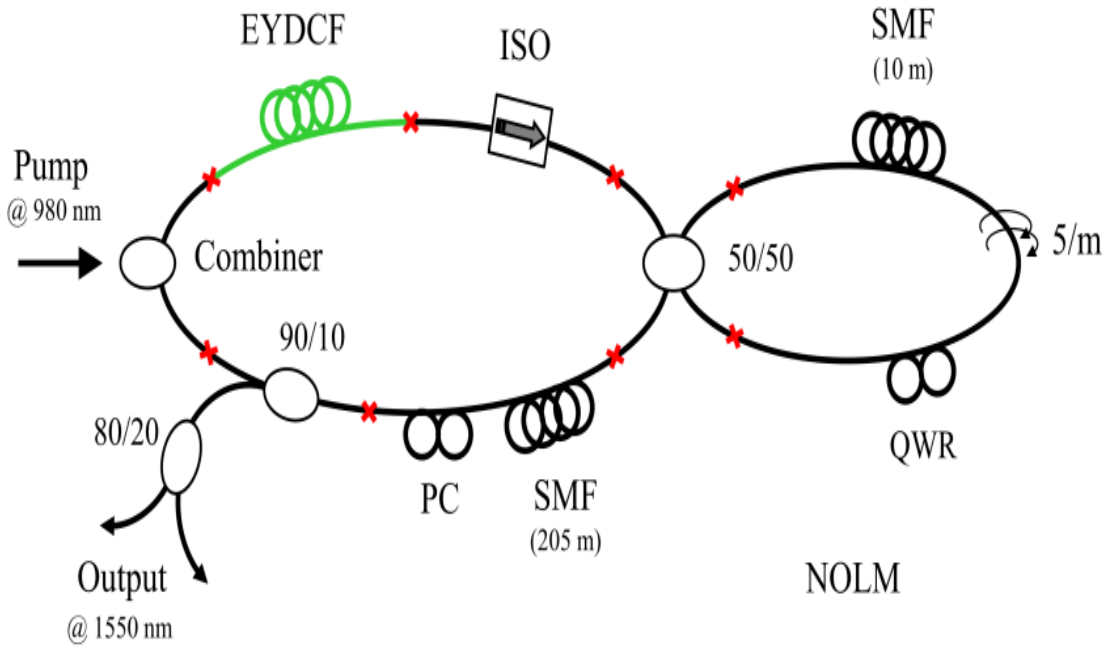
Recent results



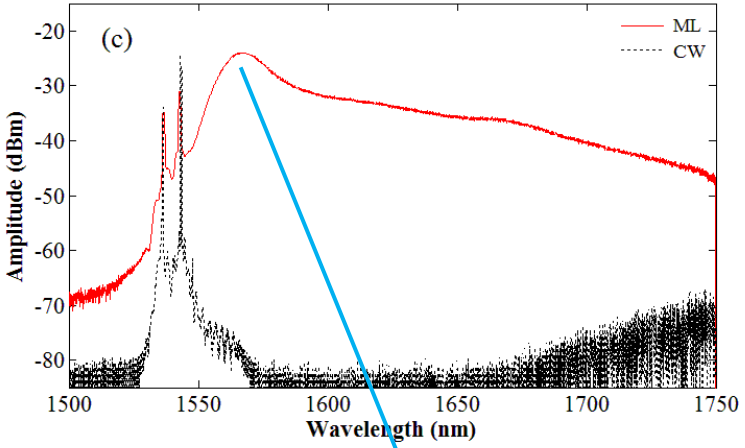
Pablo Lauterio et al., CIO 2016

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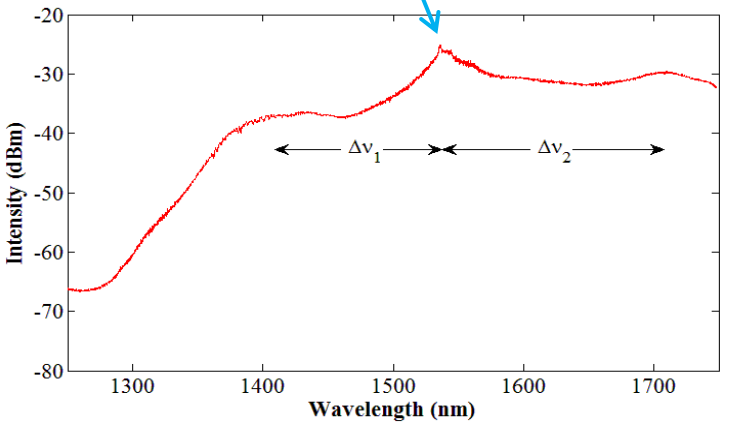
NLP-SC laser



Spectrum at laser output



After 100-m HNLF

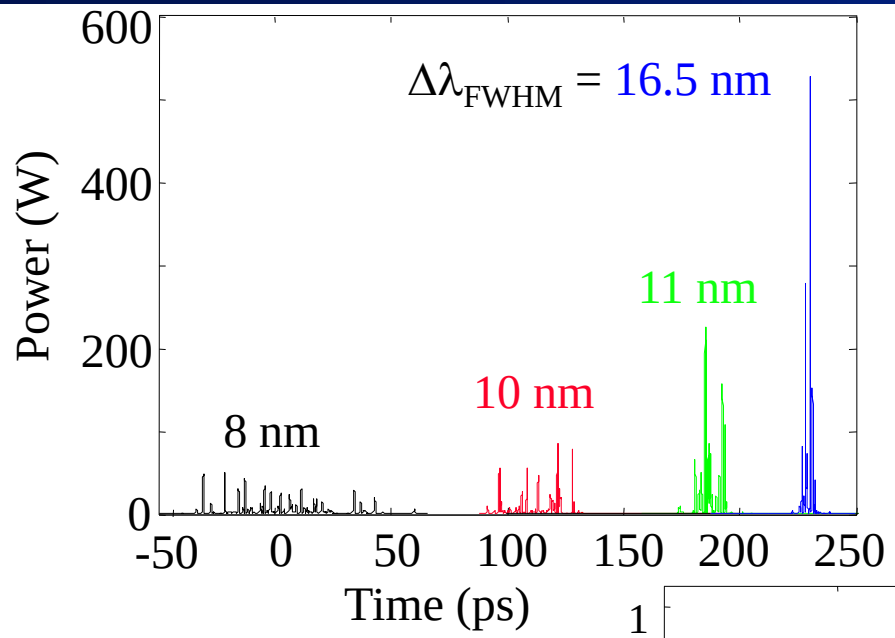


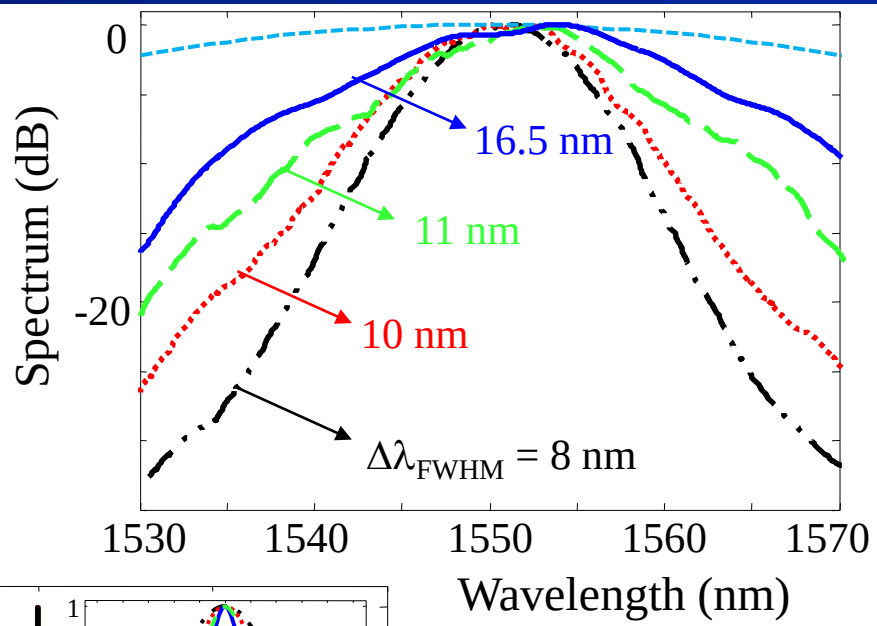
No pulse breaking, NLP energies up to 300 nJ, wide and flat optical spectrum

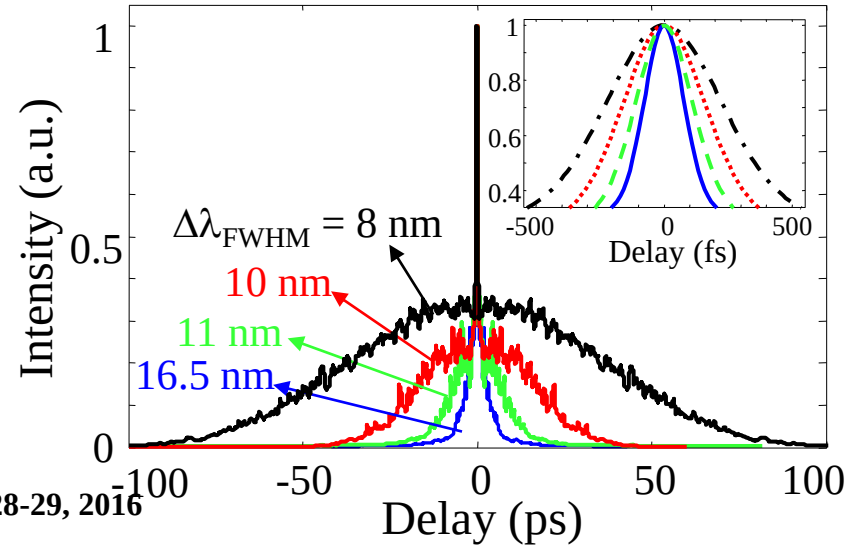
📖 Lauterio-Cruz et al., Opt. Express 285 (2016) 13778-13787

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Adjustability is observed numerically



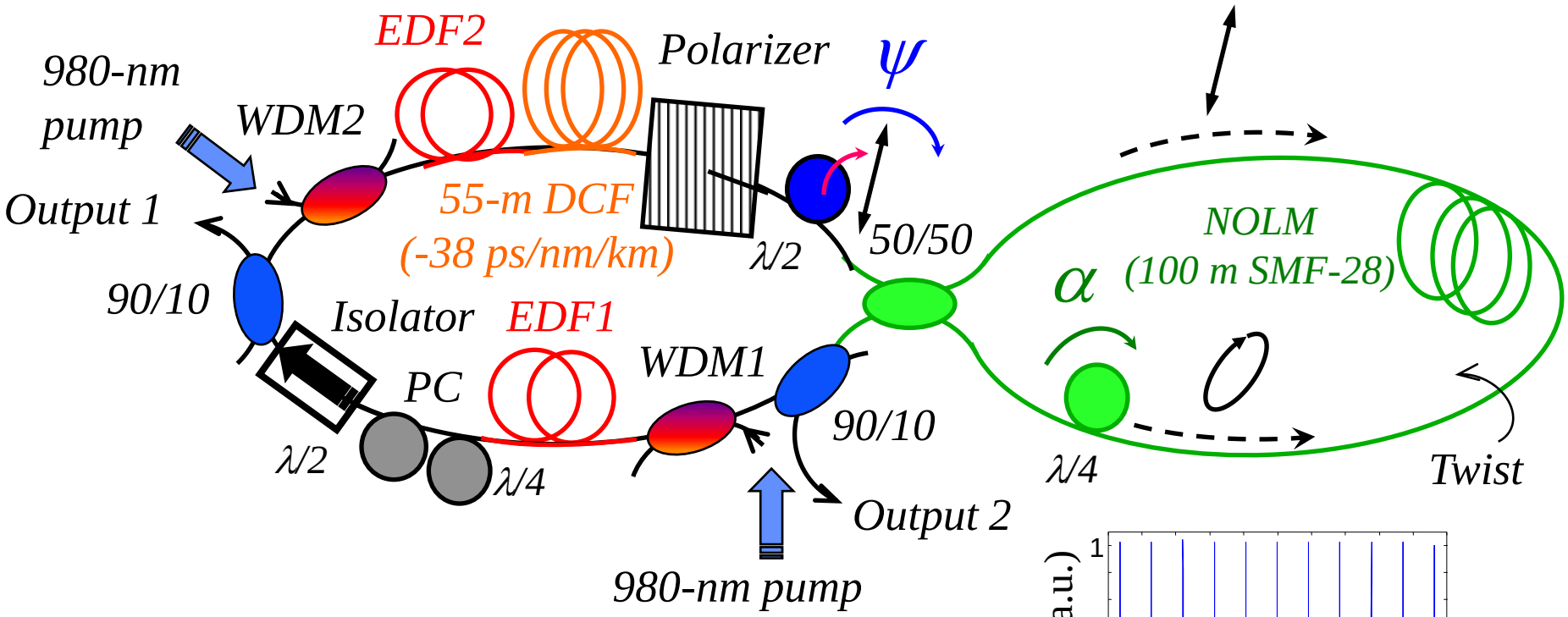




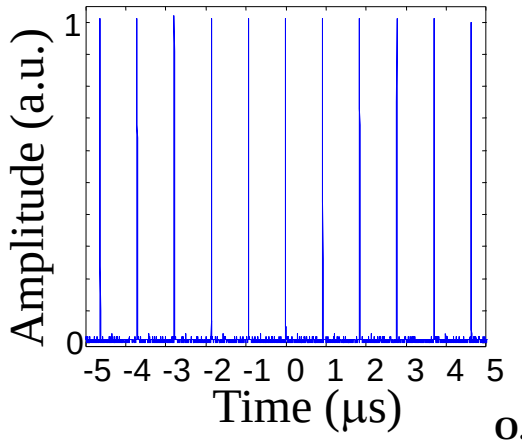
Pottiez et al., Appl. Opt. 50 (2011), E24-E31

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Figure-eight laser with dispersion compensation



- ✓ L = 200 m
- ✓ Dispersion close to 0

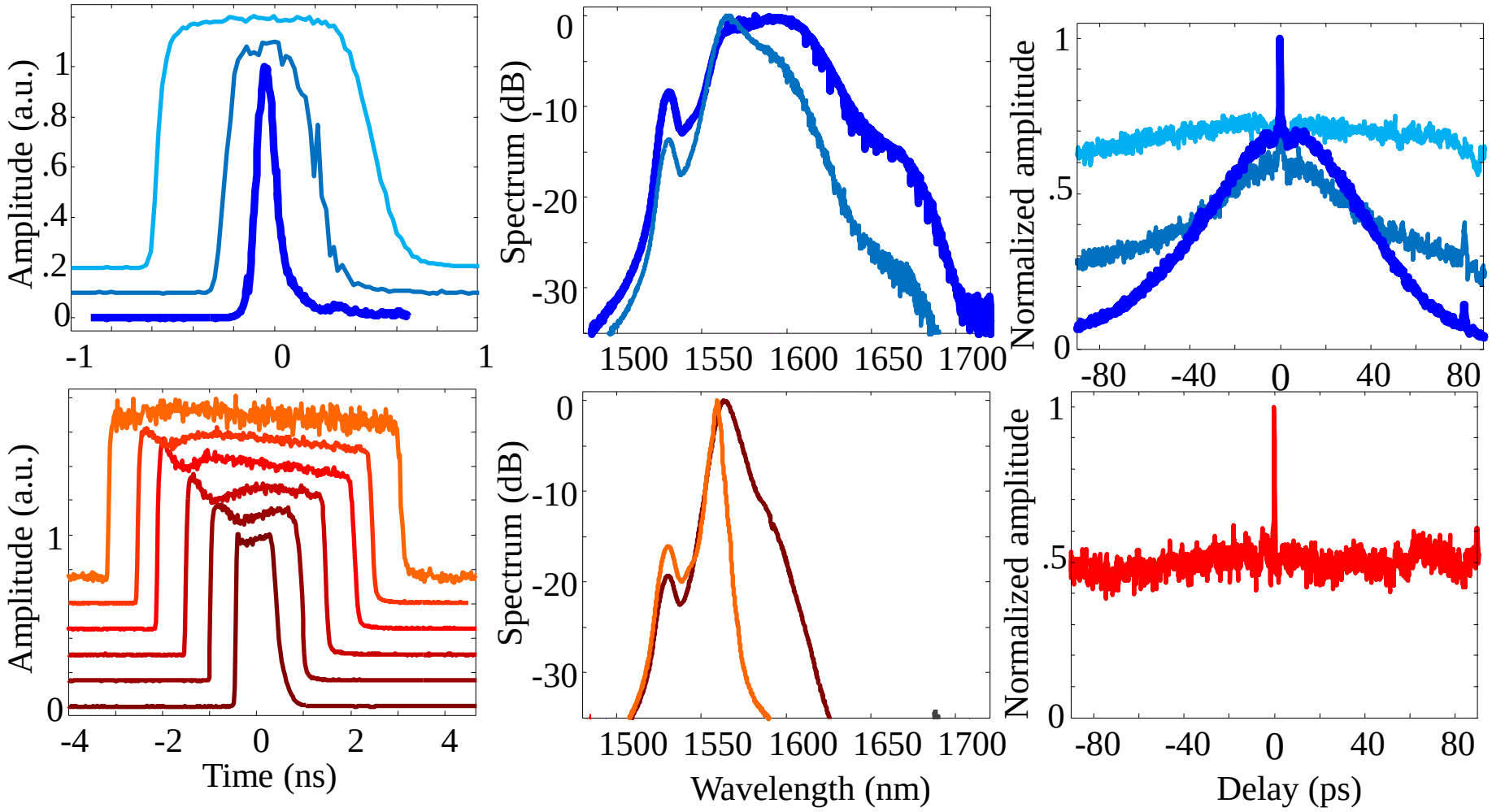


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Pulses with adjustable duration (60 ps – 6 ns) and spectrum (3 – 60 nm)

Short-pulse regime

Long-pulse regime



Two regimes of noiselike pulsing

Pottiez et al., Laser Phys. 24 (2014), 105104

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Controlling pulse duration is essential for applications

Case of micromachining (Ti):

📖 Özgörenet al., Opt. Express. 24 (2011), 17647

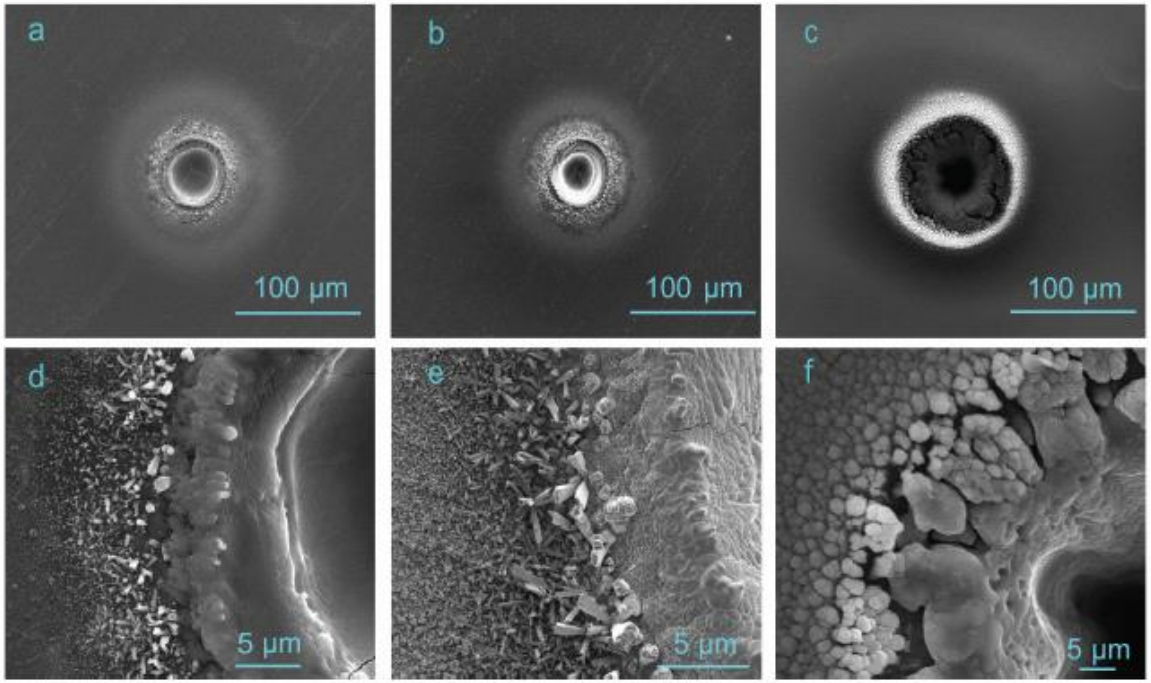


Fig. 4. Wells on the polished Ti surface drilled by (a) 115 ps, (b) 1 ns and (c) 100 ns pulses in comparison. (d,e,f) show corresponding close-up scanning electron microscope (SEM) images.

Range of pulse duration between those of conventional mode-locked lasers (solitons, ~ ps) and Q-switched lasers (~ µs)

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Summary

- ✓ We studied **noiselike pulse** formation in different **fiber laser architectures**.
- ✓ **Pulse energies as high as 0.3 μJ** have been obtained experimentally.
- ✓ Wide and smooth **spectral bandwidths beyond 100 nm** have been reached at the laser output, readily extendable by further propagation through different kinds of fiber. **Flat supercontinuum spectra up to 400 nm** have been obtained, which illustrates the potential of these sources for many applications.
- ✓ By simple WR tuning, it is possible to **adjust** the noiselike **pulse duration by a factor of 100** (60 ps – 6 ns) **and** its **spectral bandwidth 20-fold** (3 nm – 60 nm). Such adjustment possibility is crucial for applications like materials processing.
- ✓ Although single noiselike pulsing is most common, **pulse splitting** occurs in some conditions and **multiple pulsing** is observed, in particular in the form of **harmonic mode locking**. Harmonic orders beyond 1200 have been evidenced.
- ✓ **Information on the inner structure** of the noiselike pulses has been extracted **using** the ultrafast response of a **NOLM transmission**. In particular, the existence of an **intermediate degree of organization at the sub-ns** scale has been evidenced for a specific variety of pulses. Besides, the **statistics of the sub-pulses** has been measured, indicating the existence of **optical rogue waves** in the inner structure of the bunch.
- ✓ The study of noiselike pulse dynamics is also progressing thanks to **sequence analysis** in the time domain. In particular, an **original dynamics**, in which sub-ns sub-pulses are released from the main waveform and drift away from it, has been evidenced, which bears some analogy with the soliton rain/release of solitons.