Generation of noise-like pulses from a fiber laser and their application to supercontinuum generation

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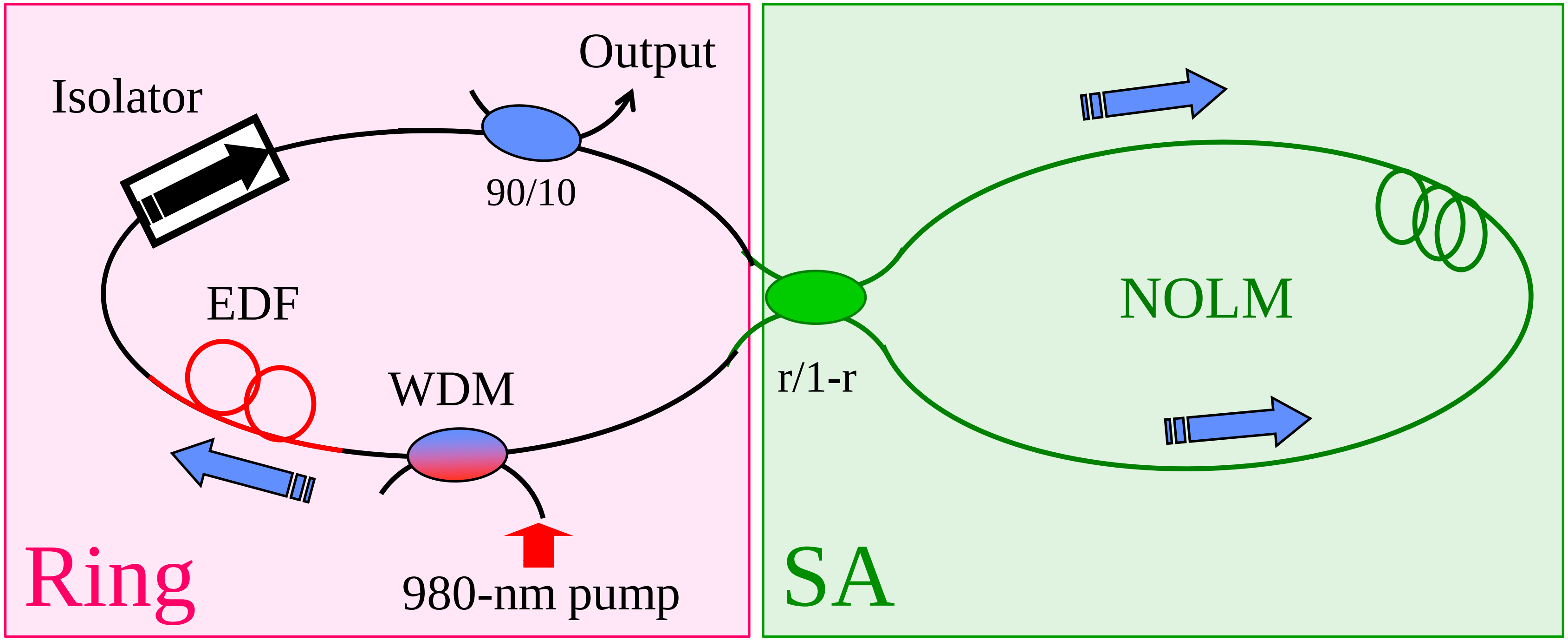
Introduction

- **Passively mode-locked fiber lasers** are simple, compact and low-cost sources of ultrashort pulses. An attractive architecture is the **figure-eight laser**: saturable absorber (SA) action provided by a **Nonlinear Optical Loop Mirror** (NOLM) (or NALM).
- For some applications like supercontinuum generation or metrology, desirable characteristics include high pulse energy, large optical bandwidth and low temporal coherence.
- In general however, energy of ultrashort pulses from fiber sources is limited by nonlinearities in the fiber (0.1 nJ for soliton lasers, 2-3 nJ for stretched-pulse fiber lasers). Moreover, due to their large bandwidth and optical coherence, such pulses broaden and vanish rapidly in long dispersive fibers.

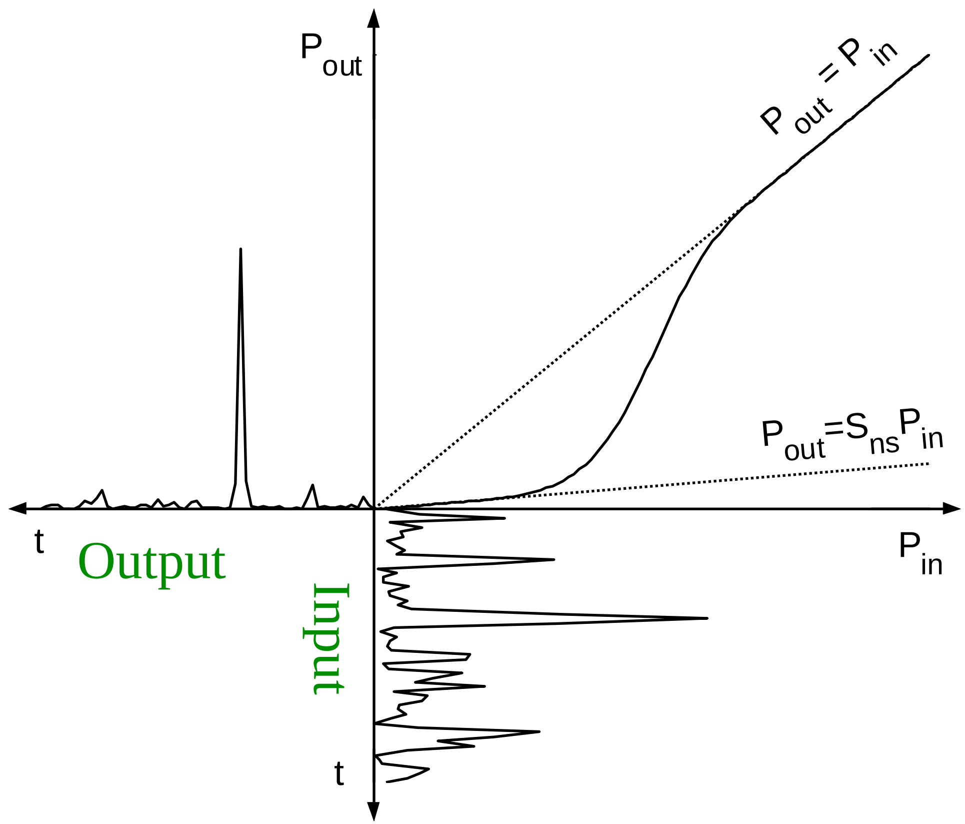
We report on advances of the study of a passively mode-locked fiber laser that generates sub-nanosecond wave packets with subpicosecond temporal coherence, > nJ energy and a wide bandwidth of several tens of nm: the noise-like pulses. Adjustability of pulse parameters and the possibility of multiple pulsing are demonstrated.

A figure-eight laser is a ring laser including a NOLM



- ✓ A figure-eight laser consists in a ring laser (left) in which a NOLM is inserted (right)
- ✓ A NOLM (Nonlinear Optical Loop Mirror) operates as a saturable absorber (SA), favoring pulsing against continuous-wave lasing

A saturable absorber absorbs at low power and transmits at high power



The mechanism of pulse formation in a laser including a SA is passive mode locking

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The nonlinear Sagnac interferometer is a switch

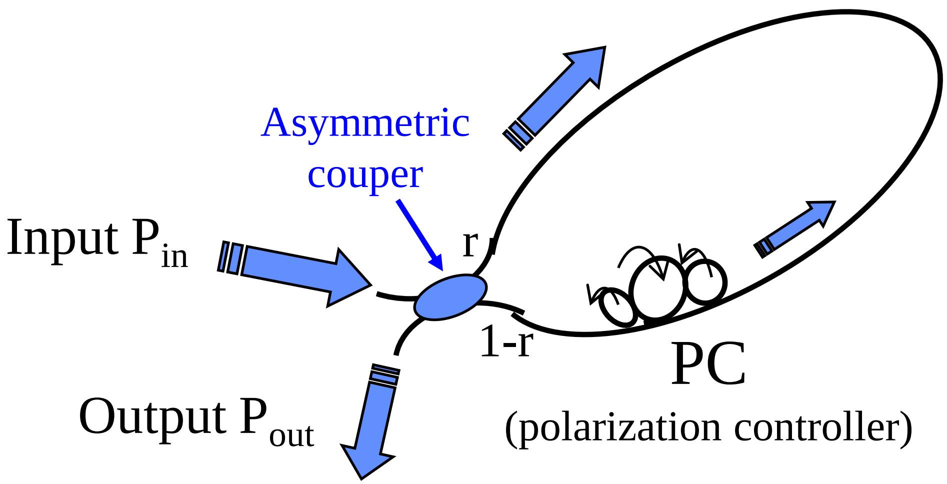
INAOE

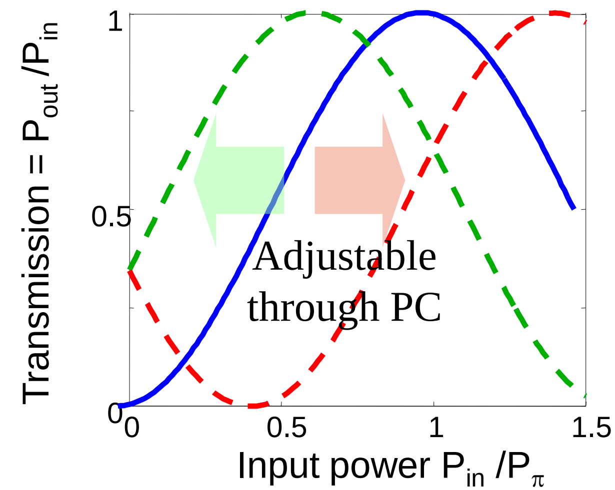
Un NOLM (*Nonlinear Optical Loop Mirror*) includes:

- ✓ A directional coupler
- ✓ A piece of fiber connecting the coupler output ports

} = Sagnac interferometer (= mirror)

- ✓ The Kerr non linear effect in silica fiber induces a power-dependent phase shift yielding a power-dependent transmission (switching)
- ✓ In convencional schemes, the loop is power-asymmetric (e.g., asymmetric coupler) :





↗ **Advantages**: extremely fast, femtosecond (fs) response time, adjustment through birrefringence bias (PC)

↘ **Drawbacks**: Transmission ajusted empíricamente through PC, low flexibility, hardly reproductible (depends on environmental conditions)

Nonlinear Polarization Rotation can induce switching, too

The nonlinear phase shift of a beam propagating in a fiber depends on its power, as well as its **polarization (Stokes parameter)**

<u>Couped nonlinear equations</u>:

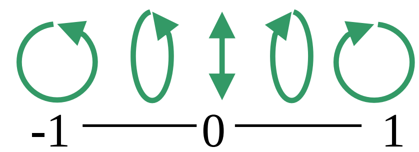
$$\partial_z C^+ = ibP\left(\left|C^+\right|^2 + 2\left|C^-\right|^2\right)C^+ = ibP\left(\frac{3}{2} - \frac{1}{2}A_s\right)C^+;$$

$$\partial_z C^- = ibP\left(\left|C^-\right|^2 + 2\left|C^+\right|^2\right)C^- = ibP\left(\frac{3}{2} + \frac{1}{2}A_s\right)C^+.$$

$$b = 4\pi\tilde{n}_2 / \left(3\lambda A_{eff}\right)$$

Power

Stokes parameter:



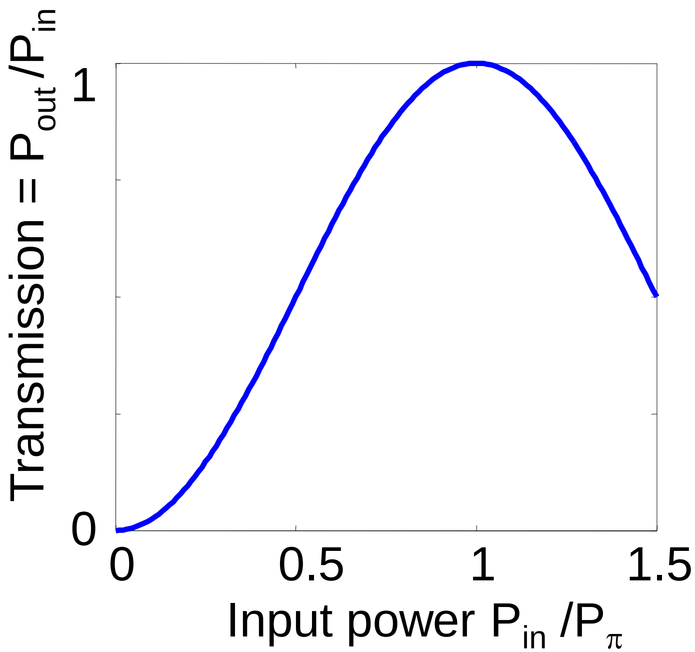
⇨ A en power-symmetric, **polarization-asymmetric** NOLM allows switching

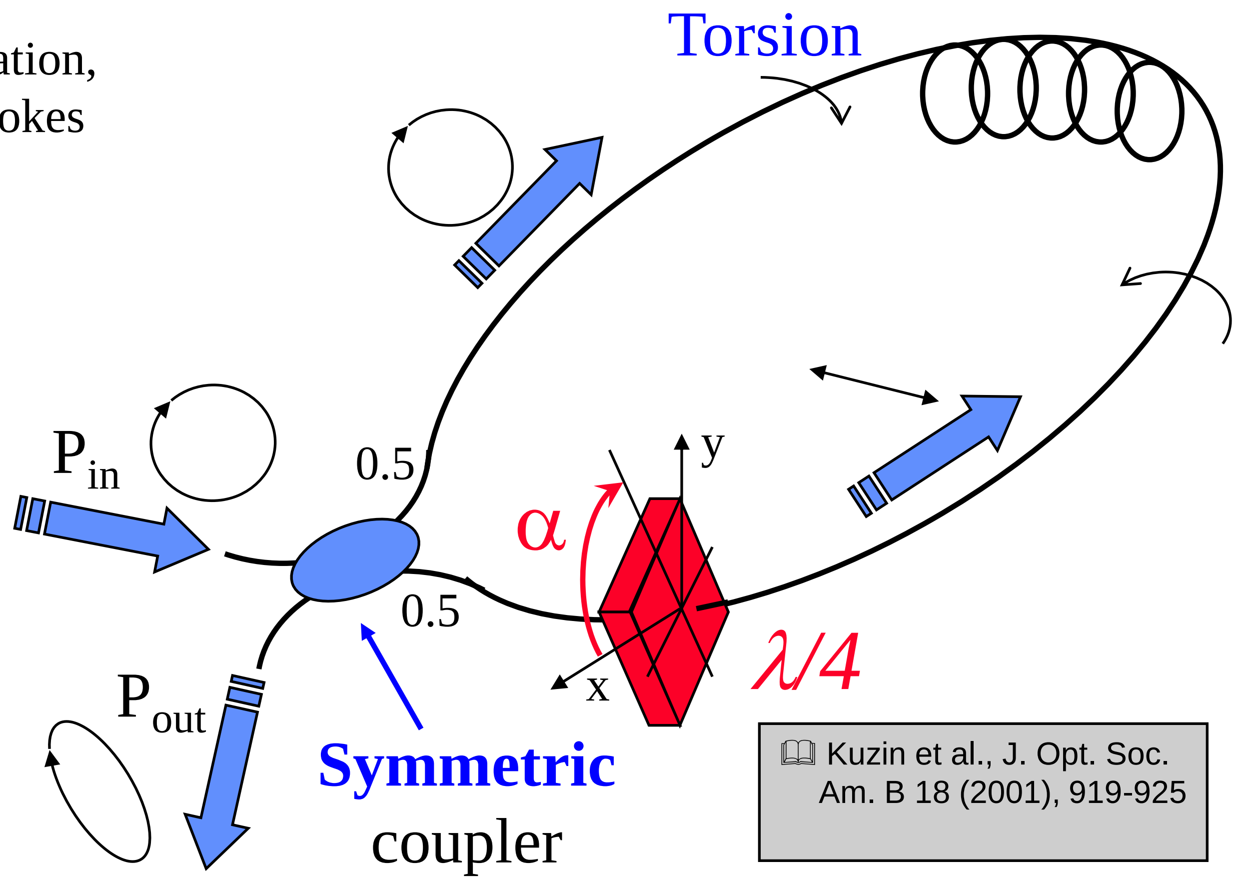
A new scheme was poposed, power-symmetric, polarization-imbalanced

✓ Polarization asymmetry between counter-propagating beams due to **λ/4 wave retarder**

✓ High torsion reduces the effect of residual birrefringence of standard fiber (~isotropic behavior)

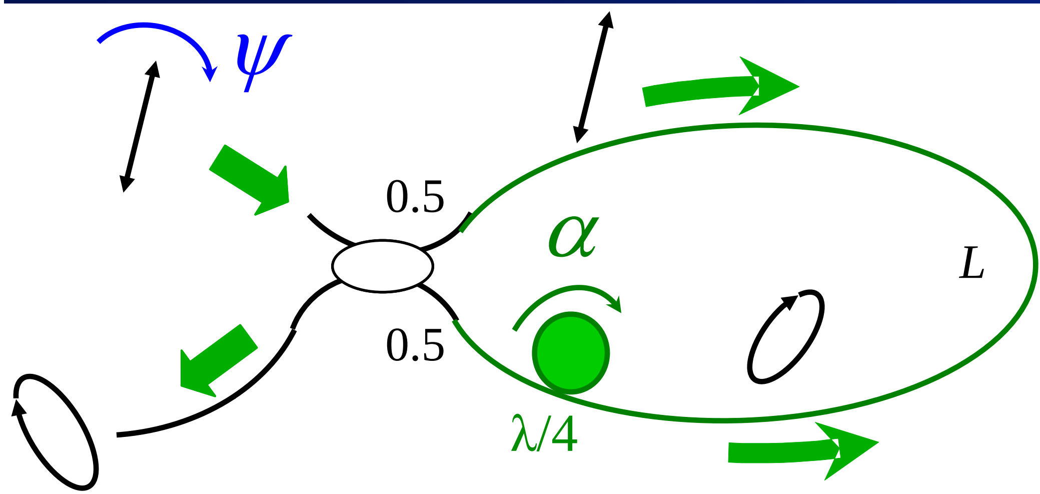
⇨ Optical activity rotates polarization, but maintains ellipticity (and Stokes parameter) of each beam

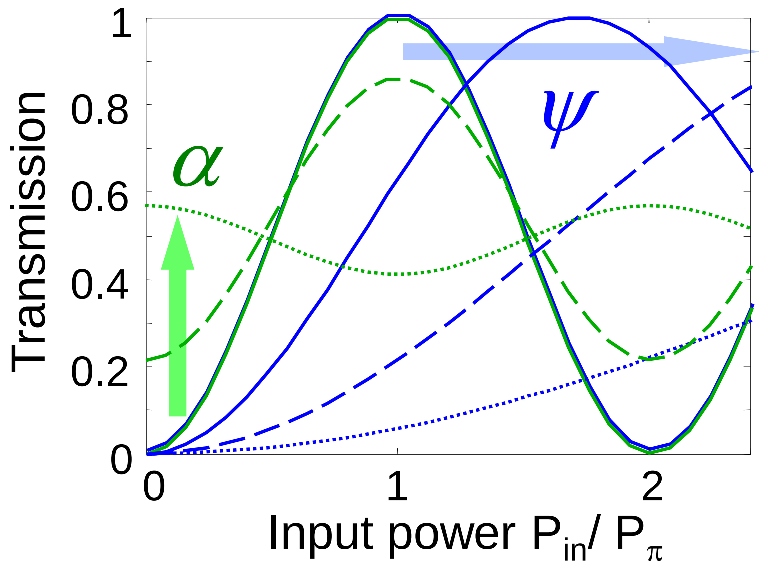




📖 Kuzin et al., J. Opt. Soc. Am. B 18 (2001), 919-925

Switching characteristic is adjustable through polarization control





For linear input polarization:

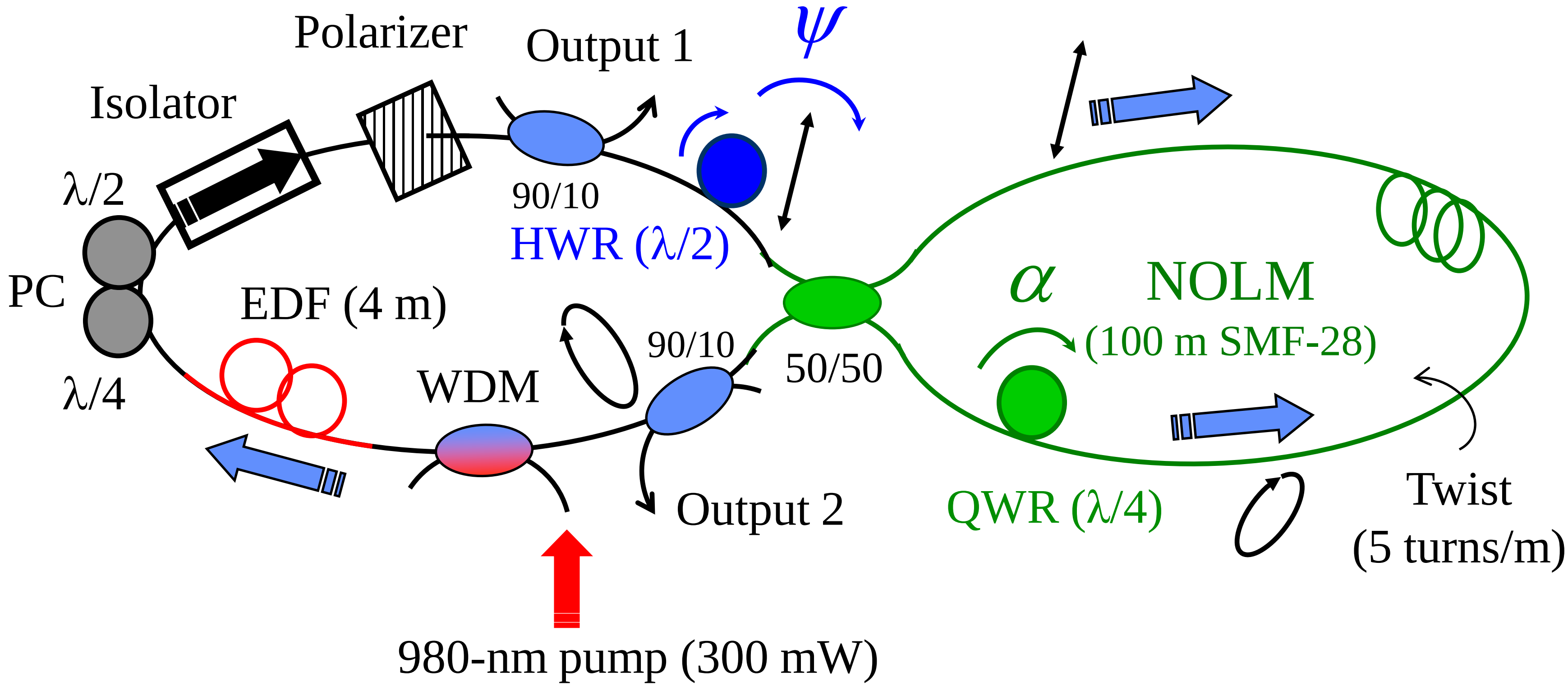
$$T = \frac{1}{2} - \frac{1}{2}\cos(2\alpha)\cos\left\{2\alpha + \pi\sin(2\psi)\frac{P_{in}}{P_\pi}\right\}$$

- ✓ Low-power NOLM transmission and slope, and dynamic range controlled through α
- ✓ Switching power adjusted through ψ

📖 O. Pottiez et al., Opt. Comm. 254, 152 (2005).

📖 B. Ibarra-Escamilla et al., Opt. Express 13, 10760 (2005).

Figure-eight laser scheme under study



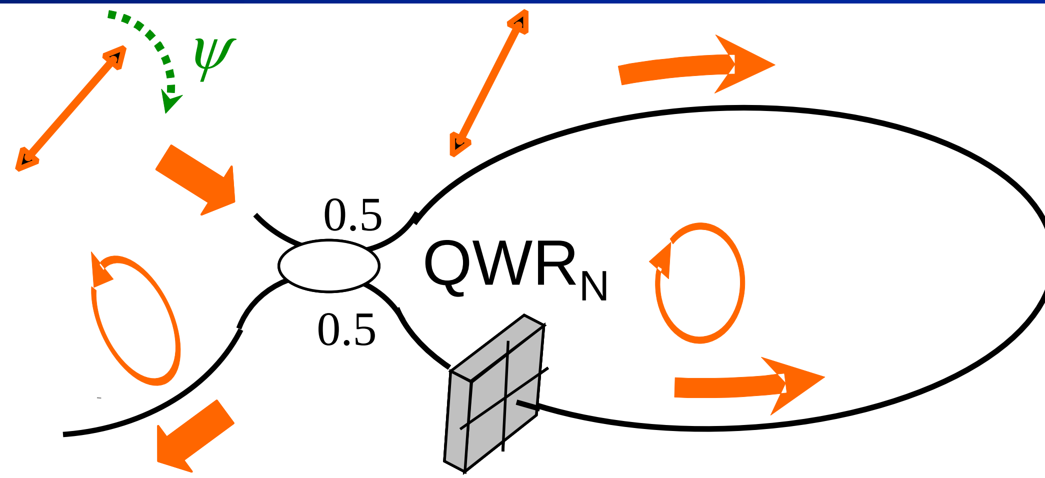
- ✓ A polarization-imbalanced NOLM is inserted in the laser
- ✓ Quarter-wave retarder (QWR) angle determines low-power NOLM transmission
- ✓ Input polarization to the NOLM is set linear
- ✓ Input polarization angle ψ, controlled through half-wave retarder (HWR), determines switching power

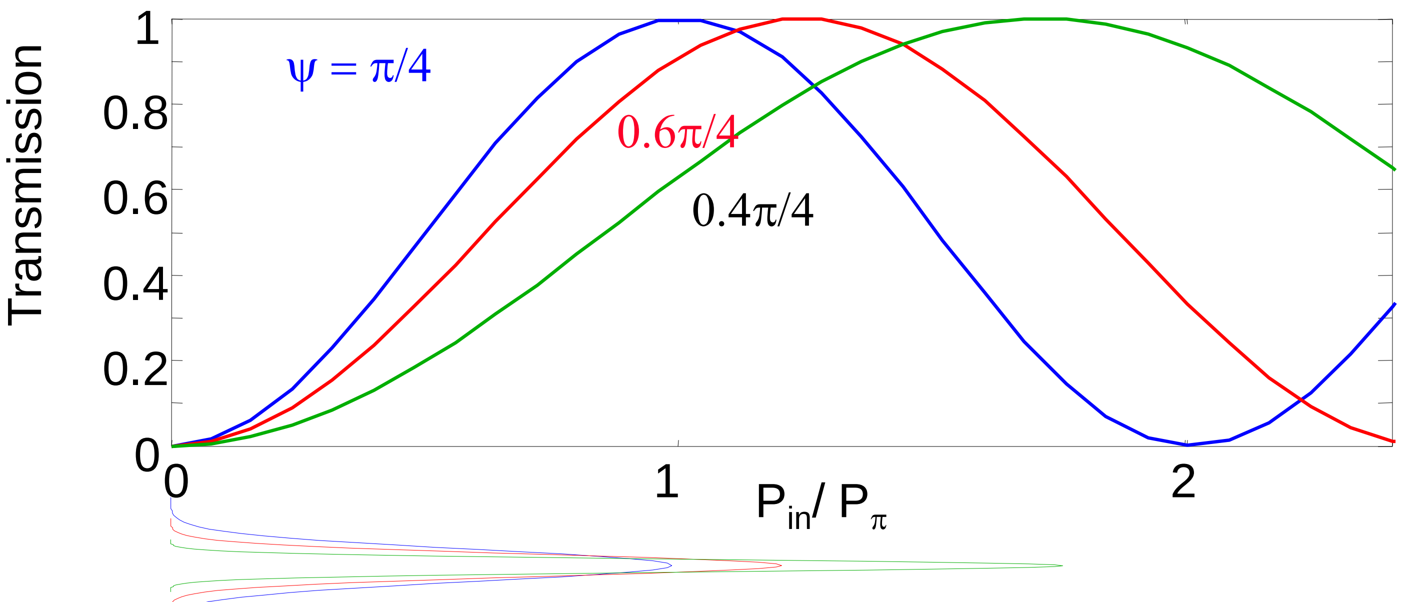
The proposed scheme allows adjusting the critical power

For linear input polarization:

$$T = \frac{1}{2} - \frac{1}{2}\cos(2\alpha)\cos\left\{2\alpha + \pi\sin(2\psi)\frac{P_{in}}{P_\pi}\right\}$$

Critical power = $P_\pi / |\sin 2\psi| \leq P_\pi$

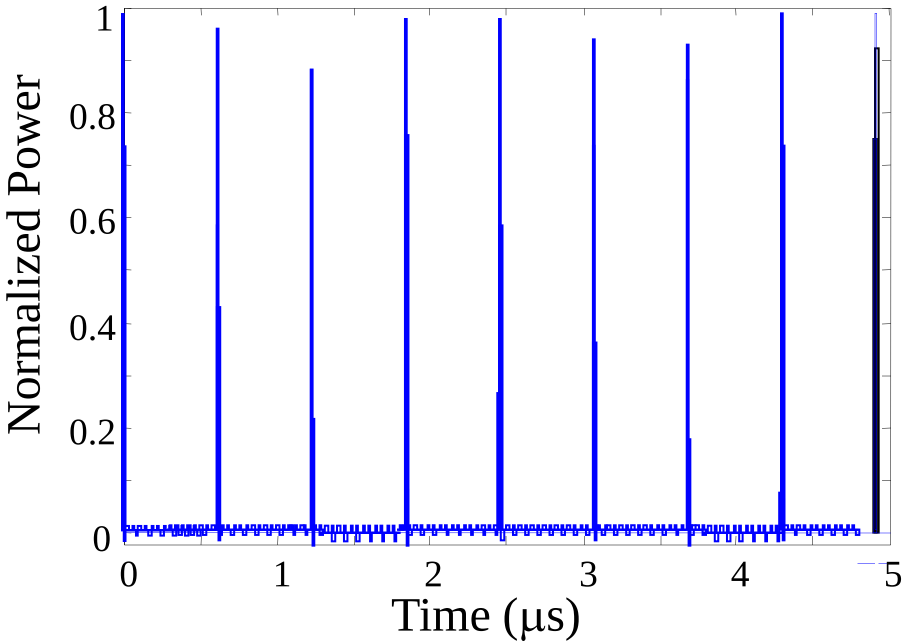


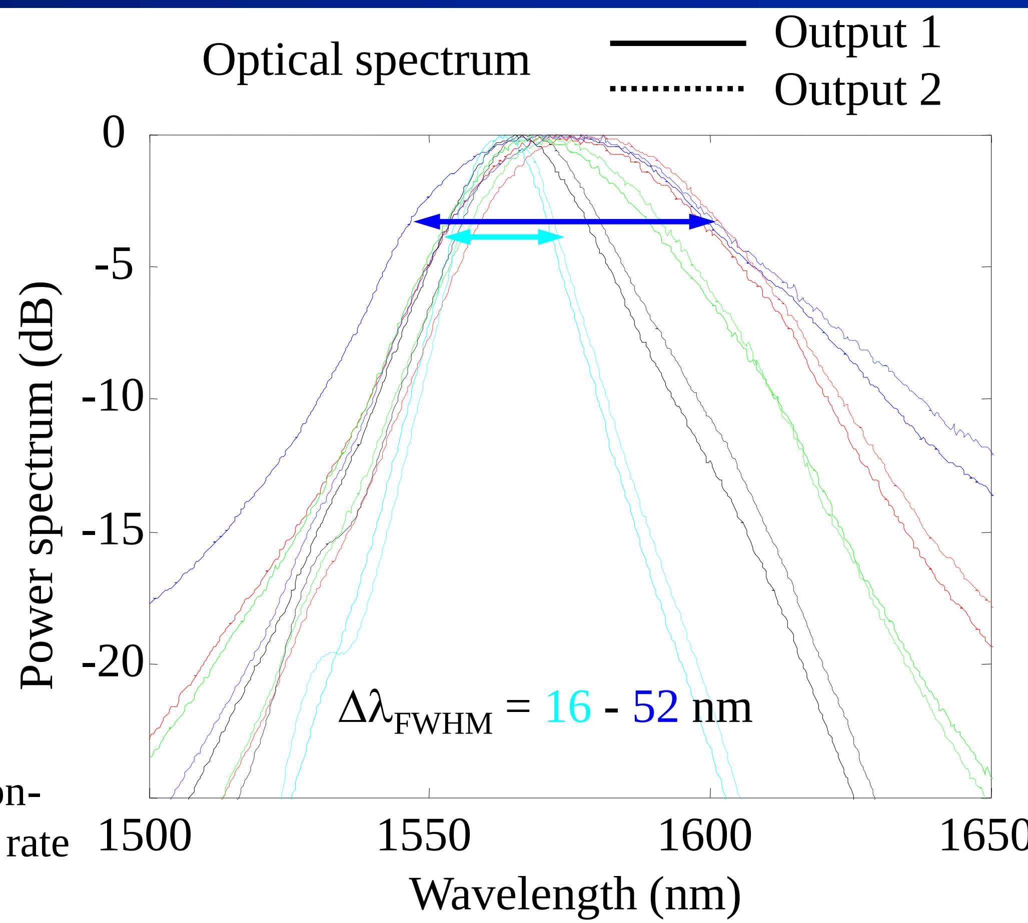


- ✓ Allows adapting the switching power to intracavity pulse peak power
- ✓ Allows adjusting temporal/spectral pulse properties

Wide and smooth optical bandwidth is observed

Oscilloscope trace

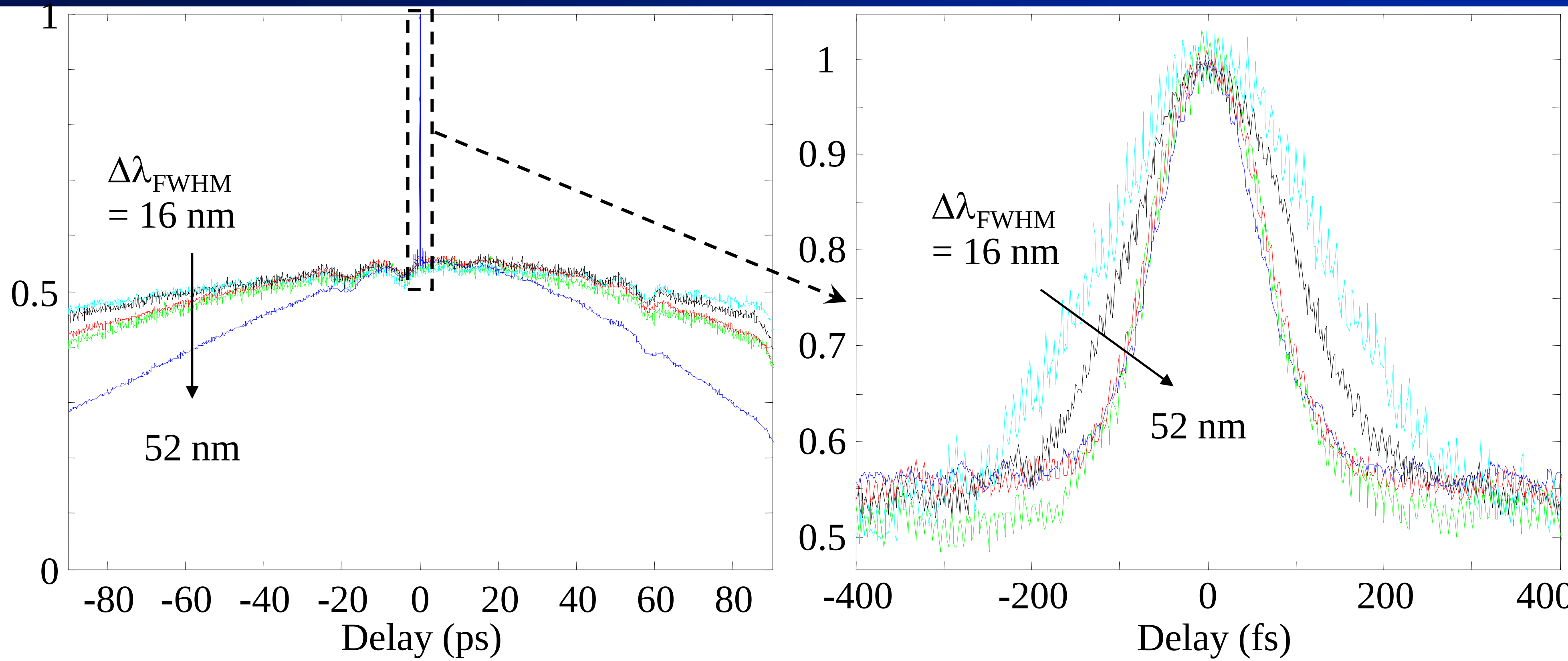




- ✓ For proper adjustments of the QWR and HWR, non-self-starting mode locking is observed. Repetition rate = *1.6 MHz*
- ✓ Spectral width varies depending on QWR and HWR adjustments

Red shift as bandwidth increases and asymmetry of the wider spectra attributed to Raman SFS

Autocorrelation traces shows sub-ps peak riding wide pedestal



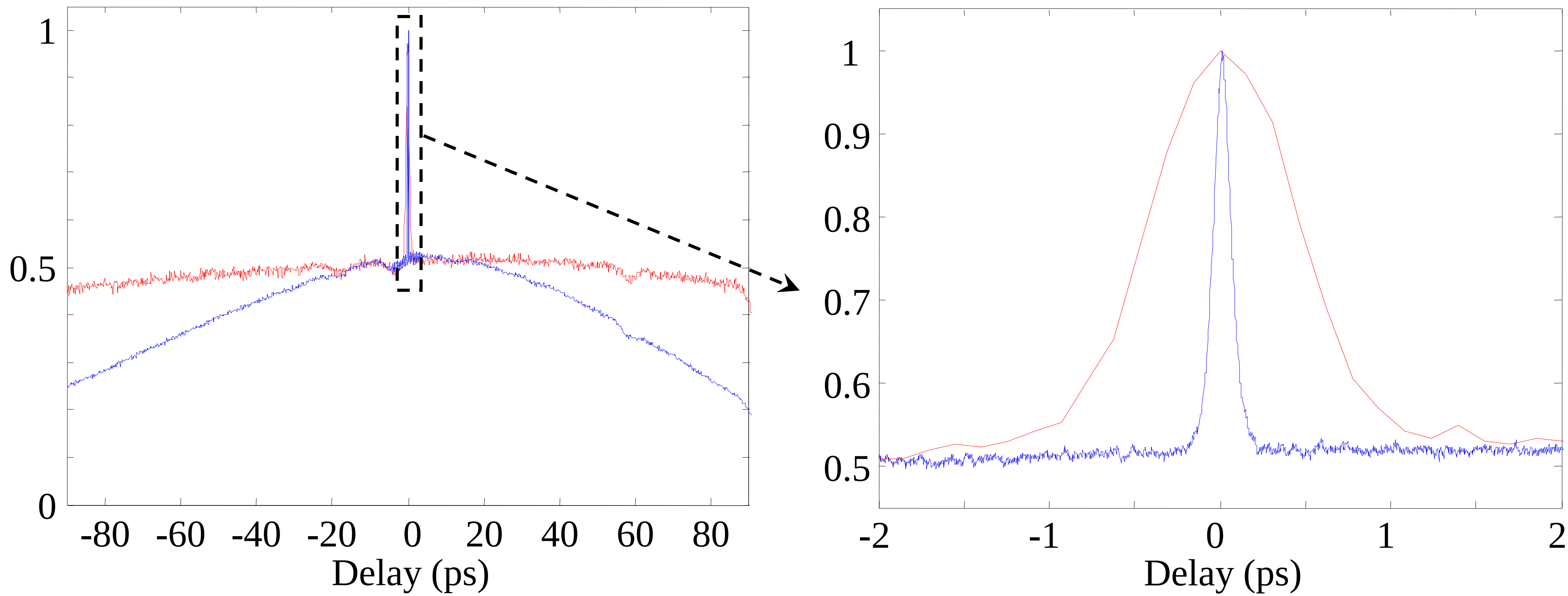
FWHM duration of pedestal varies between *200 ps* and *~600 ps*

FWHM duration of central peak varies between *140* and *270 fs*

Ratio between narrow peak and pedestal level invariably = 2:1

Coherence of pulses is small

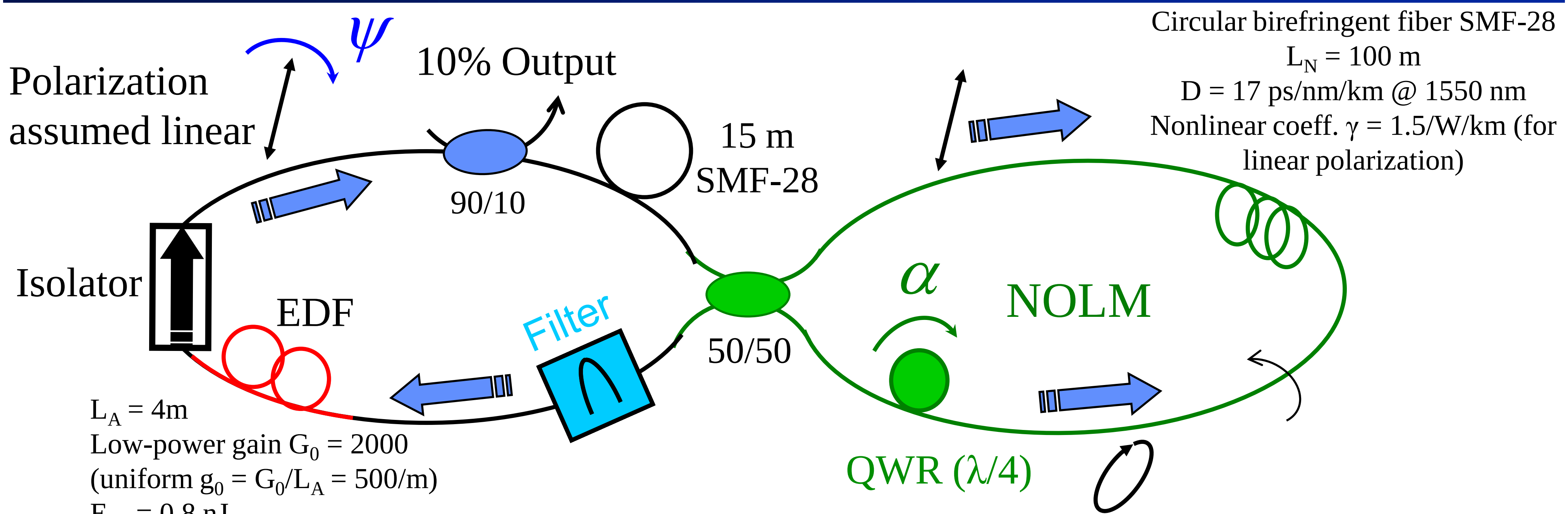
Autocorrelation traces directly at laser output and after 760 m of SMF-28 fiber (D = 17 ps/nm/km)



The central peak is still observed at the fiber output, even if it is substantially broadened (8 times) and the autocorrelation intensity is reduced

In comparison, a transform-limited sub-ps pulse with comparable bandwidth (~*50 nm*) would vanish completely due to fiber dispersion

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 $\alpha = -\pi/16$ (low-power NOLM transmission ≈ 0.1) and input polarization angle relative to QWR axes $\psi = 0.35\pi/4 \rightarrow$ switching power $P_\pi \approx 200\ W$ ($P_\pi\ min \approx 120\ W$ if $\psi = \pi/4$)

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)

$$g\left(E_p\right) = \frac{g_0}{1 + E_p / E_{sat}}$$

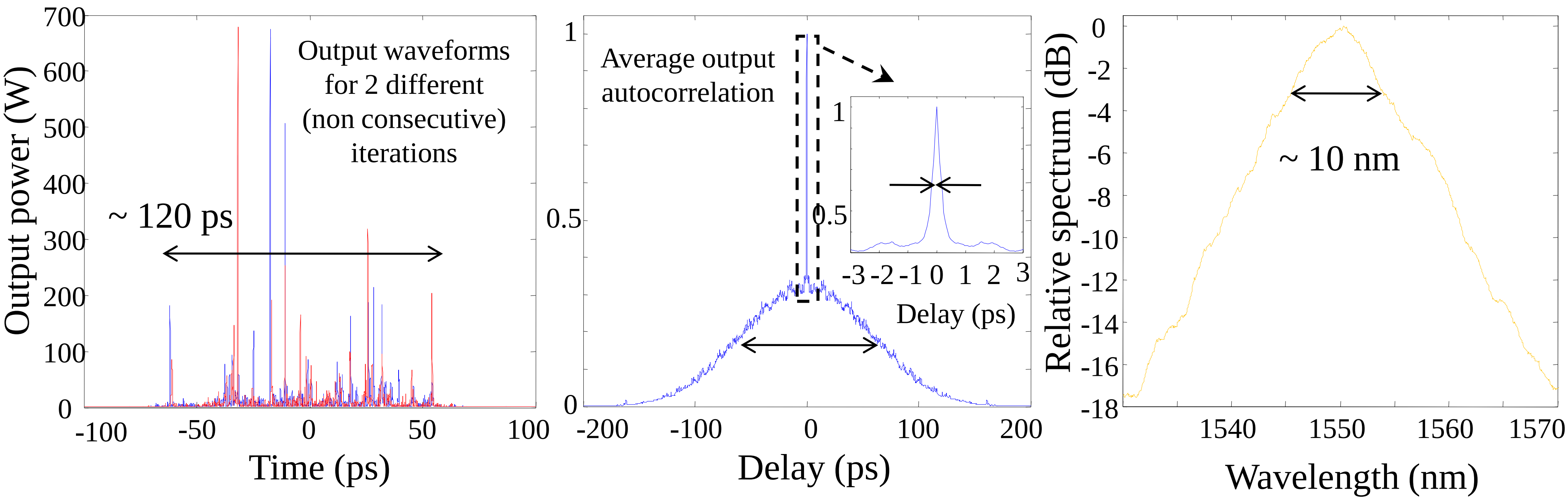
Pulse energy (E_p)

Integrated using Split-Step Fourier method

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

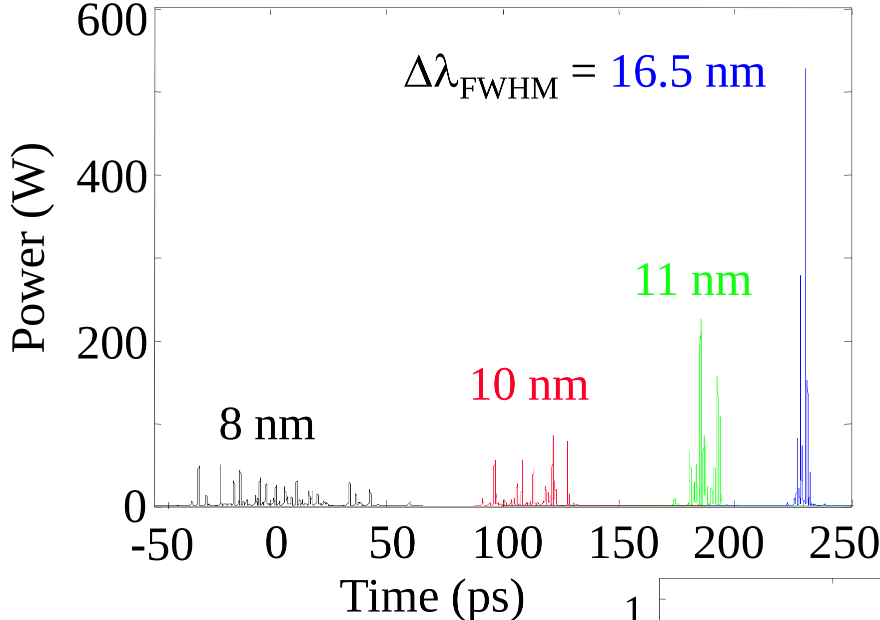
- ✓ Small-amplitude gaussian white noise is used as initial signal
- ✓ Integration is performed over several cycles until convergence is reached

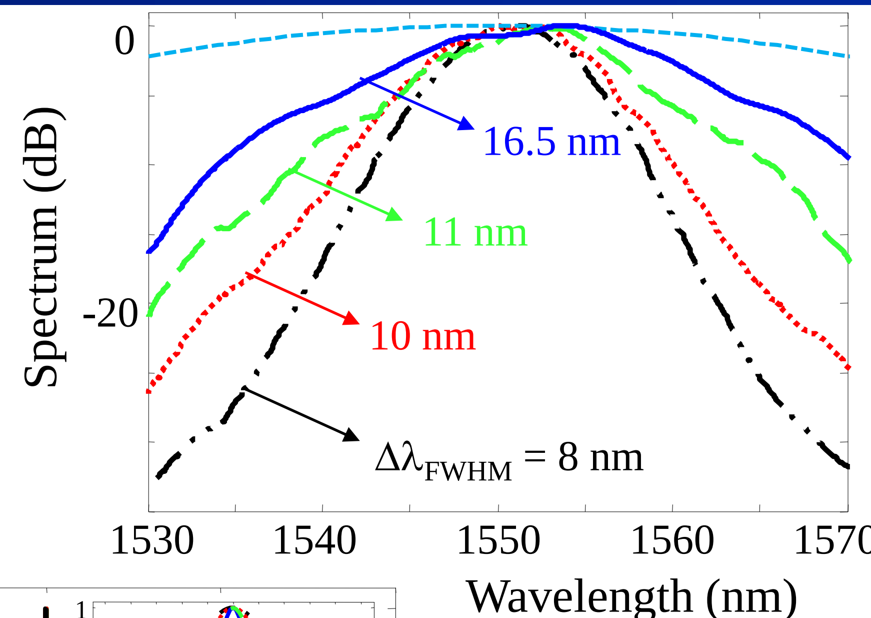
Numerical results are quite consistent with experiment

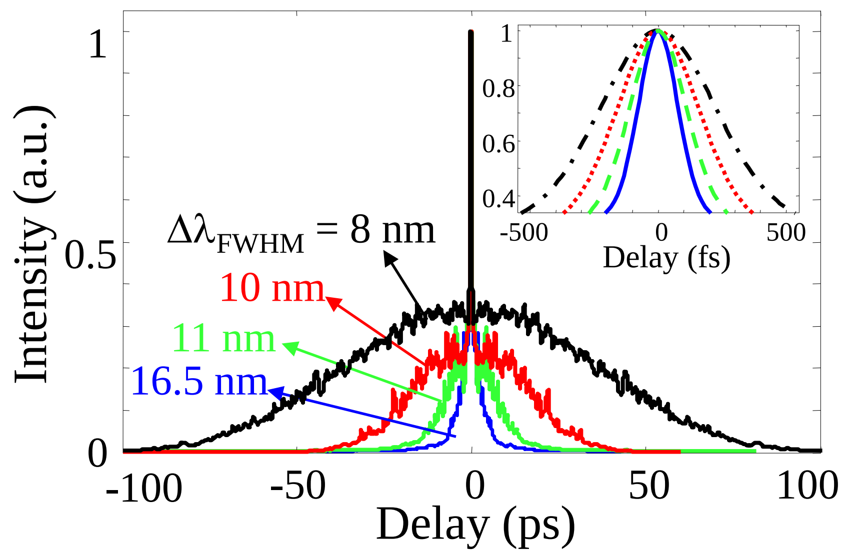


- ✓ Although there is no convergence to a constant pulse shape, a variable sub-ns packet of sub-ps pulses with stable caracteristics (peak power, duration) is maintained. Pulse energy = 1.4 nJ
- ✓ Autocorrelation trace (averaged over many cycles) presents a sub-ps central peak riding a sub-ns pedestal (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

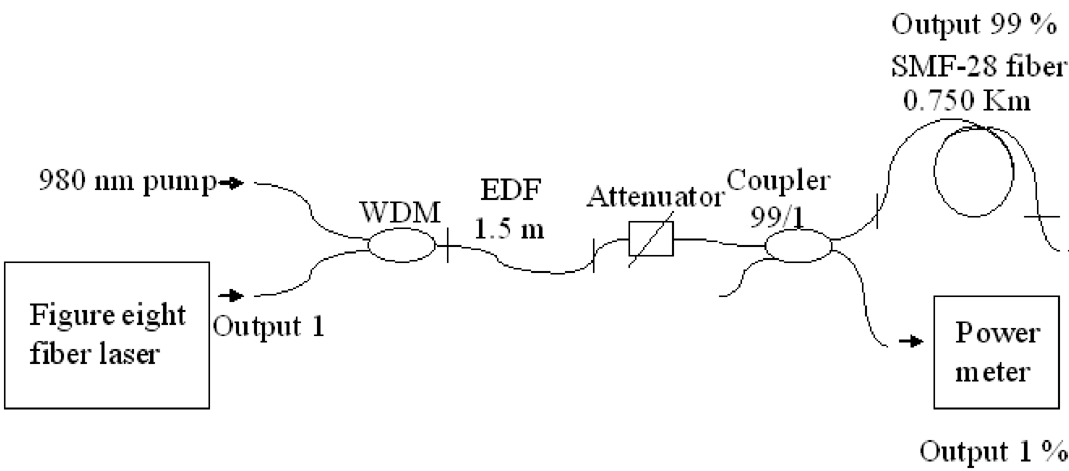
Pulse properties are adjustable







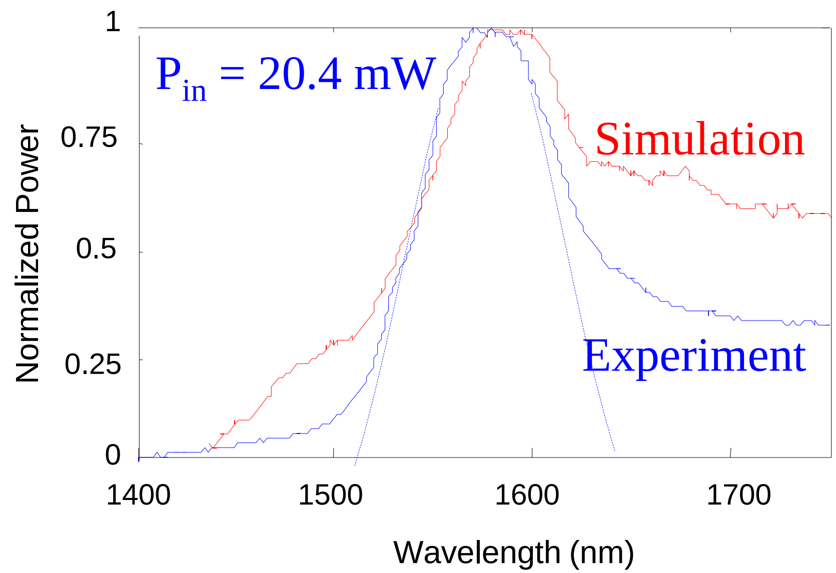
Noise-like pulses were used for supercontinuum generation in standard fiber



Advantages of noise-like pulses for SCG:

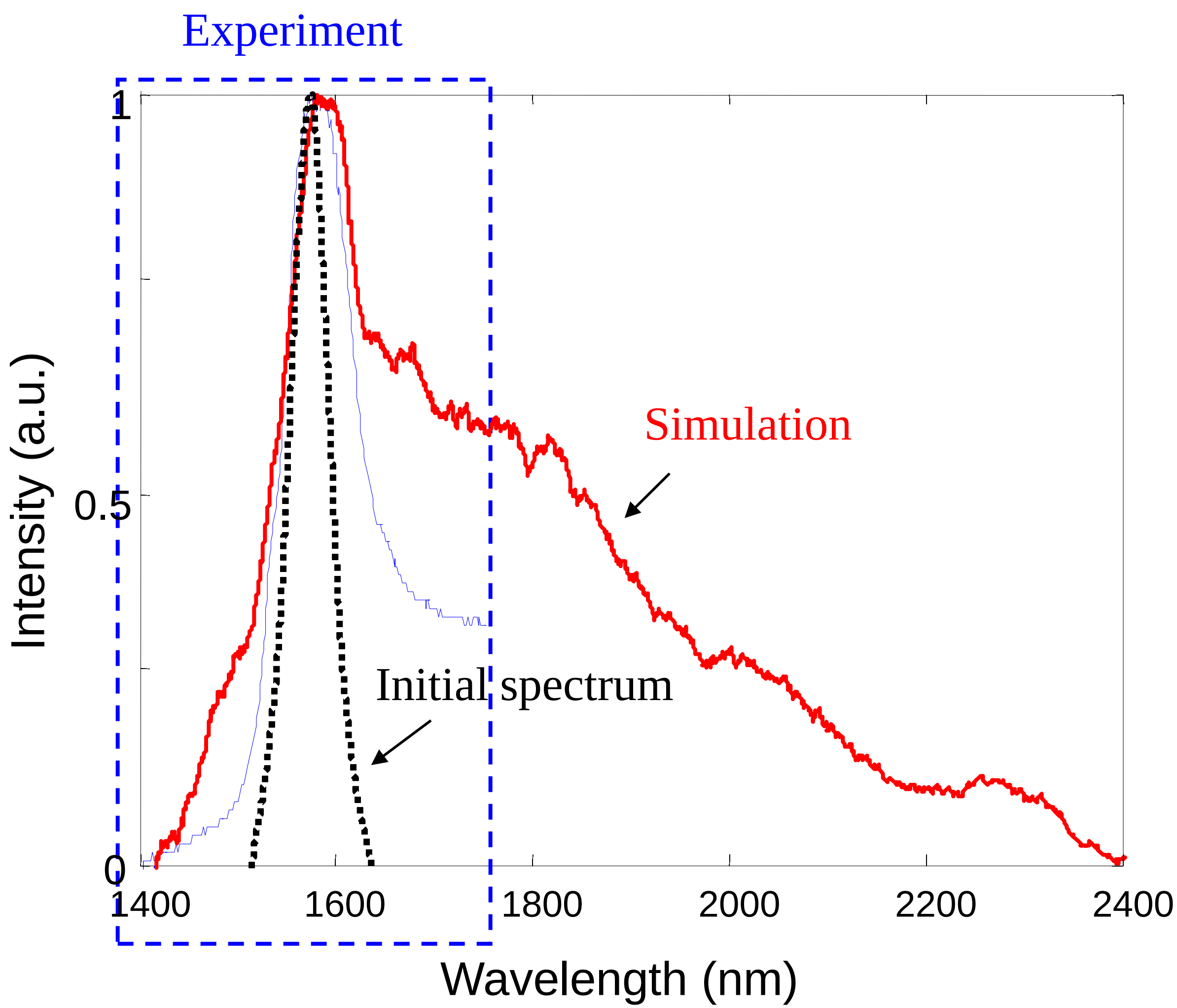
- ✓ High pulse energy
- ✓ Wide optical spectrum

📖 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

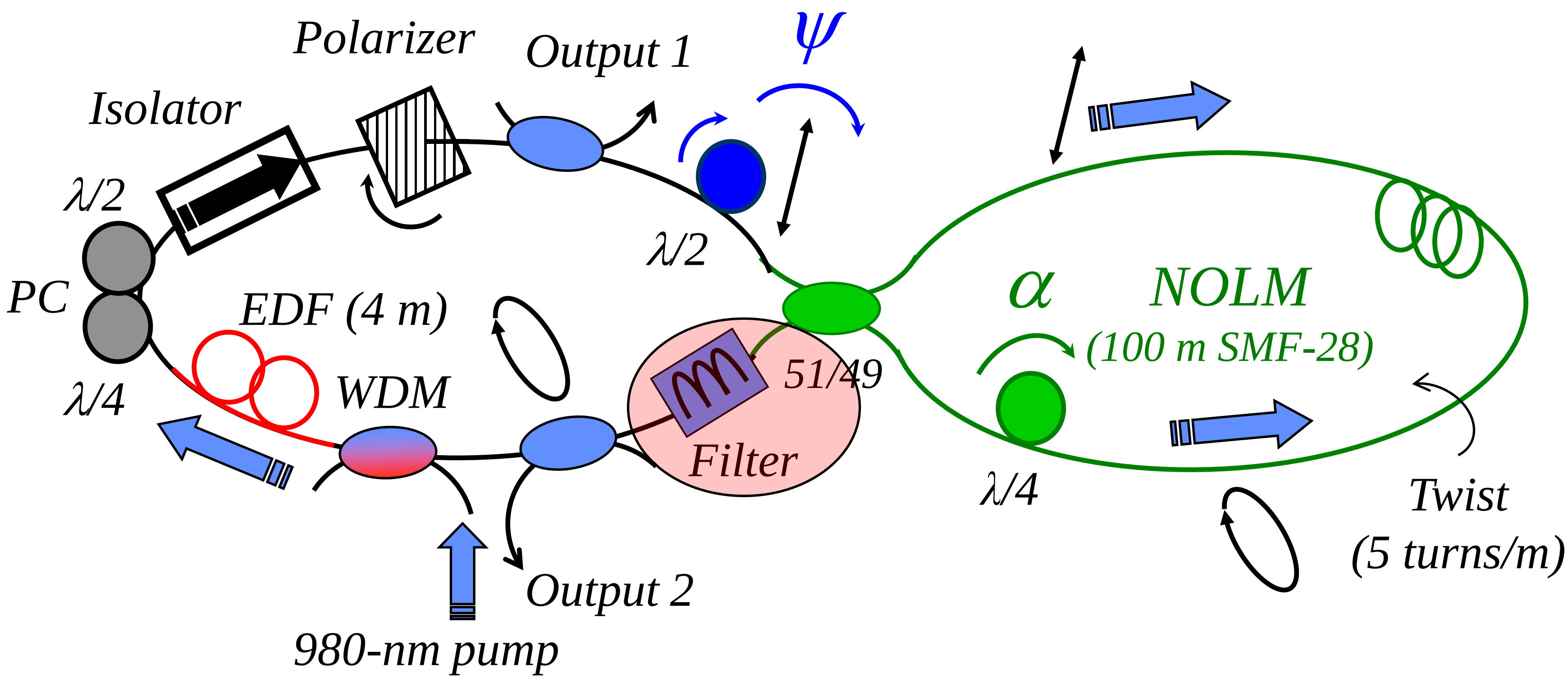
Numerical simulations predict further widening to the right



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

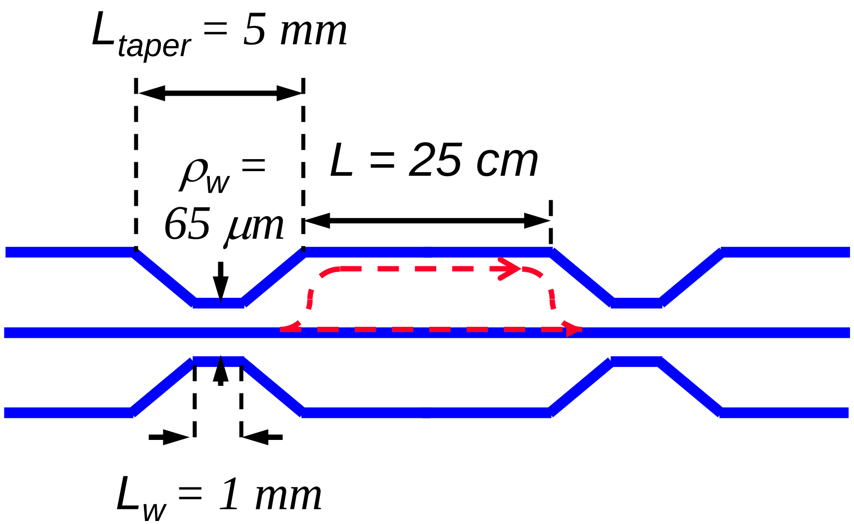
Hernandez-Garcia et al., Opt. Comm. 285 (2012) 1915-1919

A Mach-Zehnder filter was inserted in the laser

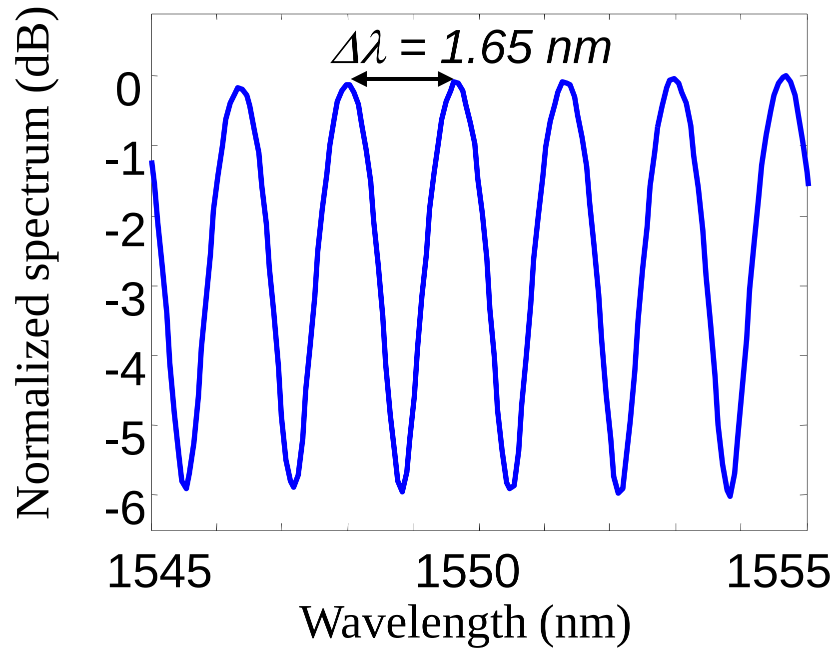


- ✓ A periodic filter made by two fiber tapers in series is inserted in the ring section of the laser

A fiber device is used for spectral filtering

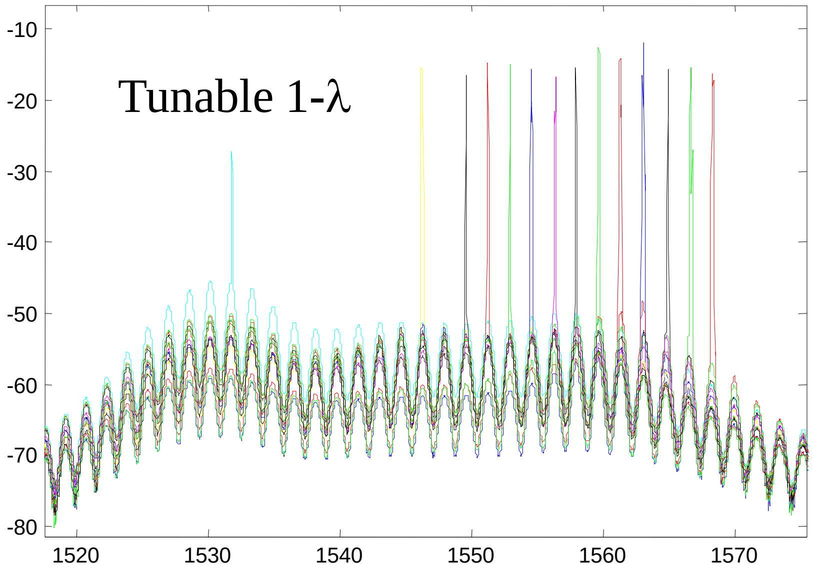


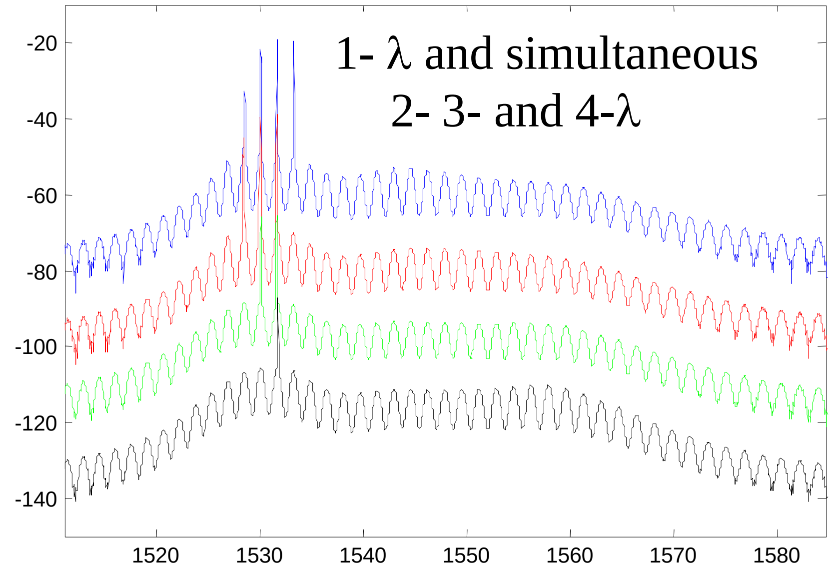
Monzon-Hernandez et al., Opt. Lett. 36 (2011), 4380-4382



- ✓ The optical filter consists of two tapers fabricated in series in a Nufern 980HP fiber
- ✓ = Mach-Zehnder interferometer: at the first taper the fundamental core mode partially couples to cladding modes, and a fraction of the light guided in the cladding modes couples back to the core mode at the second taper
- ✓ Periodic filter with 1.65 *nm* period, *6 dB* modulation depth and *~0.5 dB* insertion loss

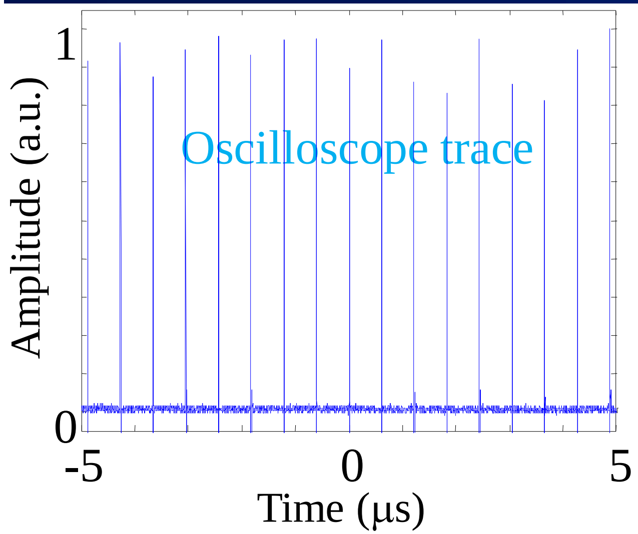
Tunable 1-λ and simultaneous 4-λ CW operations were observed

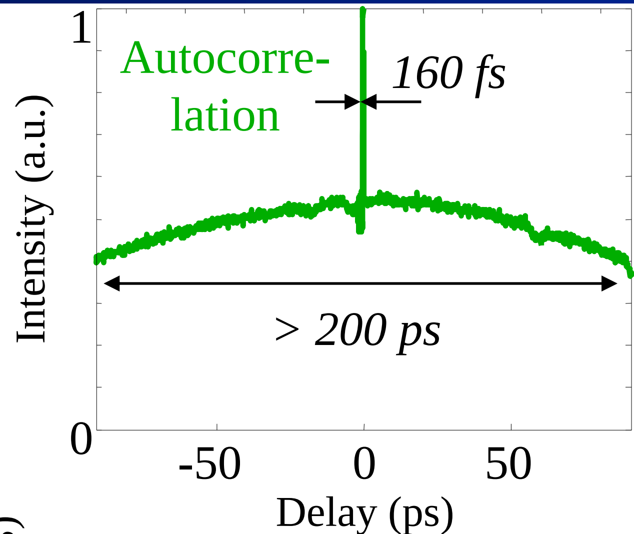


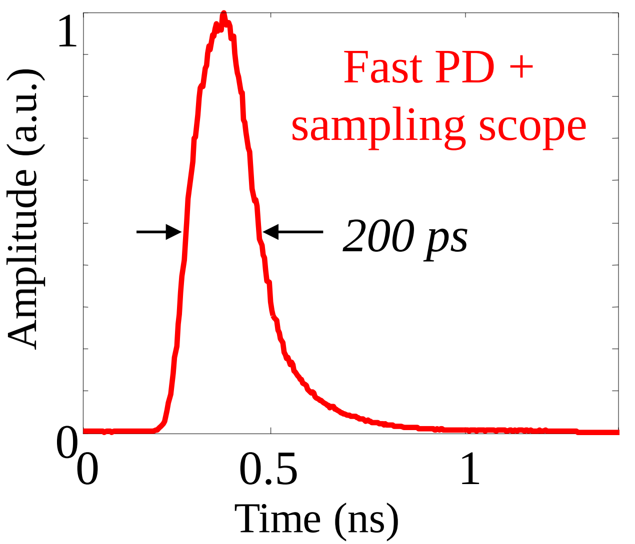


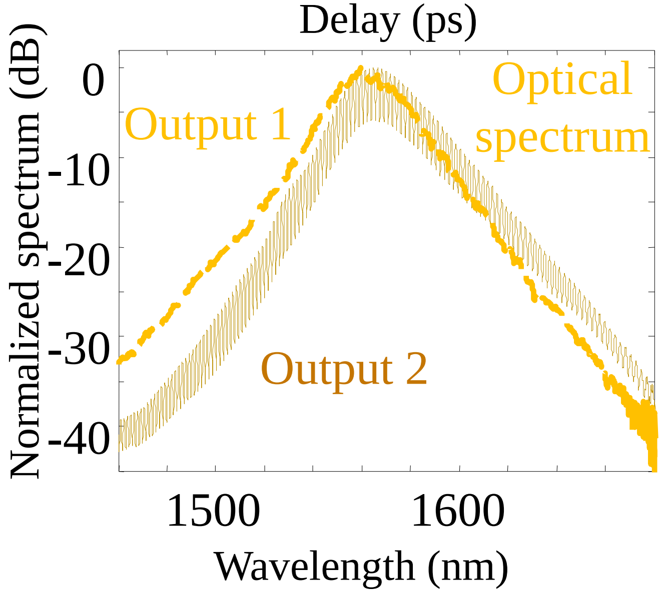
- ✓ Simple WR adjustments allow observing different CW regimes
- ✓ Single wavelength operation tunable over 22 nm by steps of 1.65 nm was possible. No lasing around 1540 nm (gain depression)
- ✓ Multiwavelength operation in the 1530 nm region was also observed, with up to 4 consecutive wavelengths (1.65 nm separation), stable over a few min in spite of gain competition (homogeneous broadening).
- ✓ Mechanisms allowing wavelength tuning through WR adjustments:
  - ✓ Adjusting QWR angle in the Sagnac loop modifies cavity loss and the balance between absorption and emission that determines gain spectrum
  - ✓ Adjustable cavity birefringence + polarizer = adjustable filtering effect

Fundamental mode-locking was observed







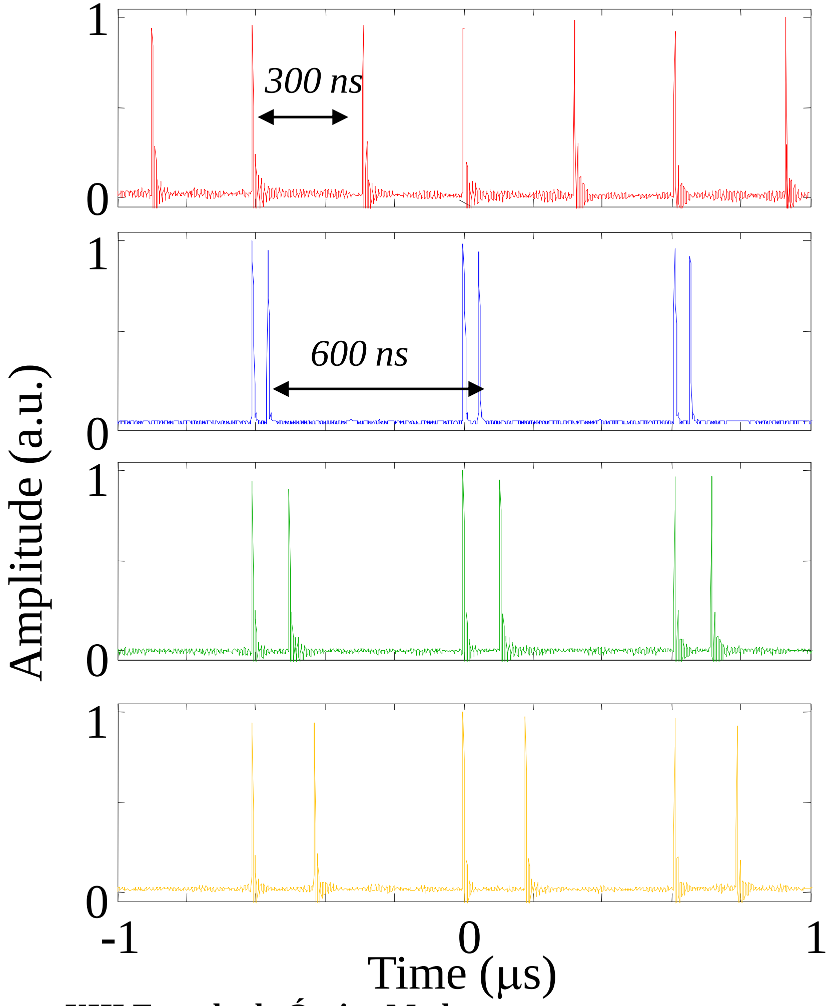


- ✓ For some adjustments, non-self-starting mode locking was observed at 1.6 MHz (fundamental mode locking)
- ✓ Measurements indicate that pulses are noise-like pulses (large collections of sub-ps pulses with random amplitudes and durations)
- ✓ Results similar to filterless laser ⇨ filter has little influence on mode locking except for introducing *~40%* loss

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

2nd-harmonic mode locking was also observed

Oscilloscope traces



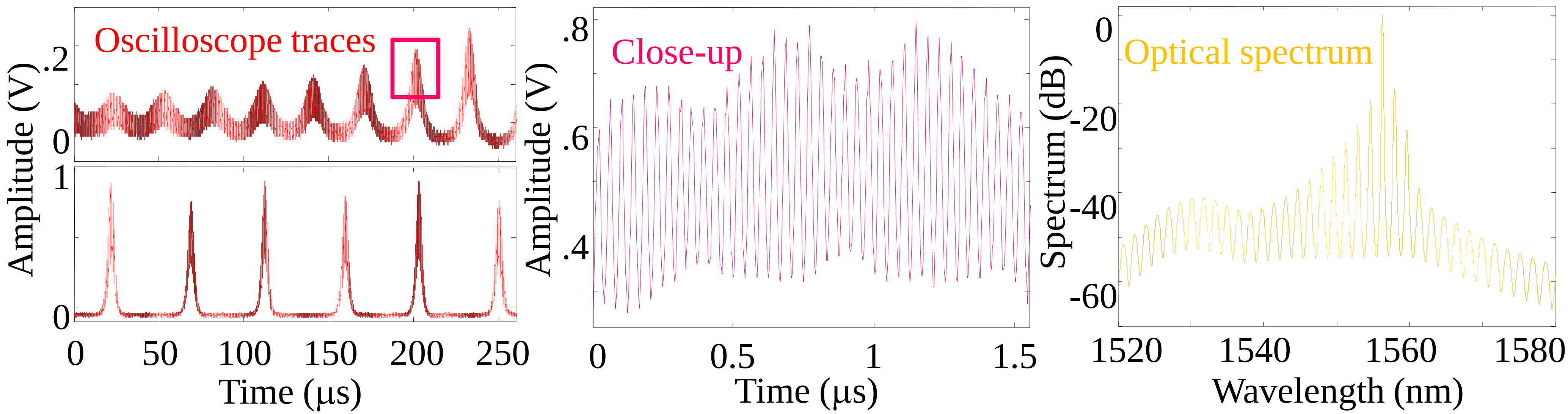
- ✓ In some cases, 2nd-harmonic mode locking was observed (2 pulses in the cavity)
- ✓ Measurements are qualitatively similar to the fundamental ML (noise-like pulses)
- ✓ During a few s, stable operation with generation of a train of equally spaced pulses
- ✓ After that, one of the two pulses suddenly vanishes, then reappears at the other pulse position and quickly moves away from it back to its initial position (~*1s*).

- ✓ WR adjustments allow adjusting phase between solitons and dispersive wave. This causes slight wavelength shifts between solitons (~*0.1 nm*). For some adjustments, pulses move apart.

Gray et al., J. Opt. Soc. Am. B 14 (1997), 144-154

- ✓ MZI filter may favor splitting of the bunch by introducing temporal shift (~*5ps*).
- ✓ Stabilization of 2HML by acoustic effects.

Multiwavelength passive Q-switching



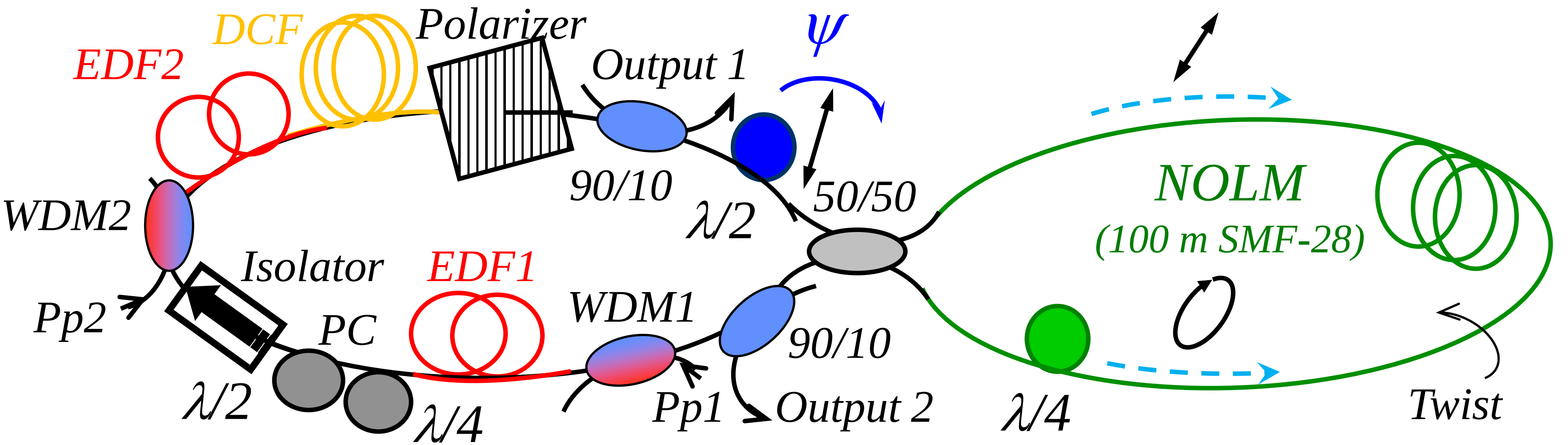
- ✓ For some WR adjustments, unstable passive Q-switching was observed. The pulses usually carry beat notes at the cavity fundamental frequency and its harmonics.
- ✓ A large number of wide spectral lines is systematically observed in the spectrum, one of them much higher.
- ✓ Highly doped Er fibers (with Er clusters) are known to behave like slow saturable absorbers, yielding pulsed behavior

  📖 S. Colin et al., Appl. Opt. 21 (1996), 1987-1989

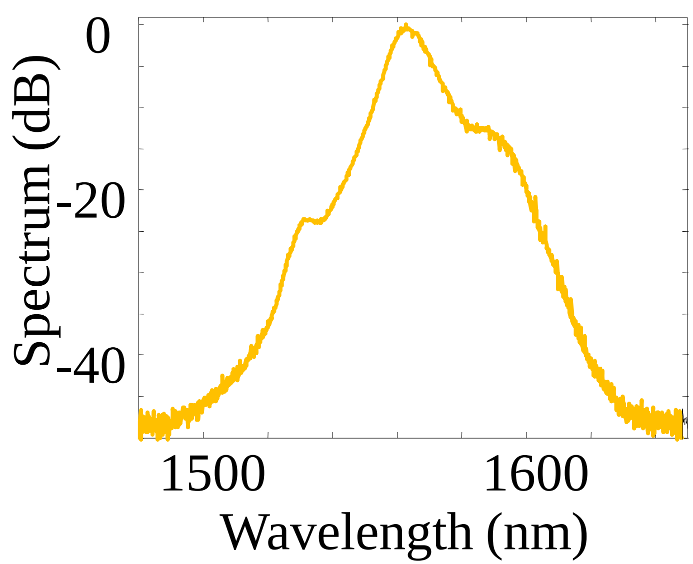
- ✓ Sagnac loop with adjustable WR = tunable attenuator. Self-pulsing appears when WR adjusted for high cavity losses (low photon lifetime).

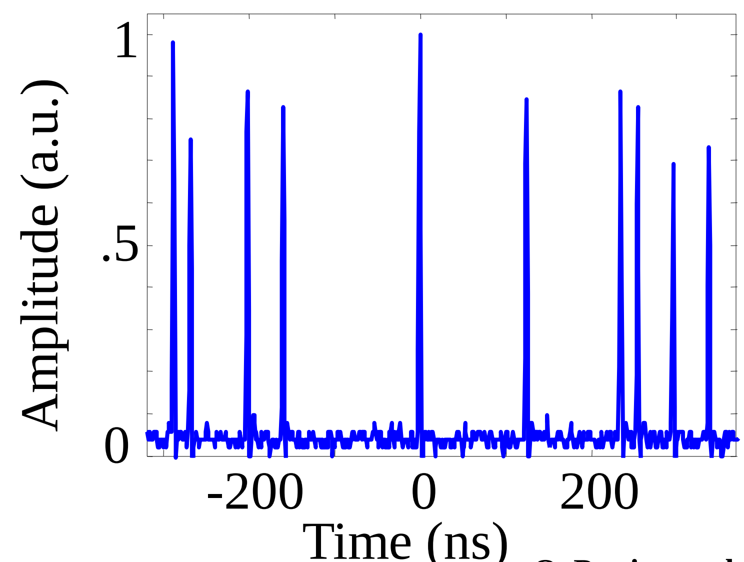
  📖 F. Sanchez et al., Phys. Rev. A 48 (1993), 2220-2229

Multiple pulsing (10) was observed in normal dispersion regime



NOLM overdriving seems to be the cause of multiple pulsing





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Conclusions

- ✓ We studied experimentally a figure-eight laser scheme including a polarization-imbalanced NOLM with linear input polarization.
- ✓ The angle of linear polarization at the NOLM input is adjustable through a HWR, which allows adjusting the NOLM switching power, and its low-power transmission and dynamic range can be adjusted through a QWR. This allows controlling the NOLM switching characteristics.
- ✓ For certain adjustments, noise-like pulses were generated. These are large sub-ns collections of sub-ps pulses with double-scaled autocorrelation and very wide and smooth optical spectrum.
- ✓ Adjusting the NOLM switching power allows adjusting the temporal and spectral properties of the noise-like pulses.
- ✓ Although usually only one noise-like pulse develops in the cavity, multiple pulsing has been observed in certain cases. Again, the adjustment of the NOLM switching power appears to be critical for multiple pulsing.
- ✓ Because they present relatively high energy, a wide spectrum and low coherence, these pulses are attractive for applications in metrology, sensing and for seeding supercontinuum generation.

Acknowledgement: This work was supported by CONACYT grant 130681