SOLITON PATTERNS FORMATION IN FIBER LASERS

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Outline of the presentation

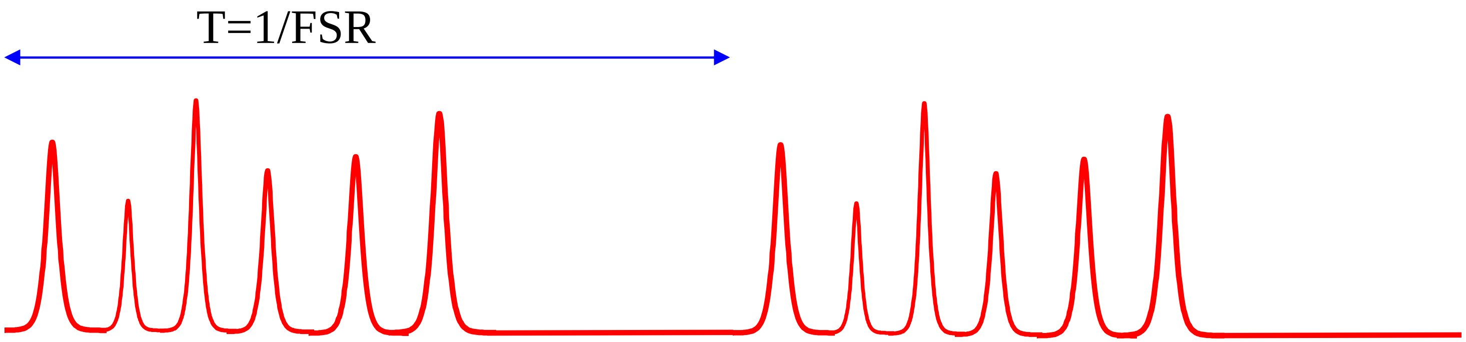
1. Introduction
2. Nonlinear polarization rotation fiber laser
3. Figure-of-eight laser
4. 10 W NLPR fiber laser
5. Conclusion

1. Introduction

Fiber laser operating in the anomalous dispersion regime

Negative GVD $\beta_2^{Tot} < 0$ ⇒ Soliton regime (energy quantization)

High pumping power ⇒ Multiple pulsing ~ 100 - 1000 pulses / cavity round-trip



⇒ Soliton interactions ⇒ Soliton pattern formation ⇒ Self-organized (or disorganized) structures analogous to the states of the matter ⇒ gas, liquid or solid

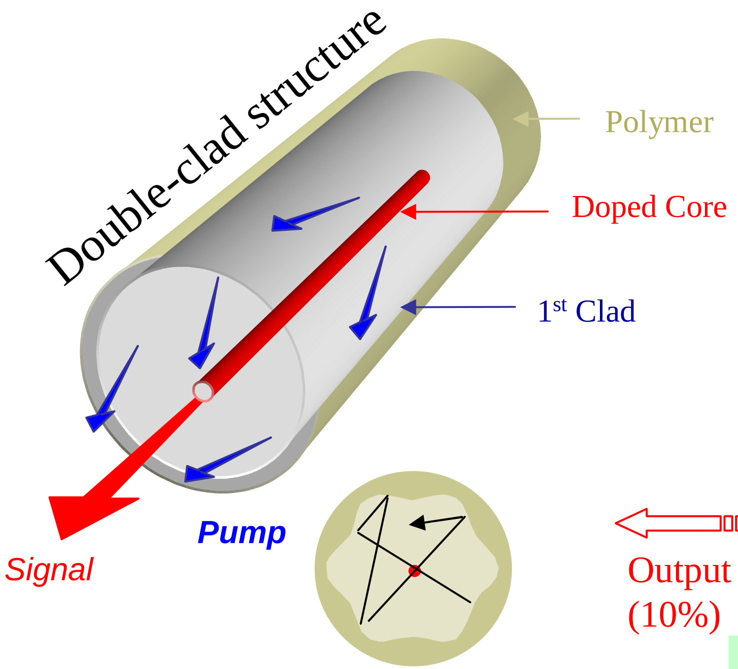
2. NLPR fiber laser

Experimental setup

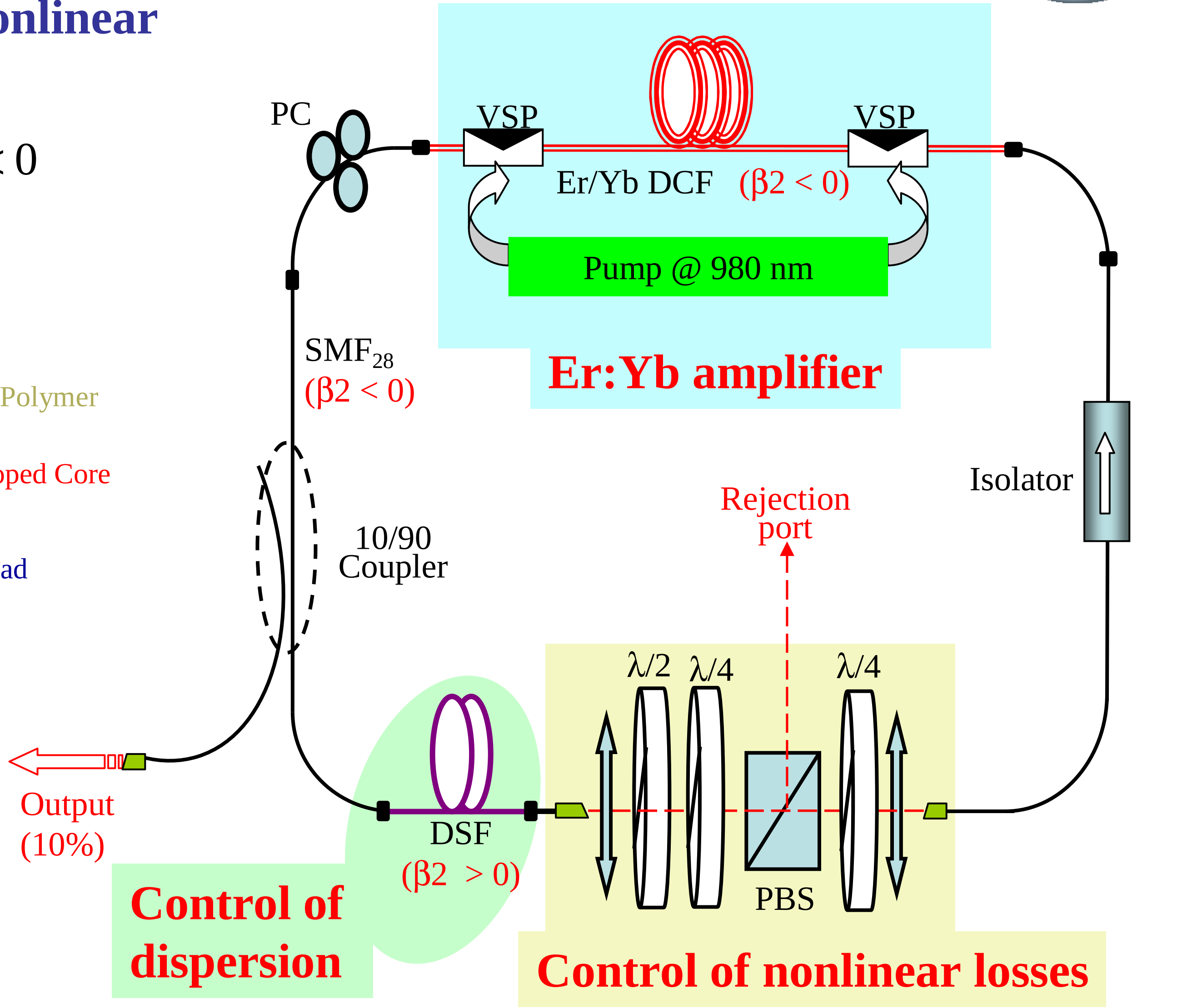
Mode-locking through nonlinear polarization rotation

$$\beta_2^{Tot} L = -0.04 \text{ ps}^2 < 0$$

Soliton regime



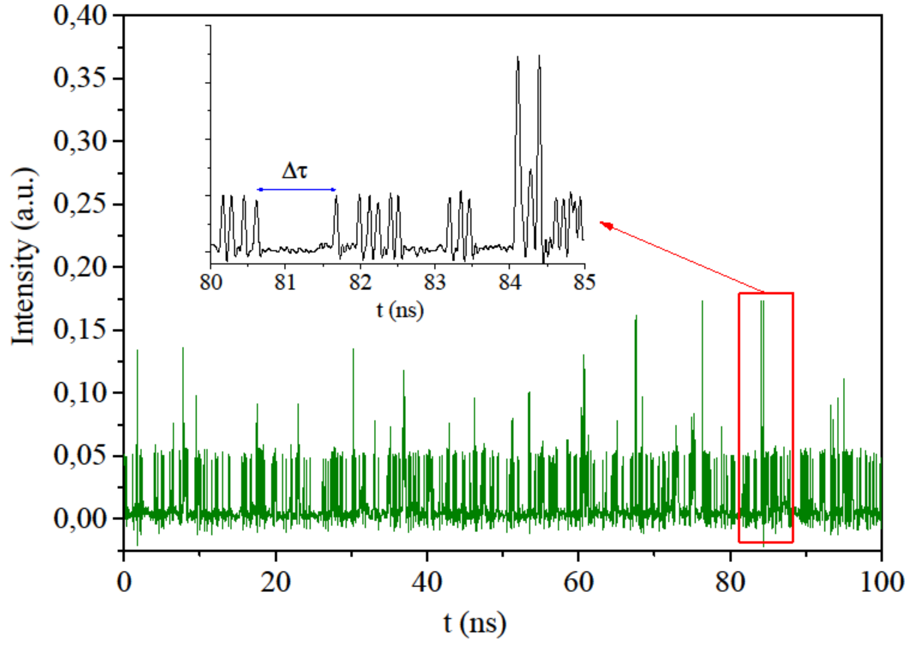
- ✓ T= 105 ns
- ✓ P_p= 3.3 W



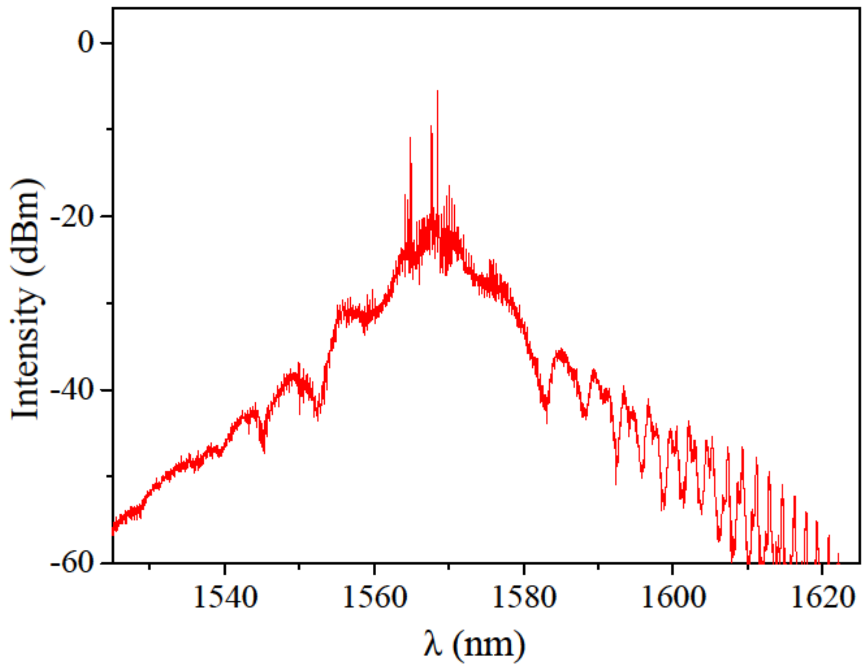
2. NLPR fiber laser

Soliton Gas

Time distribution



Optical spectrum



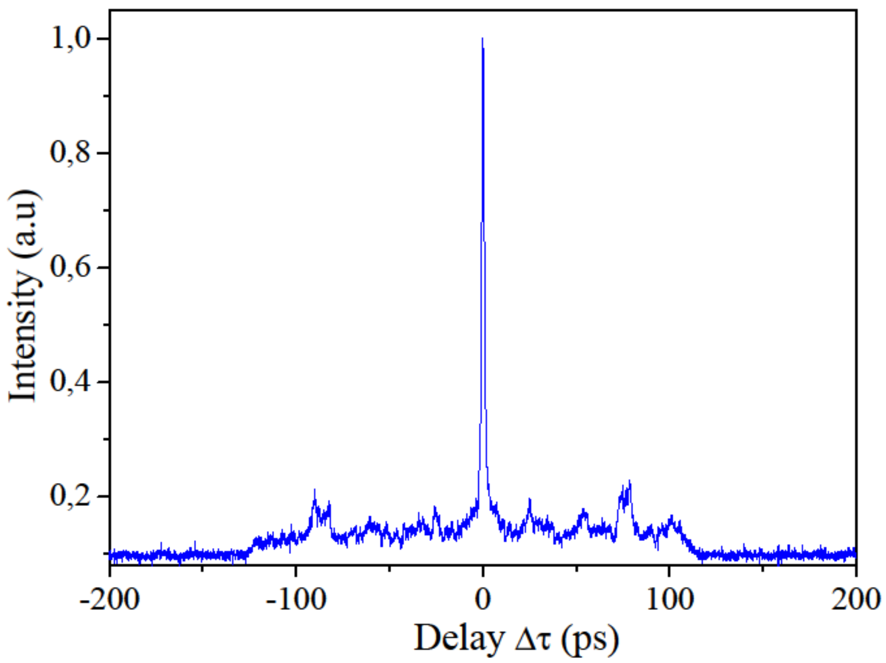
- ~ 380 solitons
- Fill all the available space along the cavity ⇒ gas
- Delays $\Delta\tau$ strongly vary

- No spectral modulation ⇒ no mutual coherence between pulses

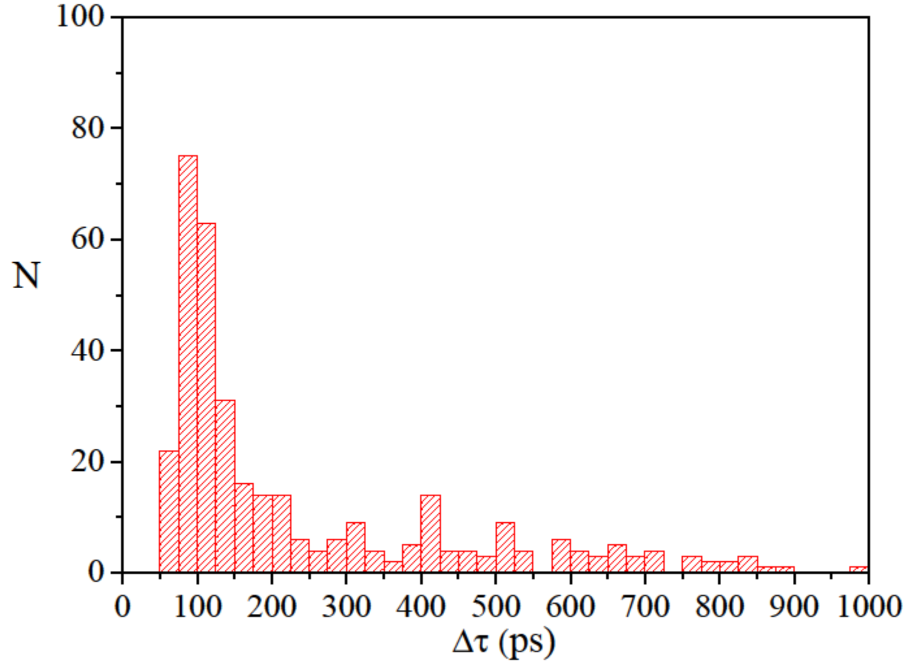
2. NLPR fiber laser

Soliton Gas

Autocorrelation trace



Histogram of the delays



- No regular distribution
- Large pedestal $\Rightarrow$ solitons are in perpetual relative movement

Mean value $\langle \Delta\tau \rangle = 236\,\text{ps}$

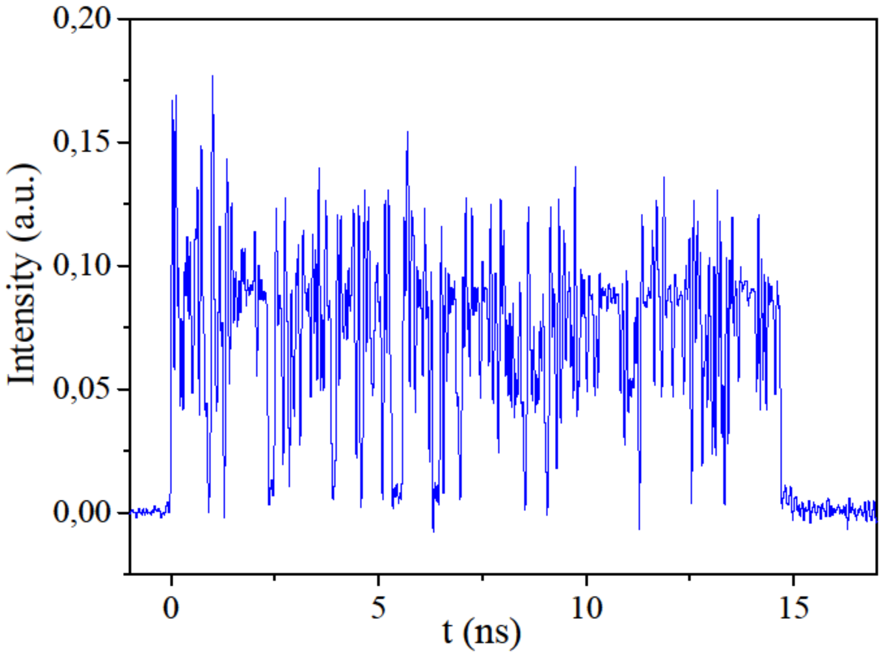
Standard deviation $\sigma_{\Delta\tau} = 207\,\text{ps}$

Analogous to a gas of solitons

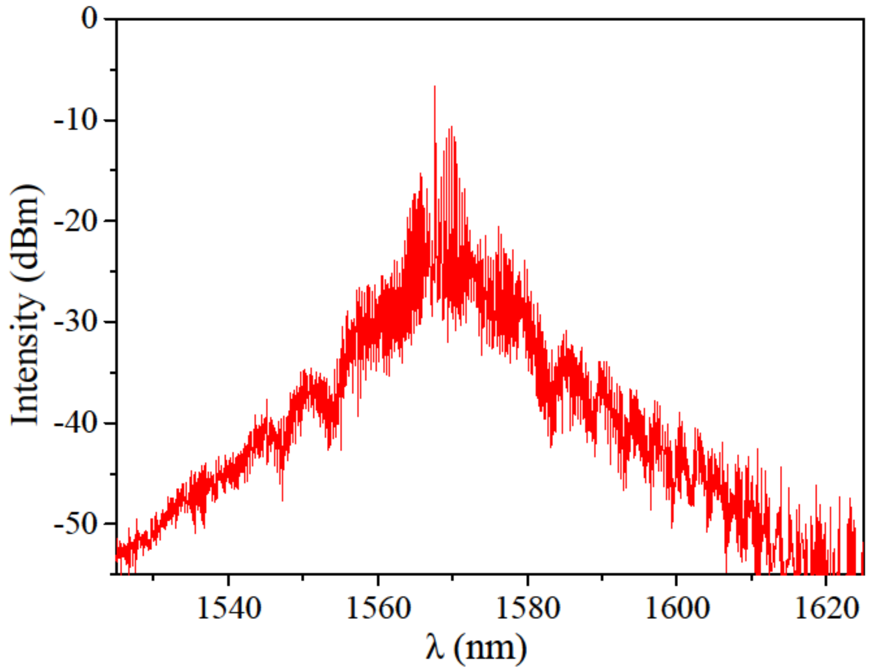
2. NLPR fiber laser

Soliton Liquid

Time distribution



Optical spectrum



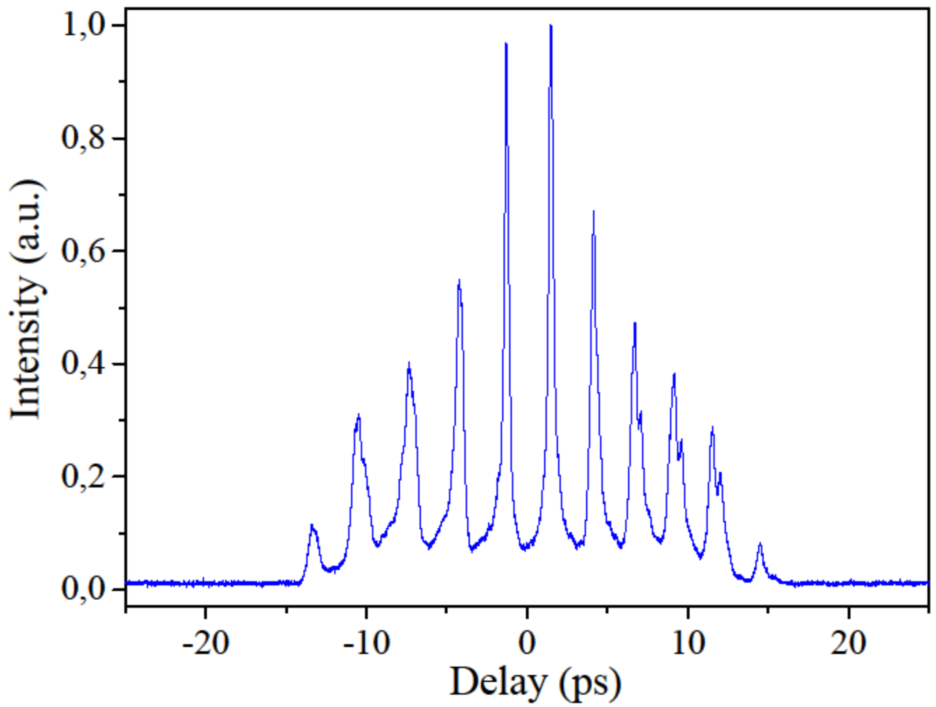
- ~ 400 solitons
- Fill only a small part of the the cavity ⇒ liquid or solid
- Solitons move ⇒ liquid

- Small spectral modulation ⇒ small mutual coherence between pulses

2. NLPR fiber laser

Soliton Liquid

Autocorrelation trace



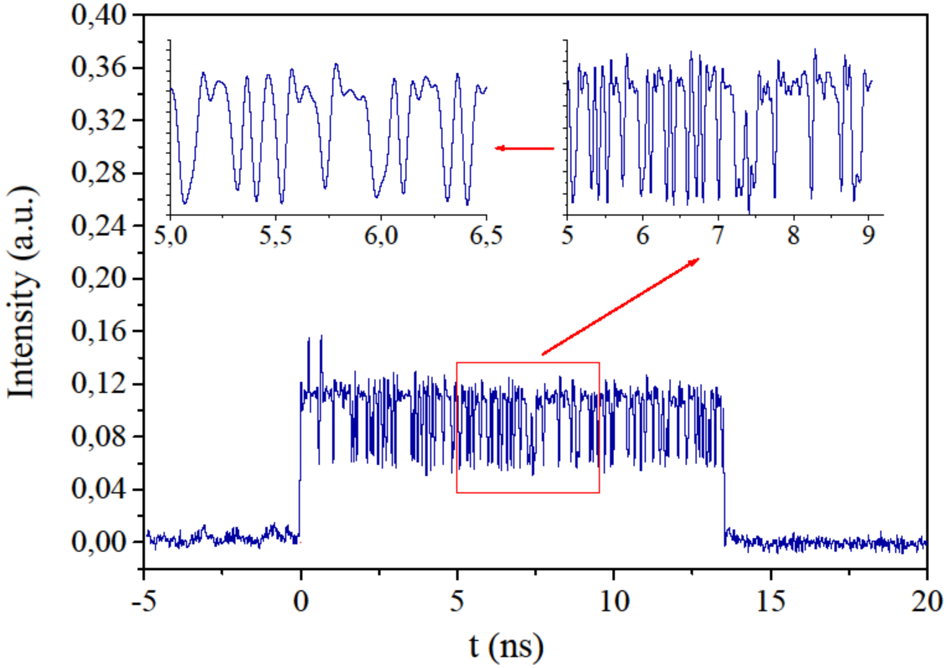
- Small pedestal ⇒ solitons are in perpetual relative movement
- Difficult to characterize due to the small separation between pulses and to their perpetual movement (bound states can be created and destroyed)

⇒ **Analogous to a liquid of solitons (or clusters of solitons)**

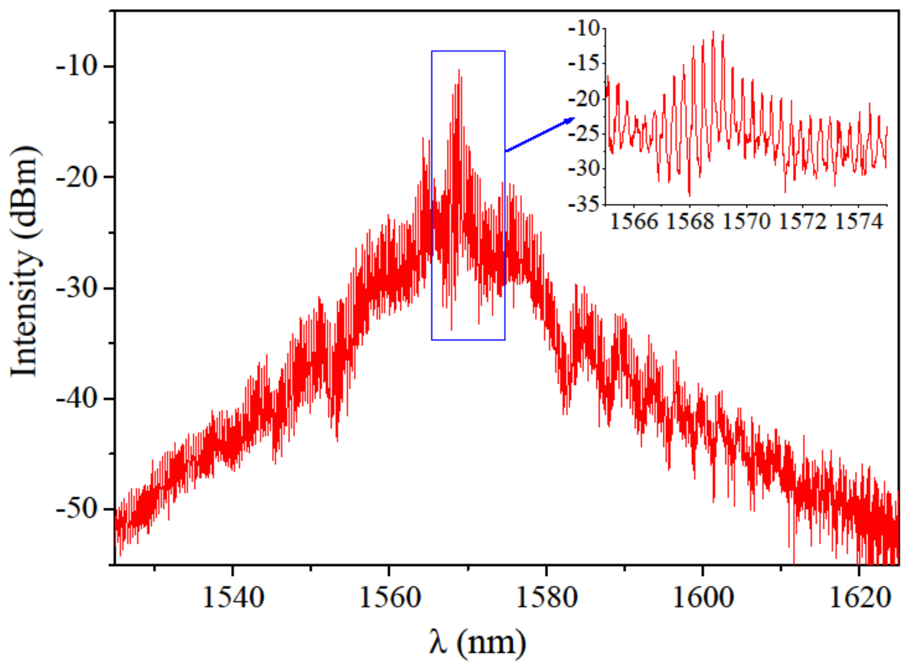
2. NLPR fiber laser

Soliton Polycrystal

Time distribution



Optical spectrum



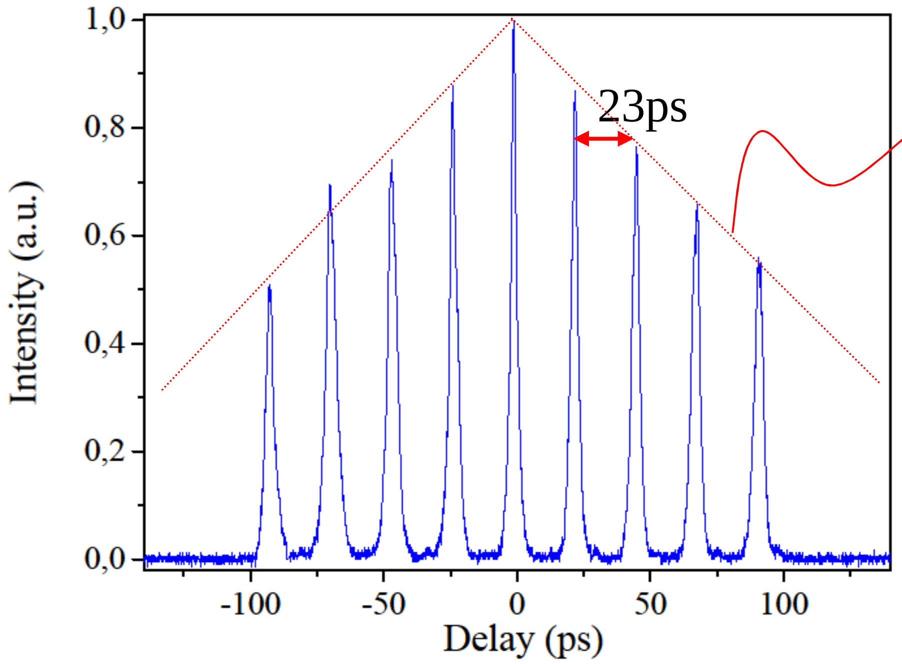
- ~ 520 solitons
- Fill only a small part of the the cavity ⇒ liquid or solid
- Solitons at rest ⇒ solid
- No order at large scale ⇒ glass

- Moderate spectral modulation ⇒ mutual coherence between pulses

2. NLPR fiber laser

Soliton Polycrystal

Autocorrelation trace



Triangular envelop ⇒ bound-state of 8 solitons

- No pedestal ⇒ solitons are at rest
- Order at small scale ⇒ microcrystal

Incoherent mixture of bound-state of variable number of solitons

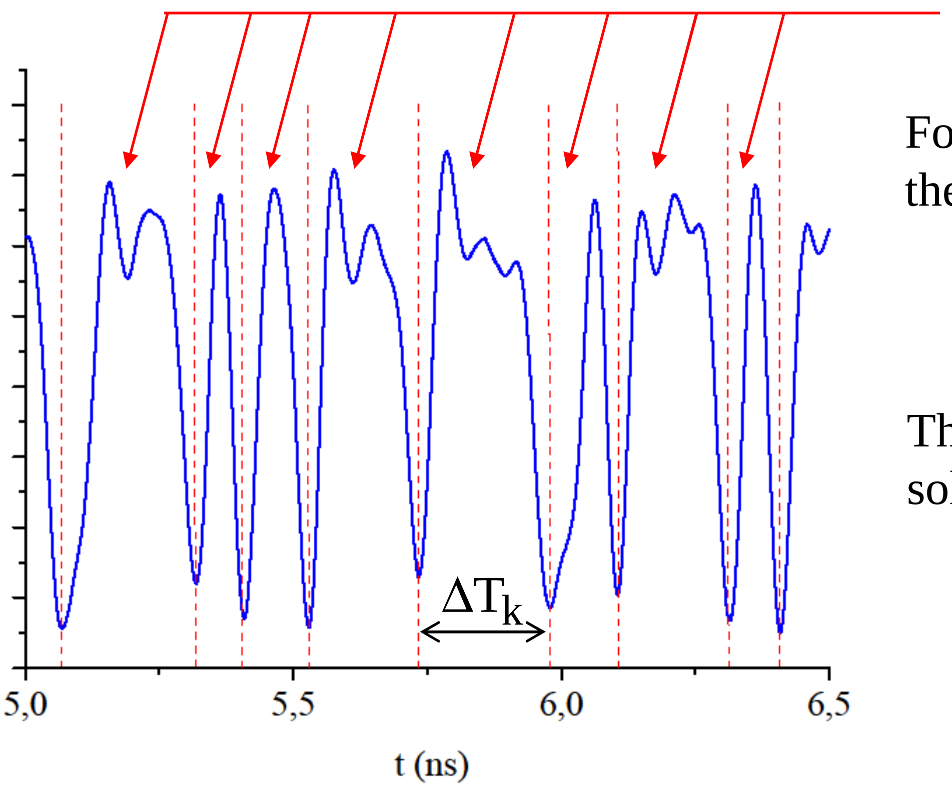
Analogous to a polycrystal of solitons

2. NLPR fiber laser

Soliton Polycrystal

How many bound-state in the pattern ?
How many solitons in the different bound-states ?

Regular spectral modulation ⇒ constant pulse separation in all bound-states, 23 ps



For a given bound-state k, the number of pulses is obtained from

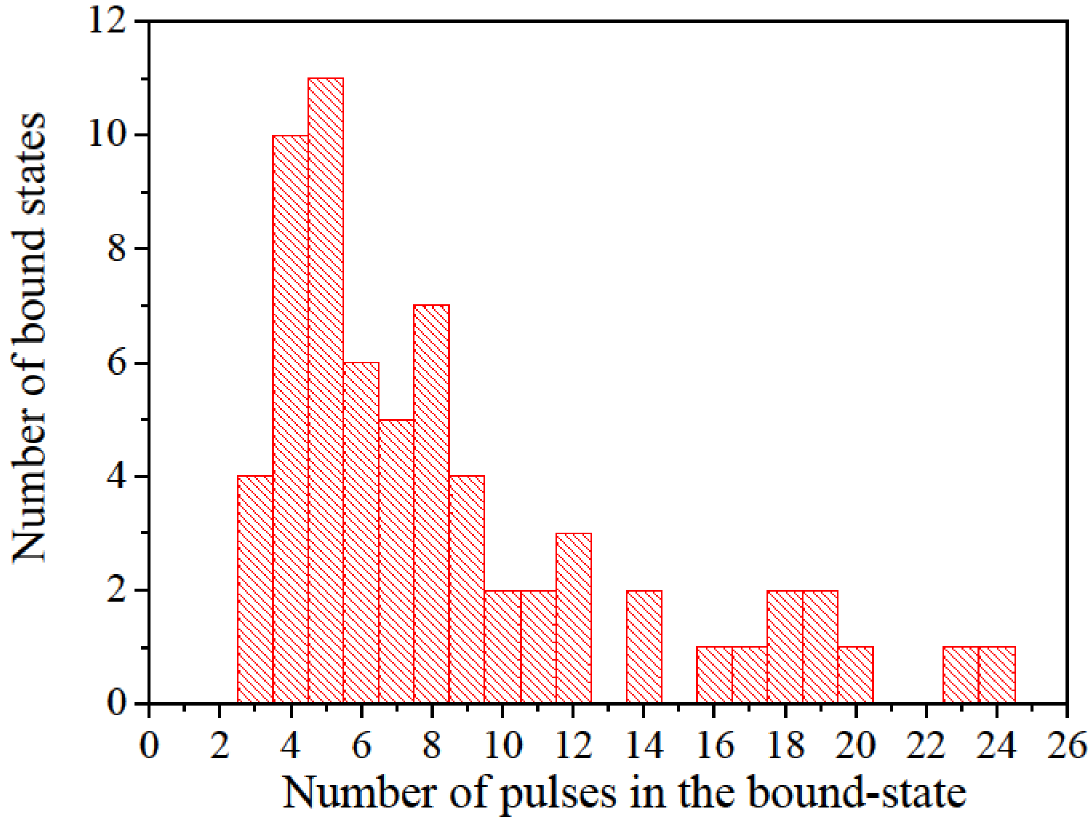
$$N_k = \frac{\Delta T_k(ps)}{23ps}$$

This is repeated for every ‘packet’ of solitons visible in the temporal trace

2. NLPR fiber laser

Soliton Polycrystal

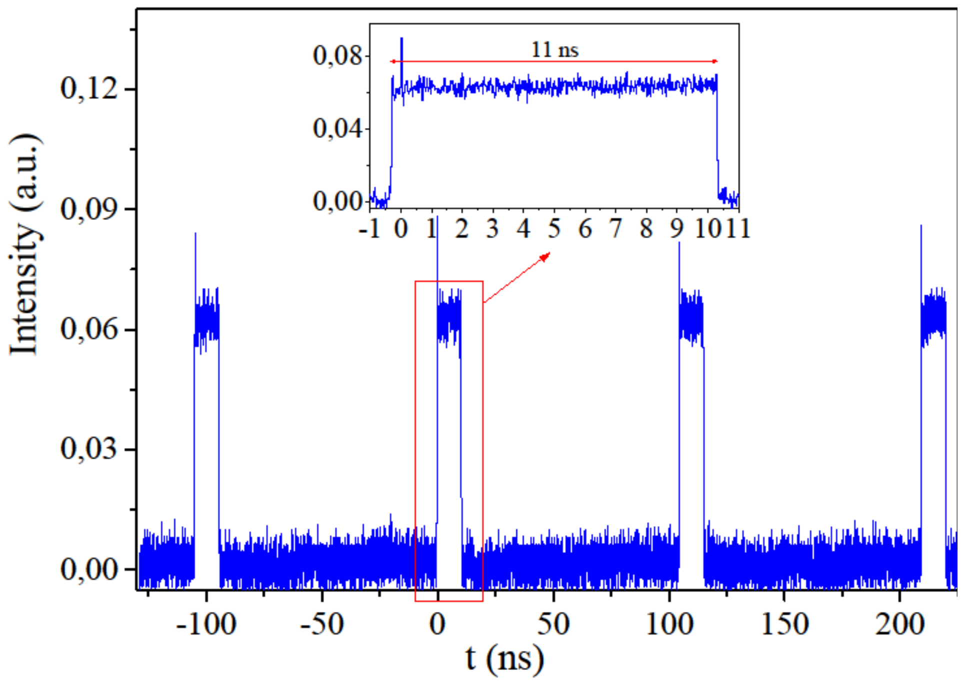
Histogram of the number the bound-states containing a given number of solitons



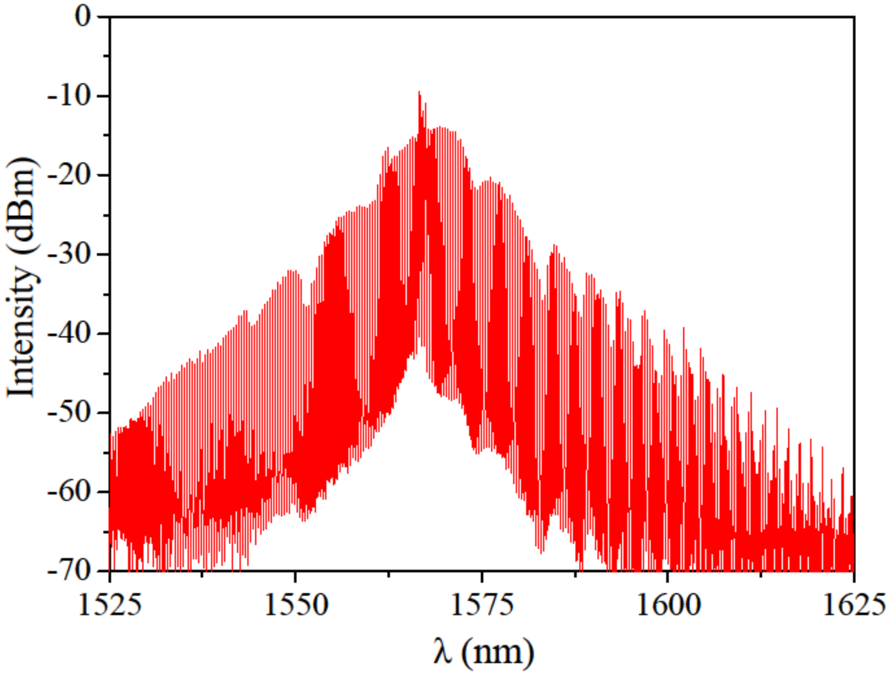
2. NLPR fiber laser

Soliton Crystal

Time distribution



Optical spectrum



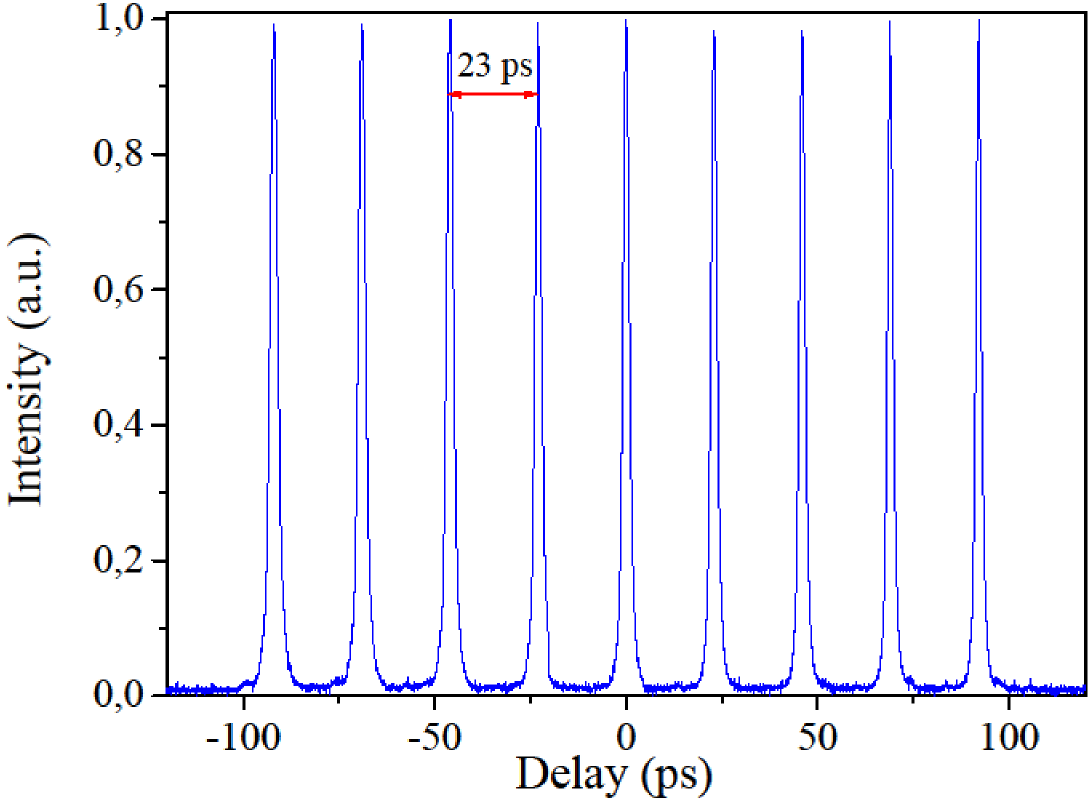
- ~ 480 solitons
- Fill only a small part of the the cavity ⇒ liquid or solid
- Solitons at rest ⇒ solid

- Strong spectral modulation ⇒ mutual coherence between pulses
- Regular modulation ⇒ pulses are equidistant

2. NLPR fiber laser

Soliton Crystal

Autocorrelation trace



- Equidistant and identical pulses

⇒ Bound-state of hundreds of solitons

$$N = \frac{11\,\text{ns}}{23\,\text{ps}} \approx 480\,\text{pulses}$$

Analogous to a crystal of solitons

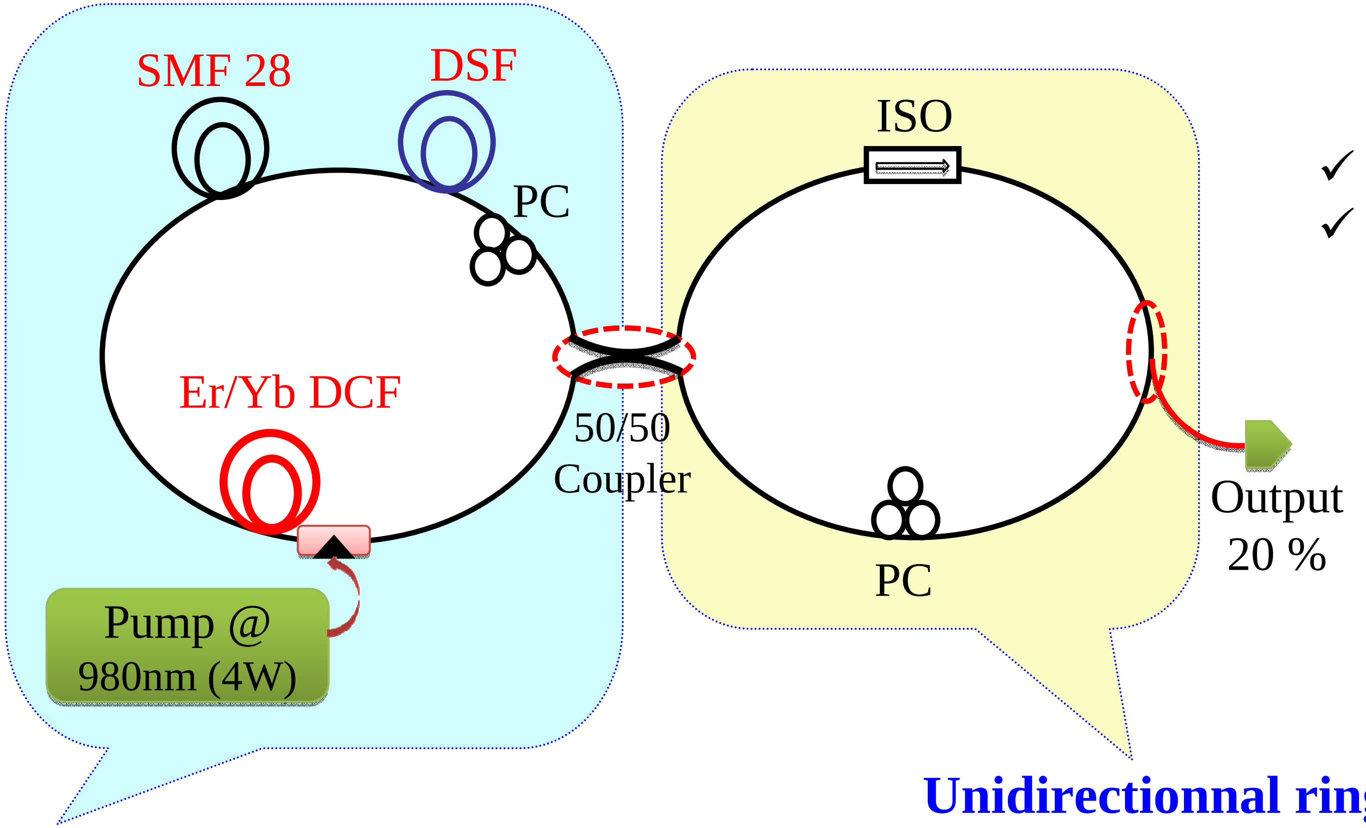
3. Figure-of-eight fiber laser

Experimental setup

Mode-locking through a nonlinear amplifying loop mirror

$\beta_2^{Tot} L = -0.04\ ps^2 < 0$

Soliton regime



- ✓ T= 136 ns
- ✓ P_p= 3.2 W

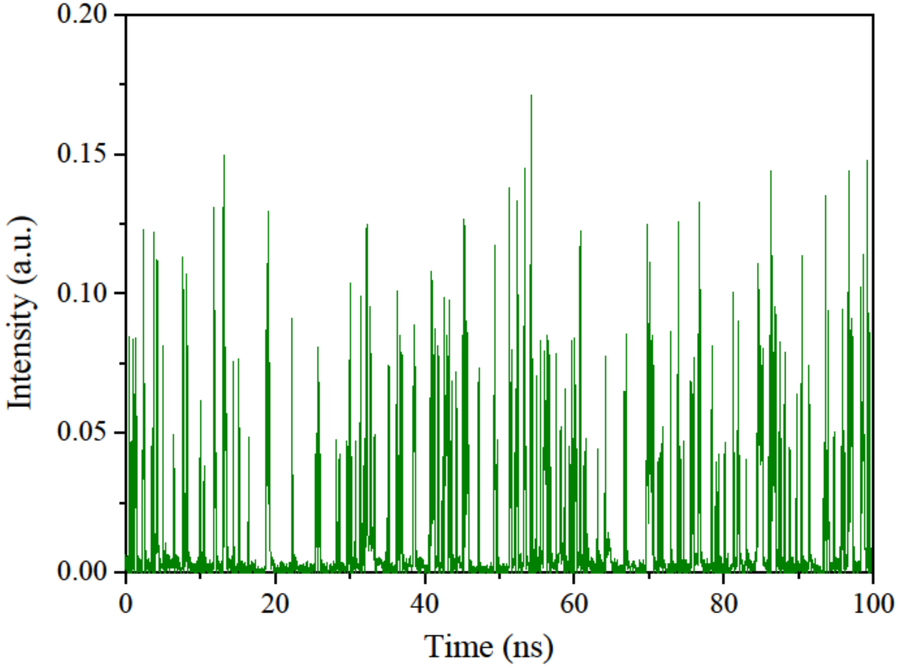
Unidirectionnal ring (UR)

Nonlinear Amplifying Loop Mirror (NLAM)

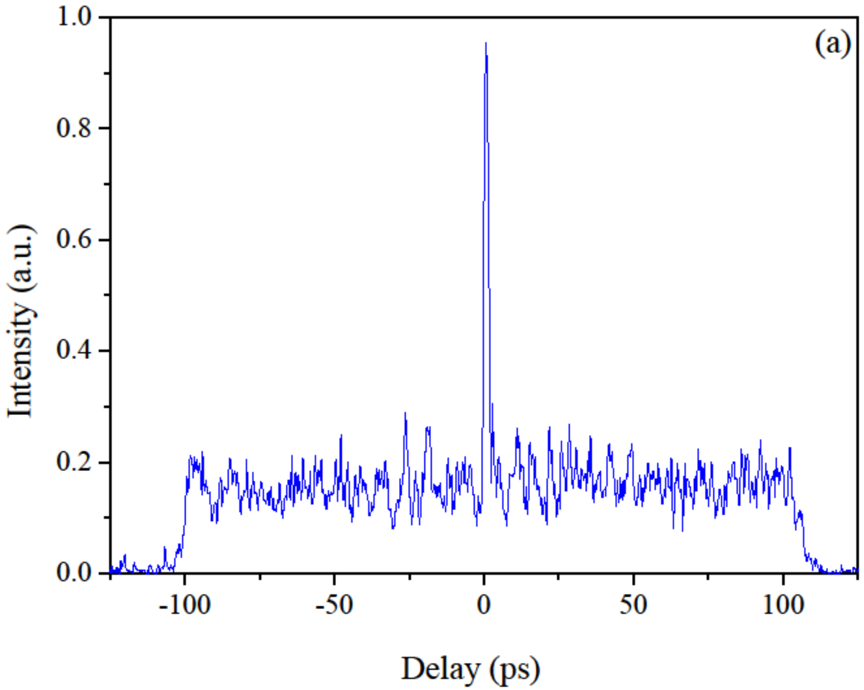
3. Figure-of-eight fiber laser

Soliton Gas

Time distribution



Autocorrelation trace



- Fill all the available space along the cavity and perpetual movement ⇒ gas

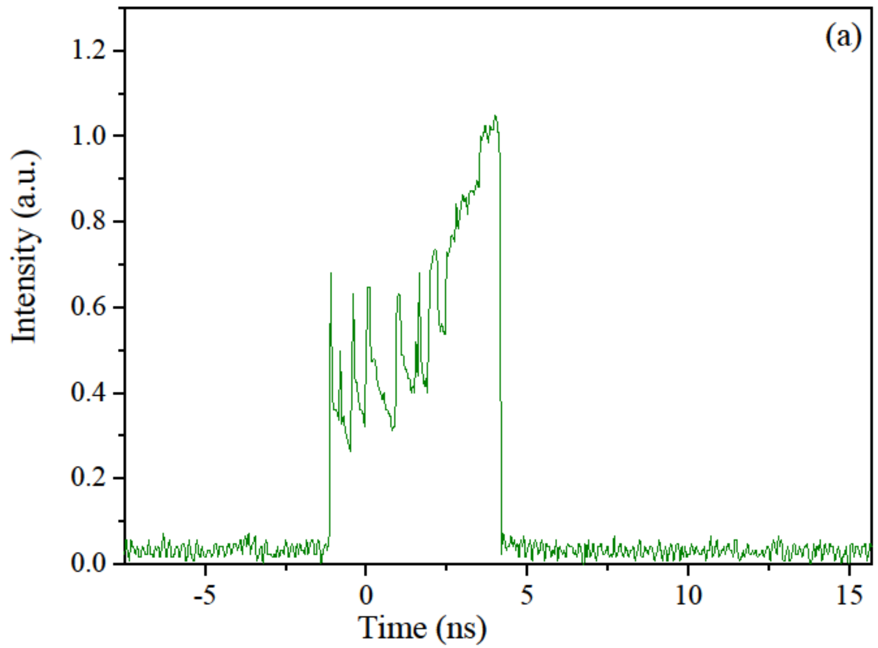
- Large pedestal ⇒ perpetual movement
- No spectral modulation ⇒ no mutual coherence between pulses

⇒ **Analogous to a soliton gas**

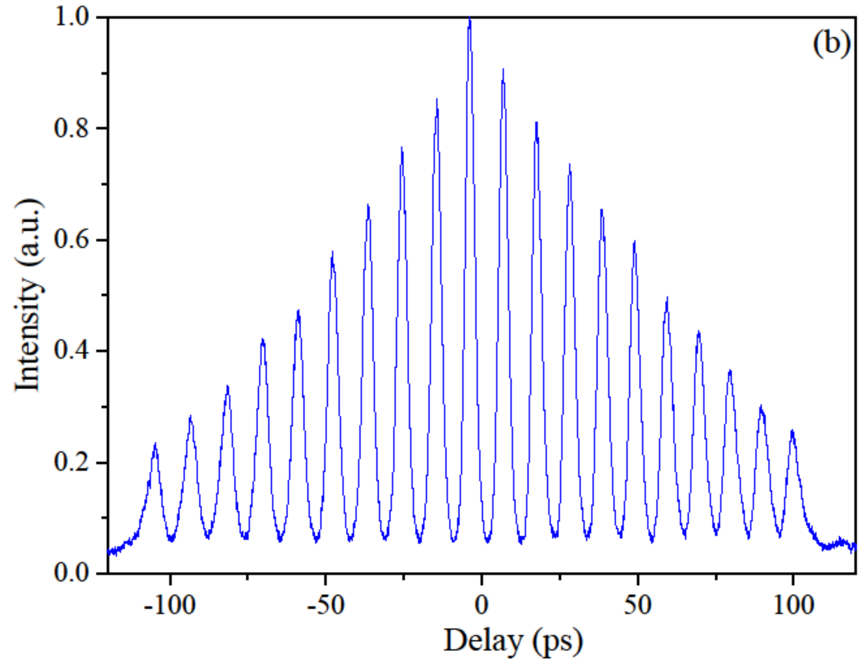
3. Figure-of-eight fiber laser

Soliton Liquid

Time distribution



Autocorrelation trace

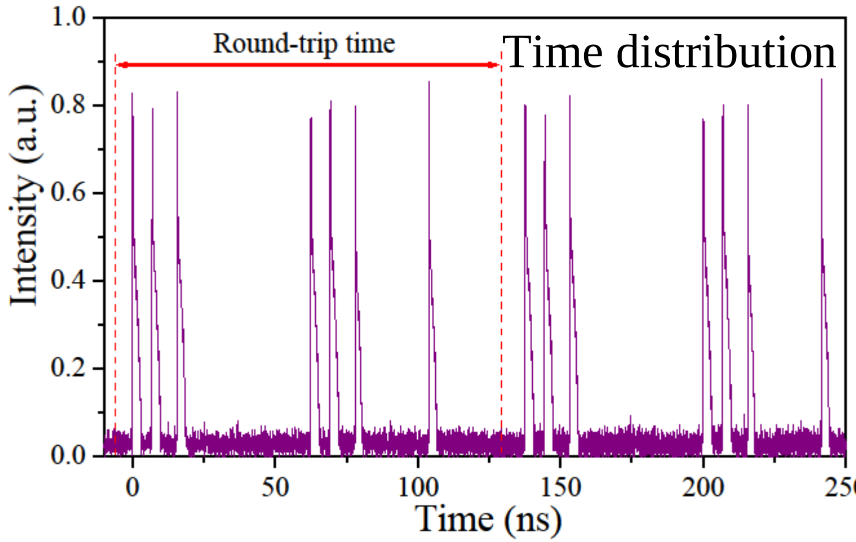


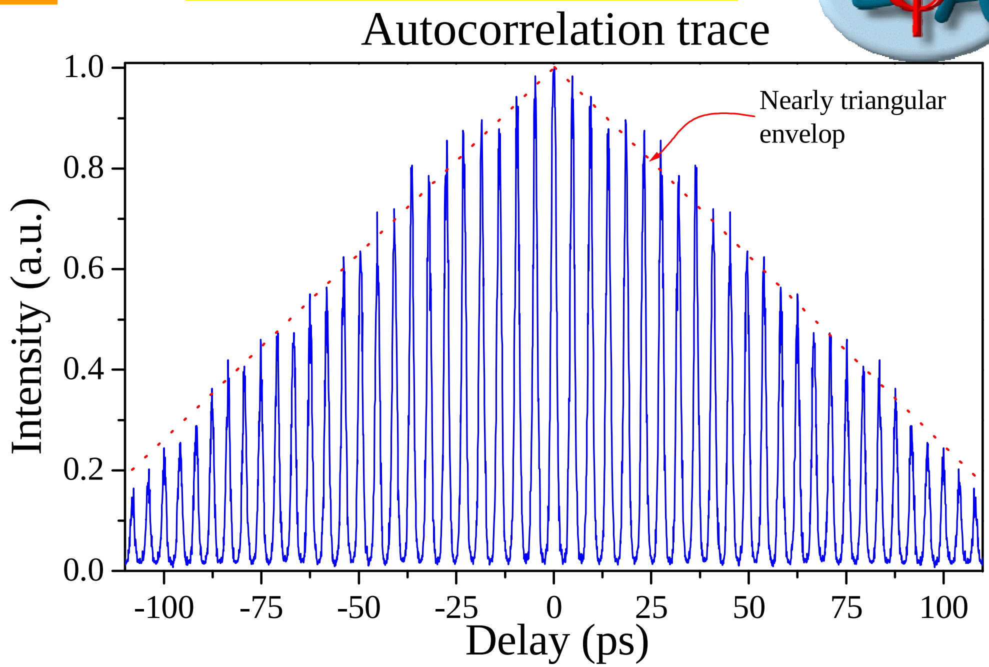
- The solitons fill only a small part of the cavity and are in relative motion.
- The autocorrelation trace exhibits some sharp and nearly equidistant peaks revealing that there exist some clusters of solitons.
- The optical spectrum points out a small modulation which suggests that a small coherence starts to occur between pulses

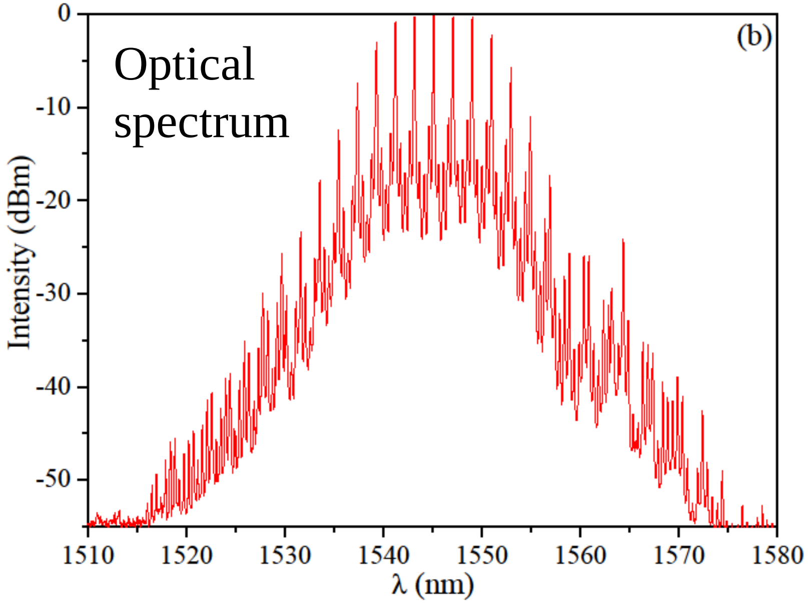
Analogous to a liquid of solitons (or clusters of solitons)

3. Figure-of-eight fiber laser

Soliton Polycrystal







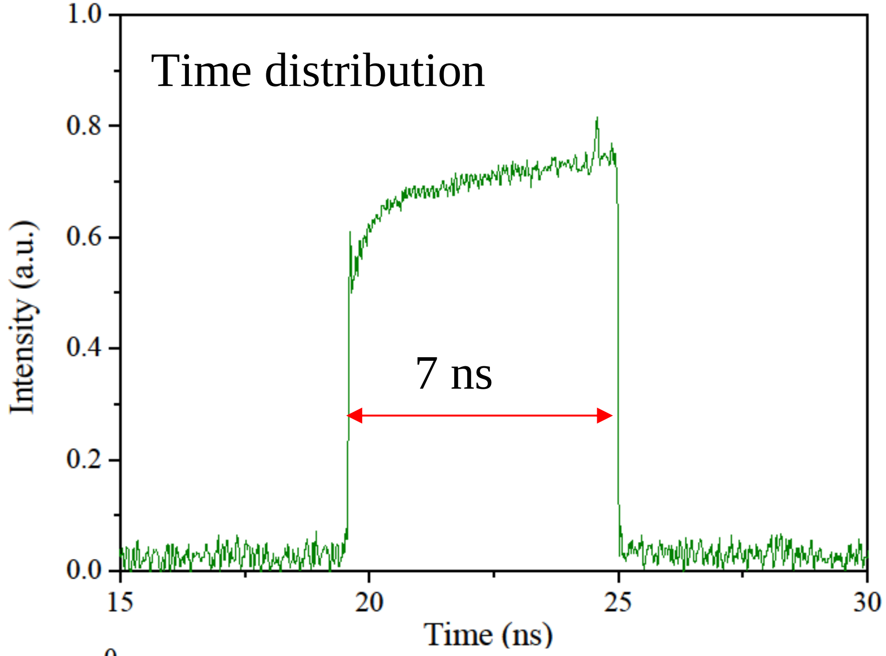
- ➢ Autocorrelation trace: equidistant peaks with a nearly triangular envelope ⇒ soliton crystals.
- ➢ Optical spectrum: strong modulation ⇒ constant phase relation between pulses inside a crystal (strong mutual coherence).

⇒ Incoherent mixture of nearly identical bound-state

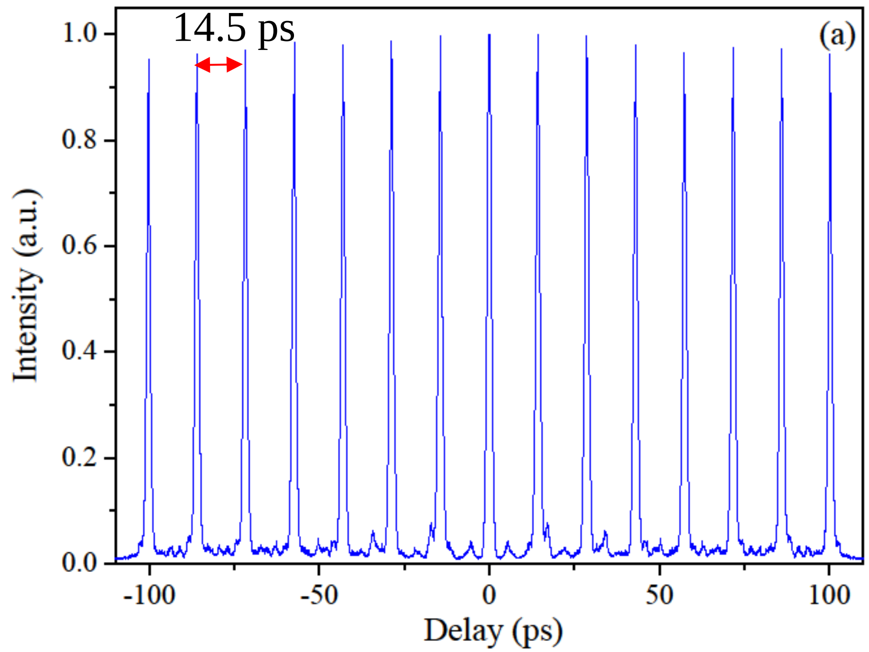
Analogous to a polycrystal of solitons

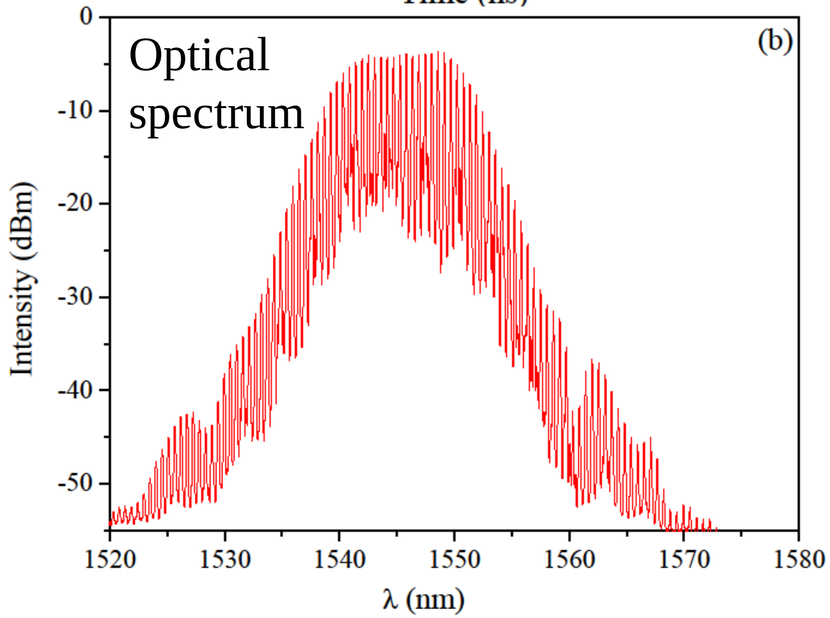
3. Figure-of-eight fiber laser

Soliton Crystal



Autocorrelation trace





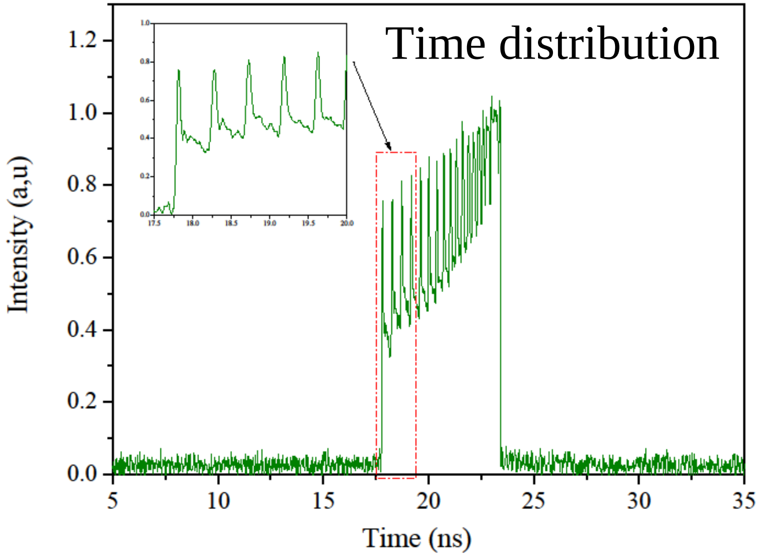
- Regular train of identical and equidistant pulses
- Strong spectral modulation ⇒ strong mutual coherence between pulses

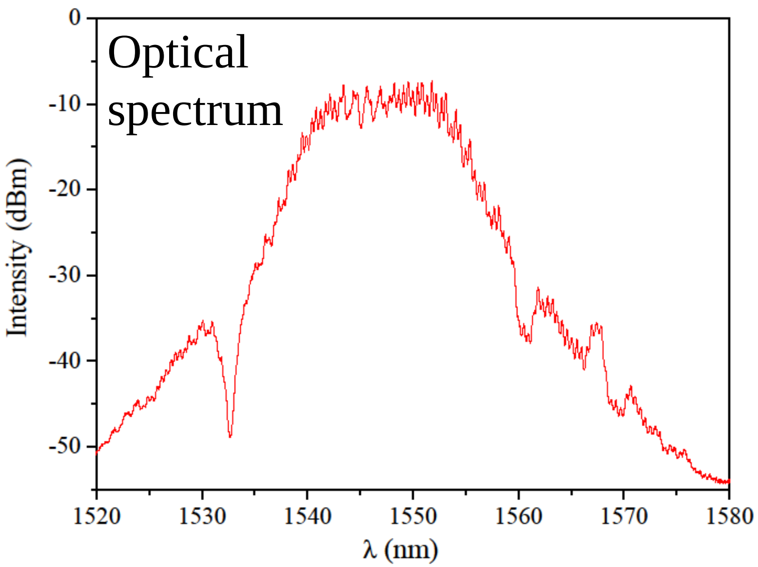
⇒ Bound-state of hundreds of solitons

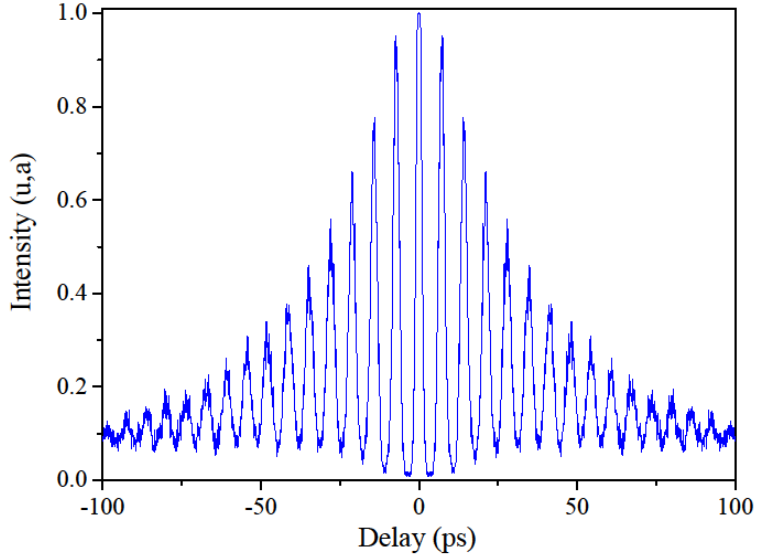
$$N = \frac{7\,\text{ns}}{14.5\,\text{ps}} \approx 480\ \text{pulses}$$

3. Figure-of-eight fiber laser

Diphasic Mixture







- Peaks: solitons are at rest
- Plateaus: solitons move
- Autocorrelation trace: regular distribution inside the peaks
- Optical spectrum: small mutual coherence

➡ Alternate series of solid and liquid states

3. Figure-of-eight fiber laser

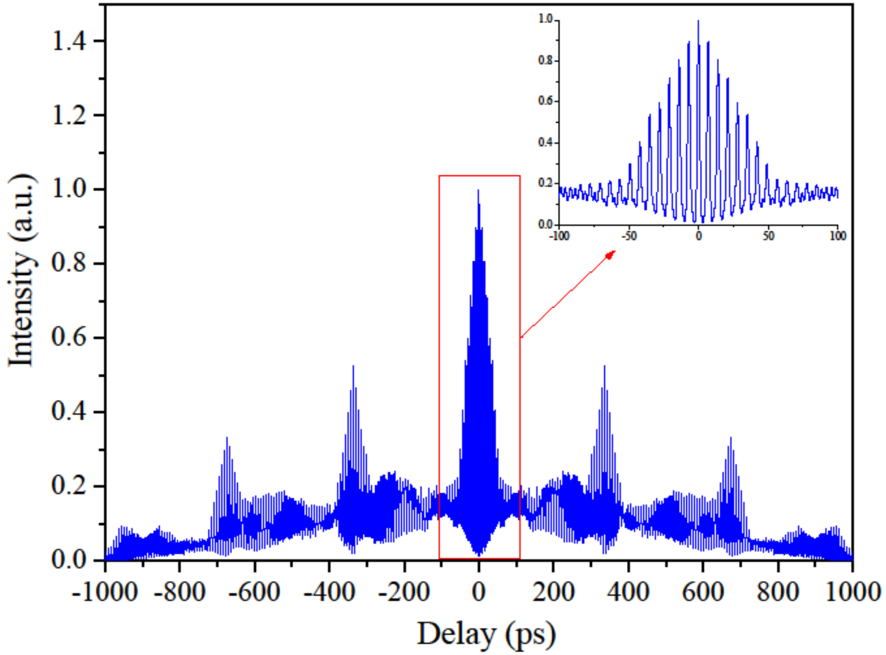
Diphasic Mixture

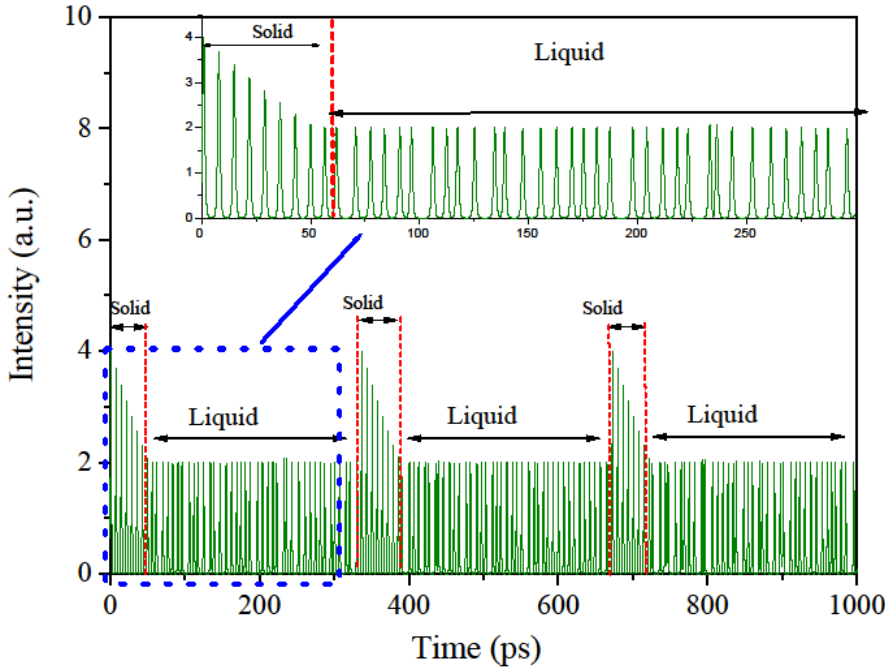
Reconstruction

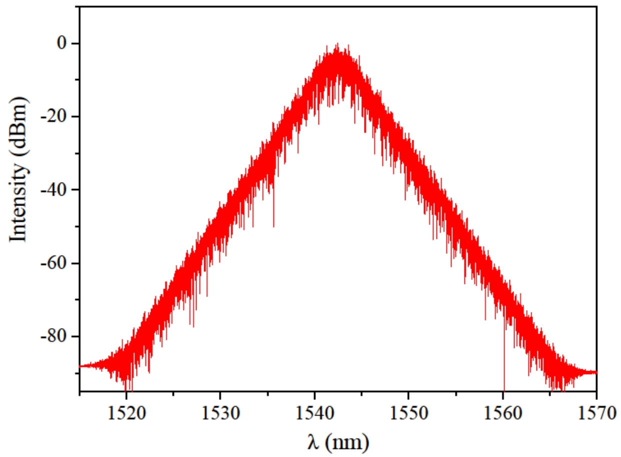
The total electric field consists in an incoherent superposition of alternate solid and liquid states

$$E(t) = \sum_{n=1}^{N} E_n \left(t - \sum_{j=1}^{n} \Delta T_j \right)$$

Odd n's: cristal. Even n's: liquid







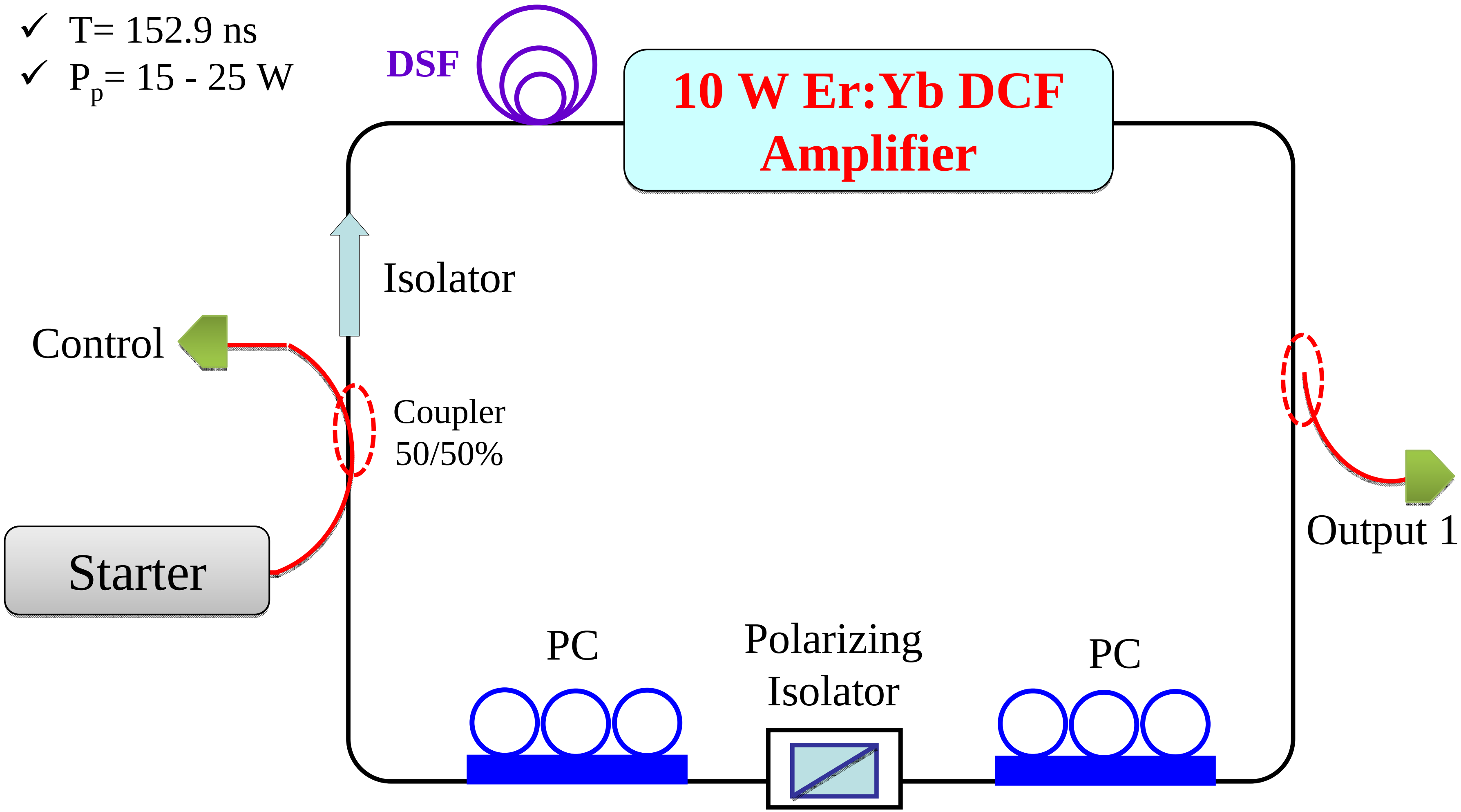
4. 10 W NLPR fiber laser

Experimental setup

All-fiber laser

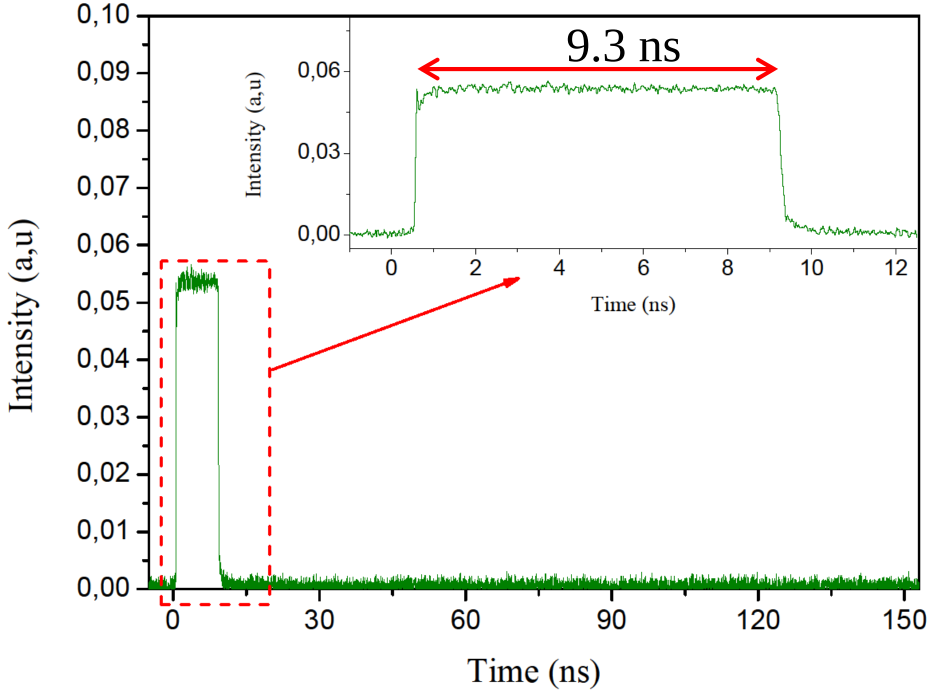
$\beta_2^{Tot} L = -0.12 \text{ ps}^2 < 0$

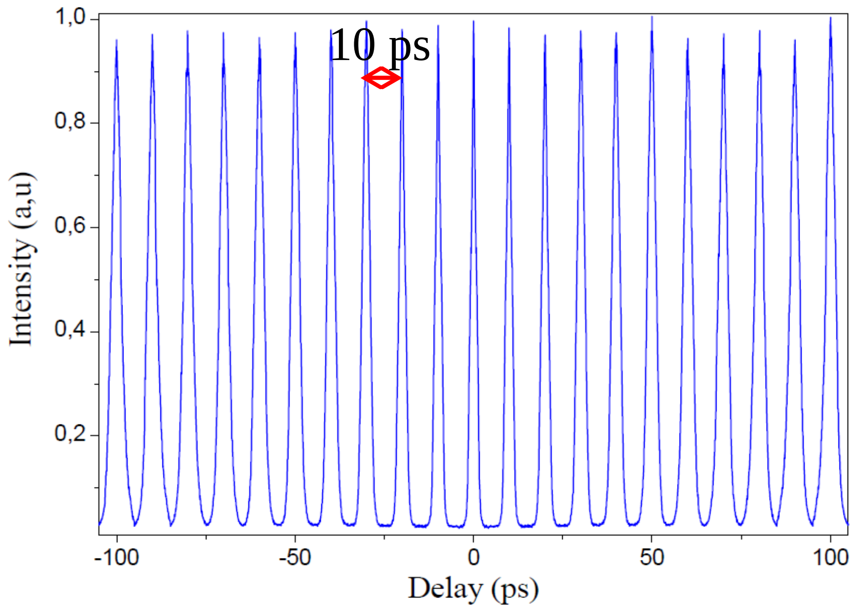
- ✓ T= 152.9 ns
- ✓ P_p= 15 - 25 W



4. 10 W NLPR fiber laser

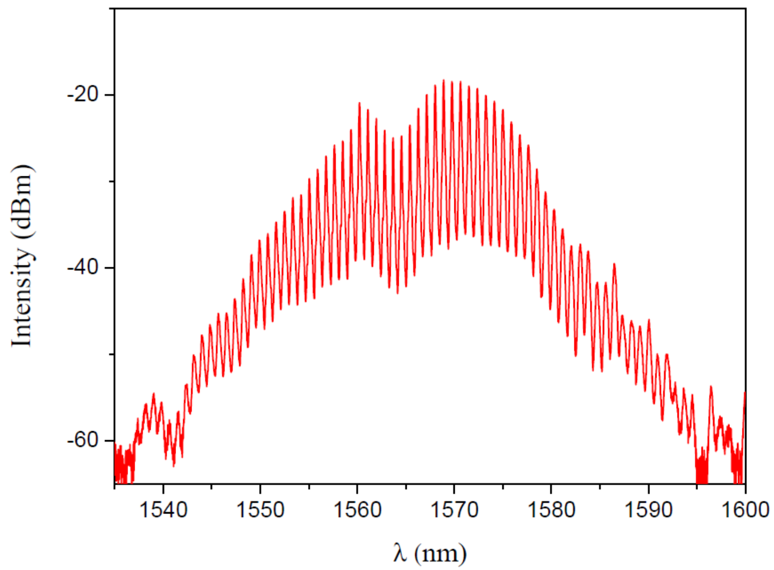
P_p = 15 W





Soliton crystal

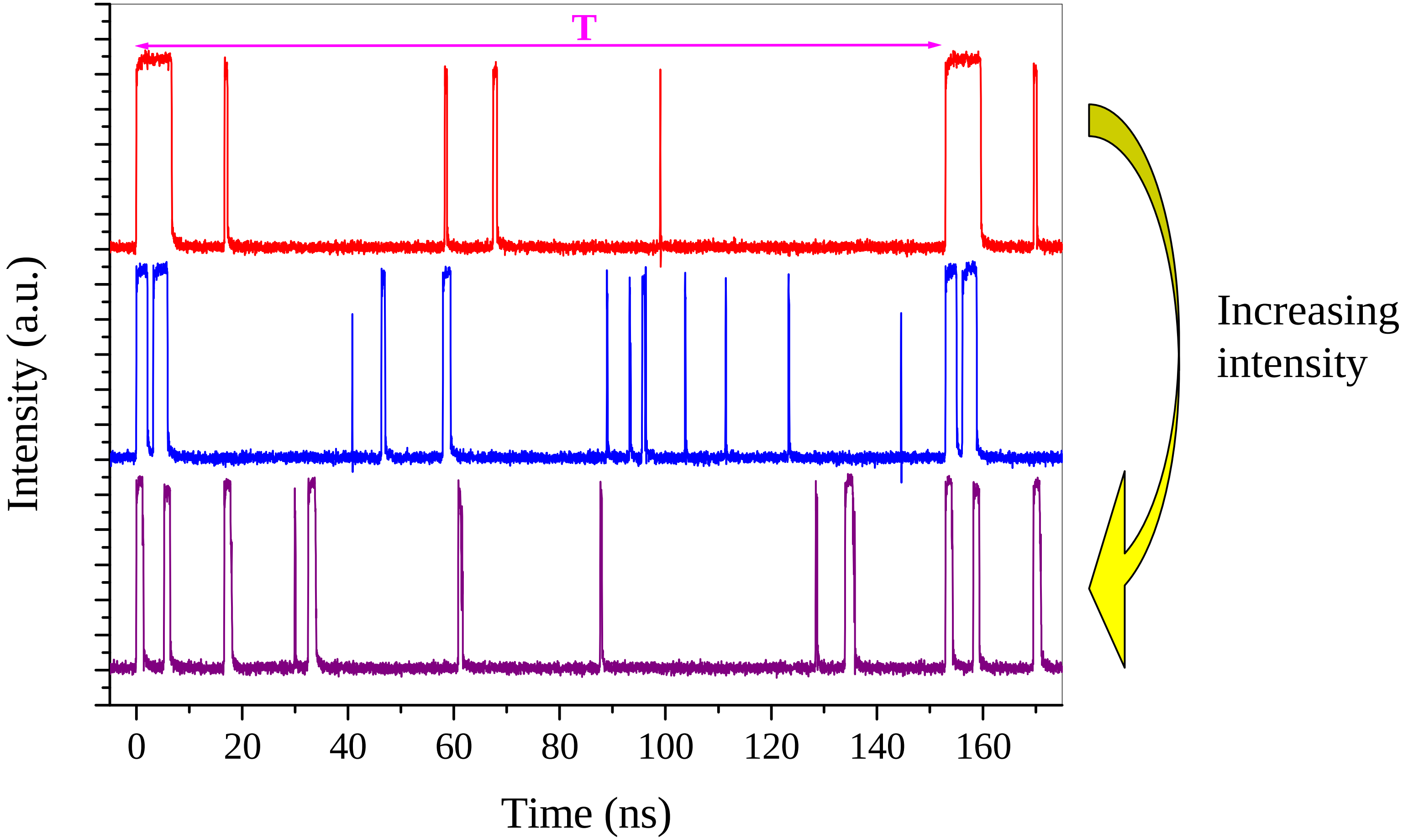
$$N = \frac{9.3\,\text{ns}}{10\,\text{ps}} \approx 930\,\text{pulses}$$



4. 10 W NLPR fiber laser

P_p = 15 W → 25 W

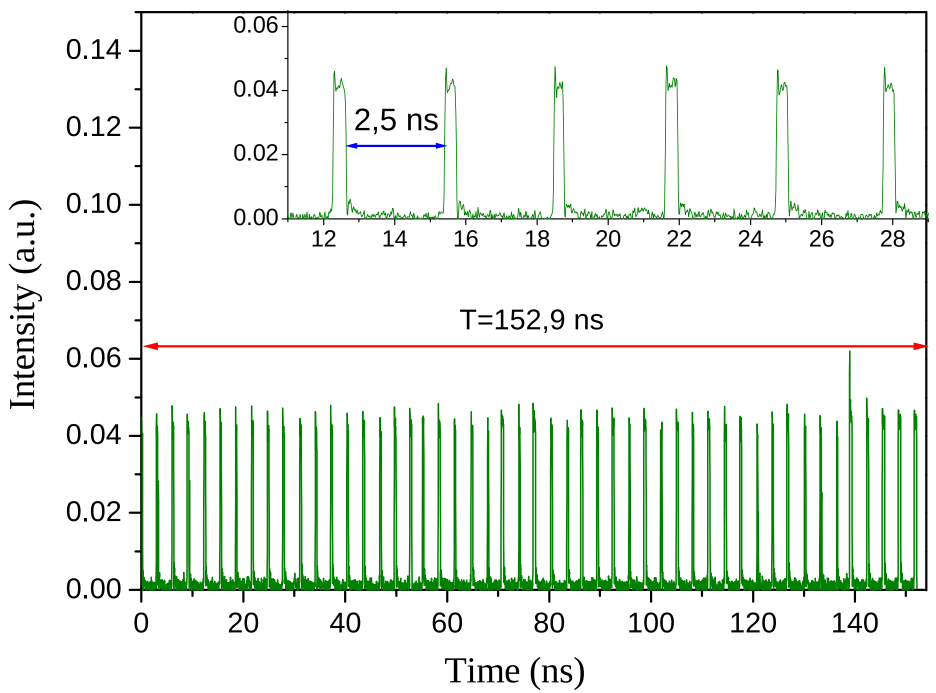
When the pumping is increased, the crystal extent first grows and then the crystal undergoes a dislocation resulting in a splitting into different parts

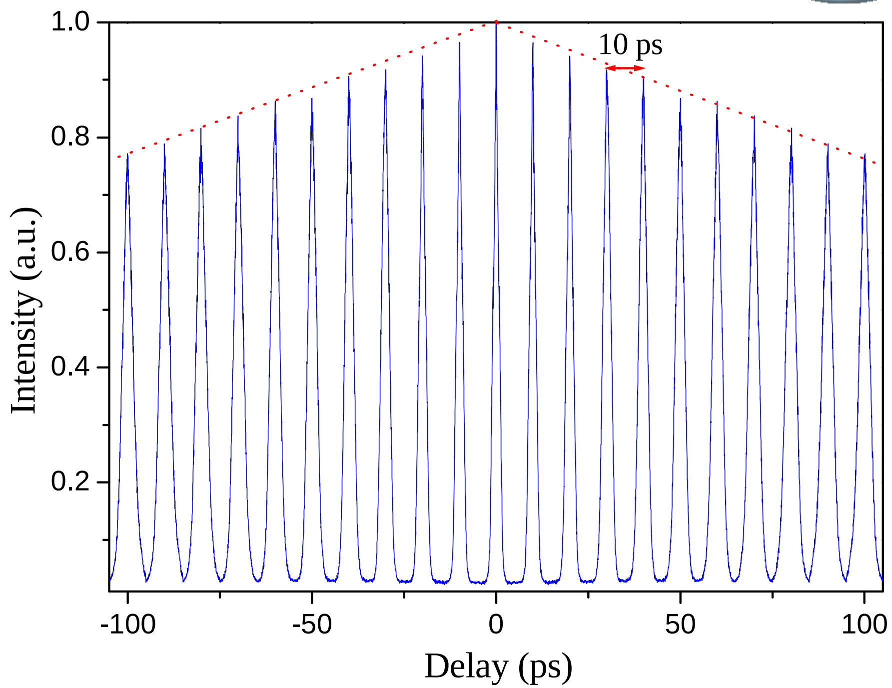


Instability of a soliton crystal of large extent

4. 10 W NLPR fiber laser

P_p = 25 W





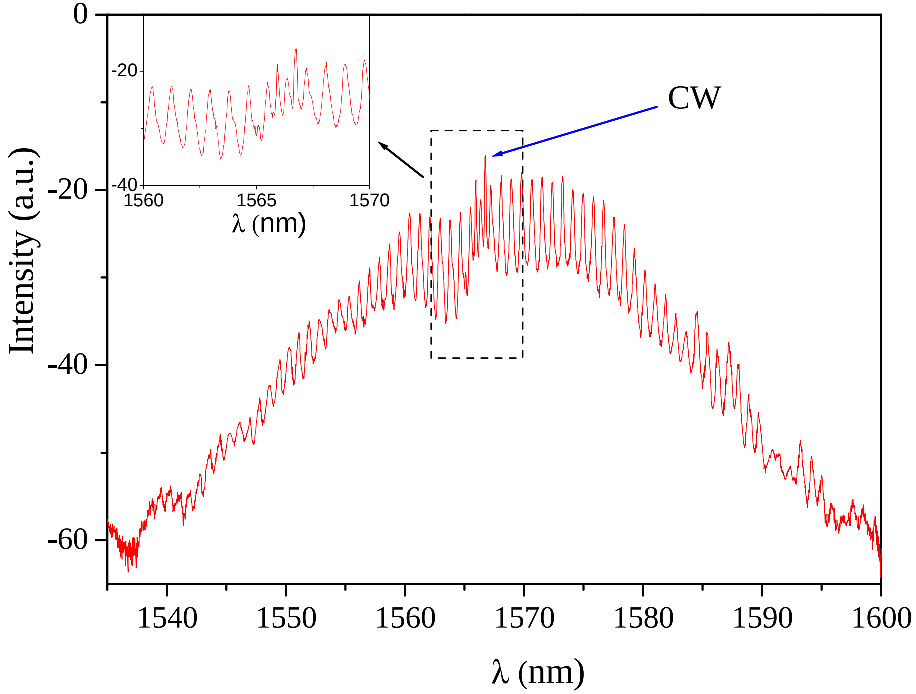
Harmonic regime of soliton packets: 50th harmonic

Each packet is a regular train of about 50 identical and equidistant solitons

⇒ 2500 solitons coexist in the cavity !

4. 10 W NLPR fiber laser

P_p = 25 W



- Spectral modulation ⇒ strong mutual coherence between solitons
- CW component characteristic of HML

Passive harmonic mode-locking of soliton crystals !

5. Conclusions

- ✓ **Soliton patterns analogous to the states of matter**
- ✓ **Comparative study of soliton patterns formation in 1 W F8L and NLPR-based fiber lasers**
- ✓ **Universality of the soliton complexes which are independent of the exact mode-locking mechanism**
- ✓ **New patterns involving distinct soliton phases**
- ✓ **Harmonic Mode-Locking of soliton crystals in a 10 W NLPR-based fiber laser**
- ✓ **Important results for the development of universal dynamical models**

Acknowledgements

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• We are grateful to EEC for partial financial support.

References

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Thank you for your attention !