Universität Konstanz

How to build an Er:fiber femtosecond laser

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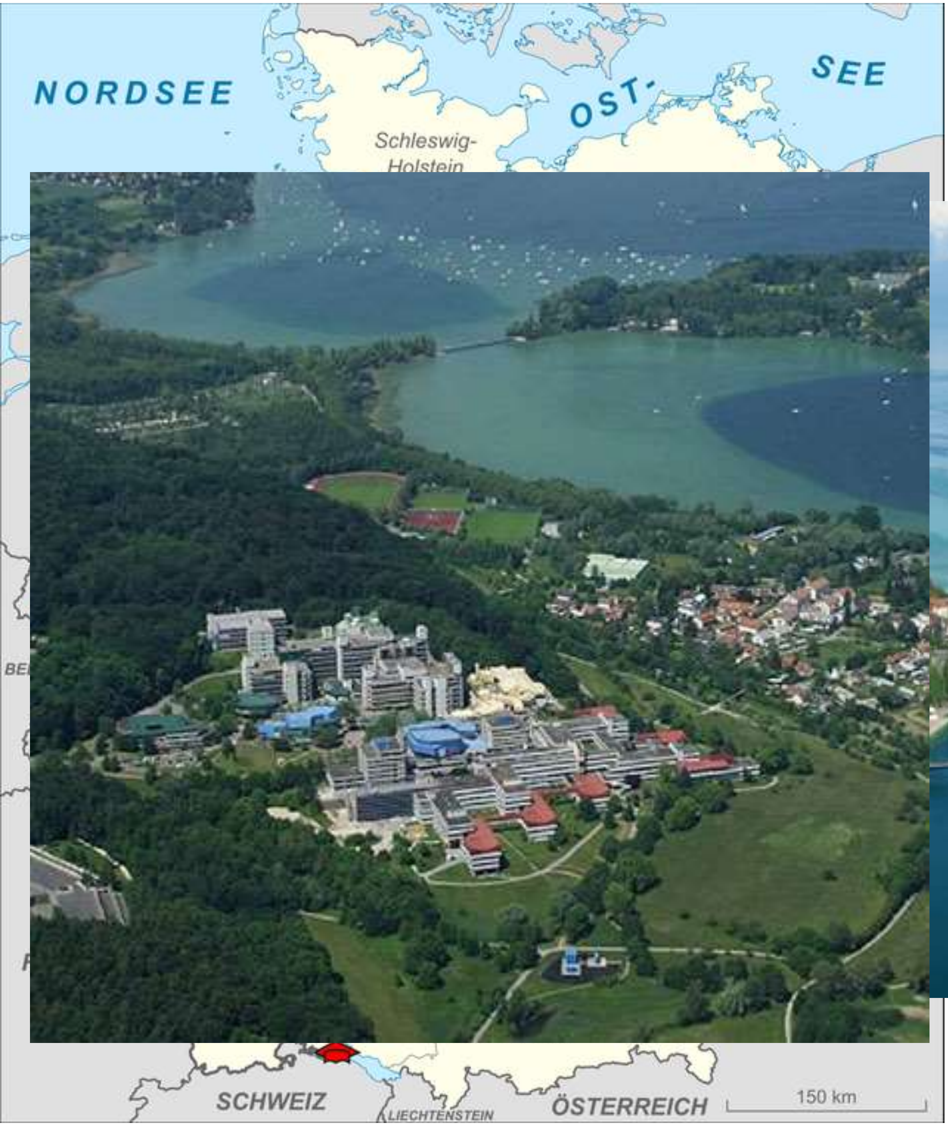
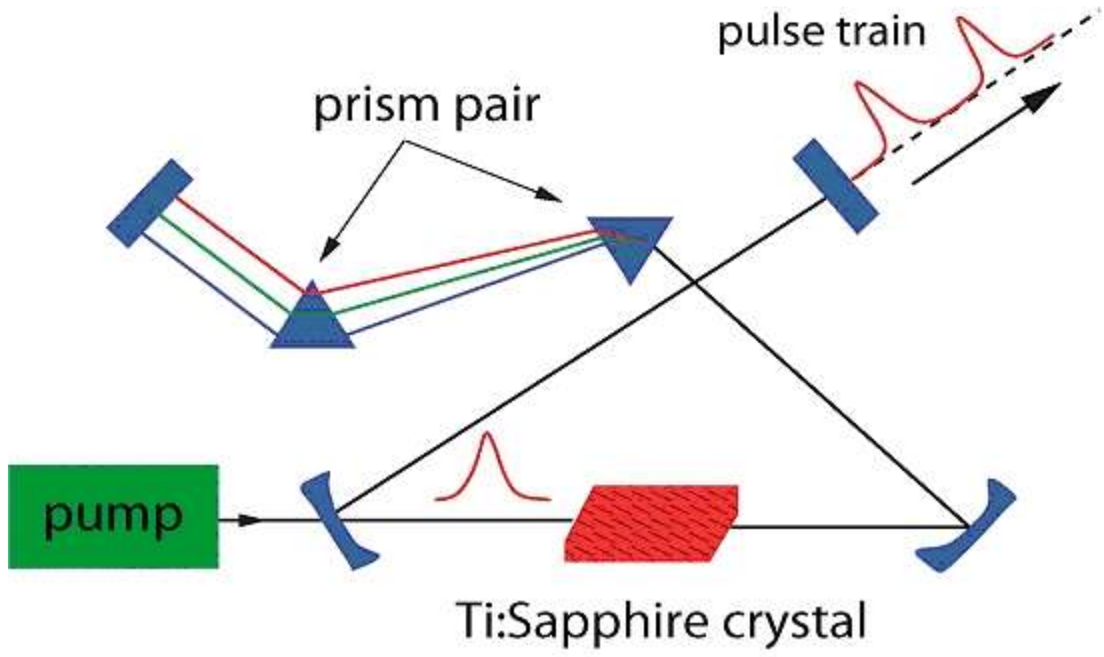
17.02.2016

Konstanz


NORDSEE
OST-
SEE
Schleswig-
Holstein
SCHWEIZ
LIECHTENSTEIN
ÖSTERREICH
150 km

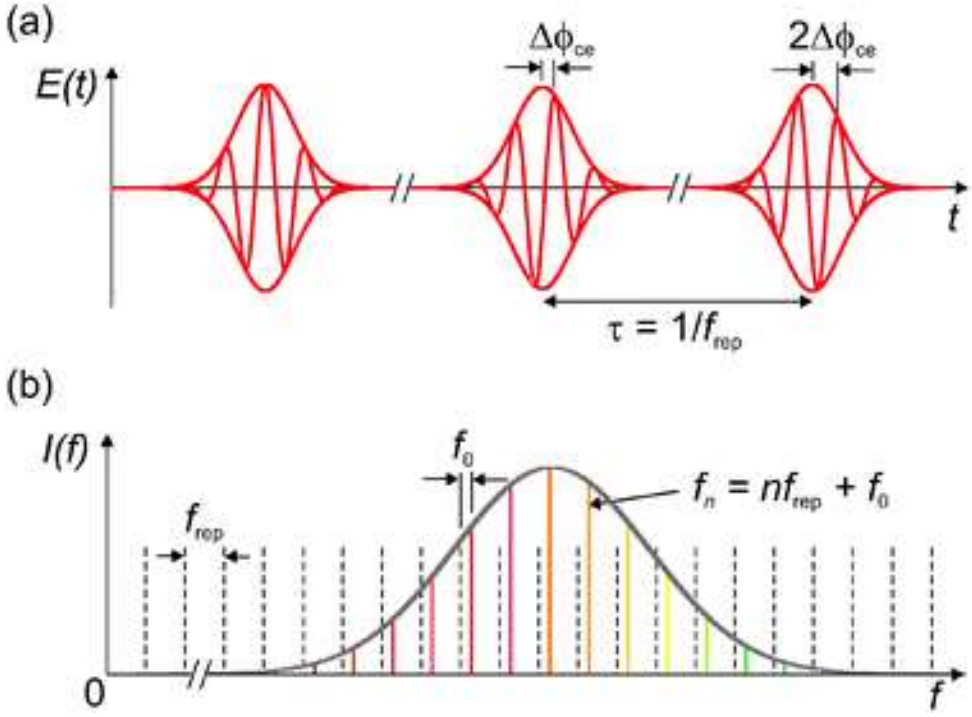
Ultrafast laser



Time domain : pulse train

Frequency domain: comb

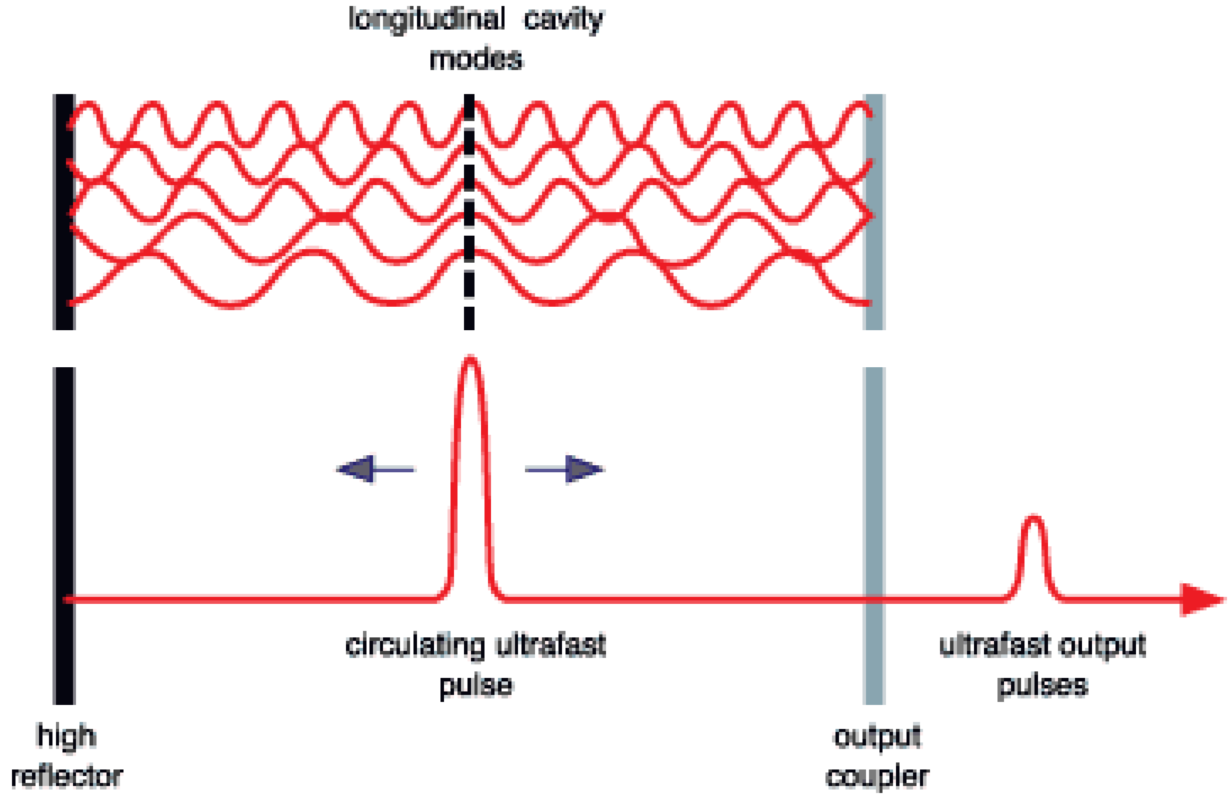
Frequency comb laser



Time domain : pulse train

Frequency domain: comb

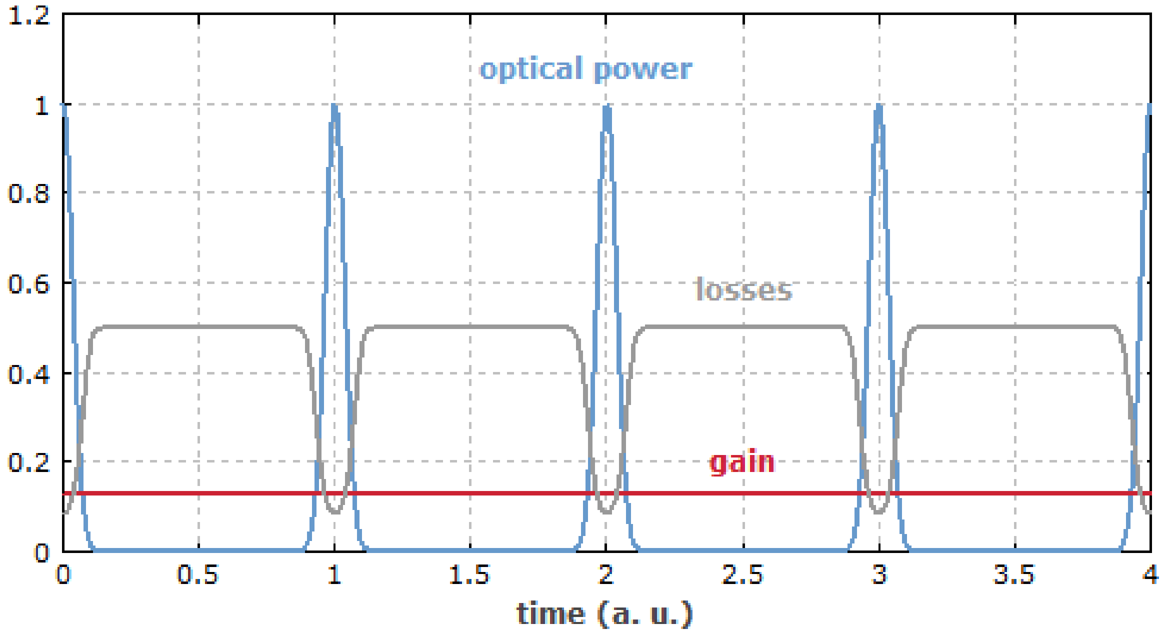
Mode locking



Establish a precise phase relation between the modes of the cavity

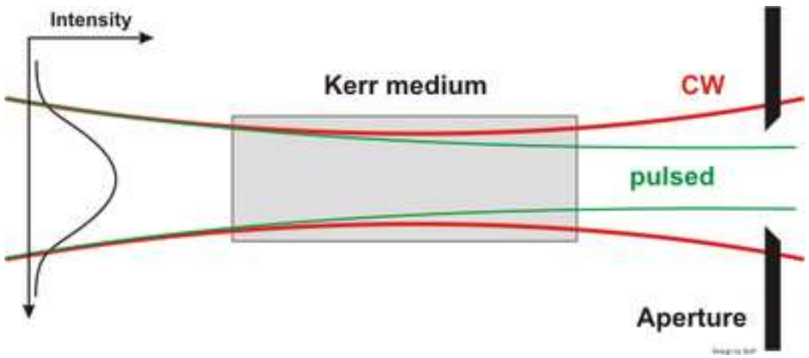
with a well defined phase -> pulses

Mode locking: How to

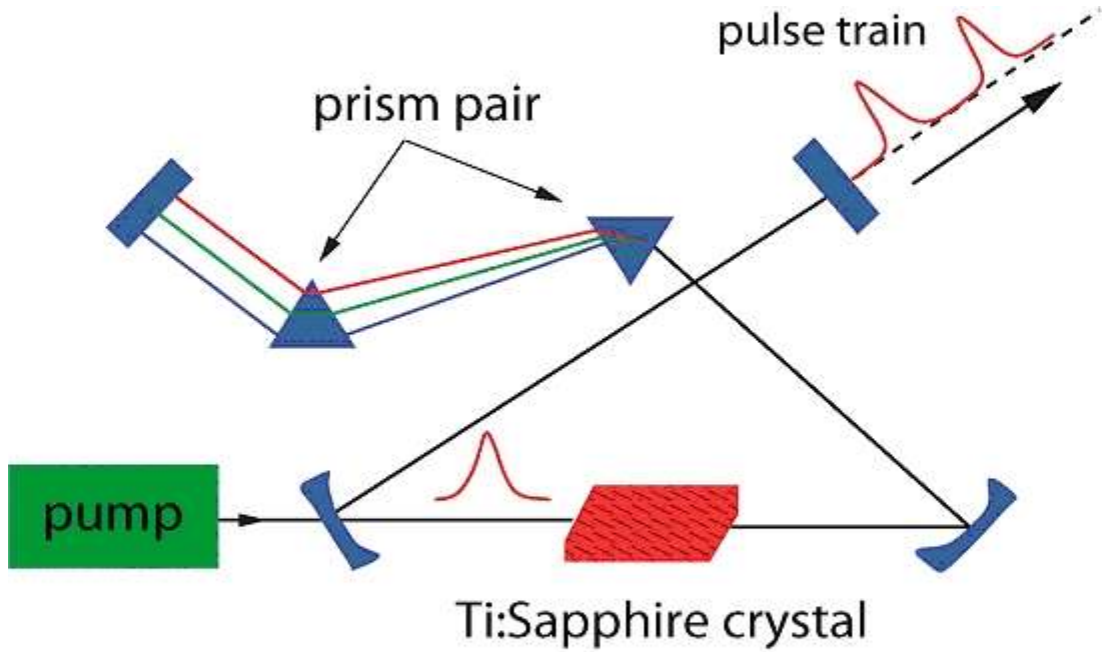


Solution: Nonlinearity

Kerr lens mode locking



Ti:sapphire laser



Time domain : pulse train

Frequency domain: comb

Fiber lasers

Guided operations: the mode is confined in an optical fiber

PRO

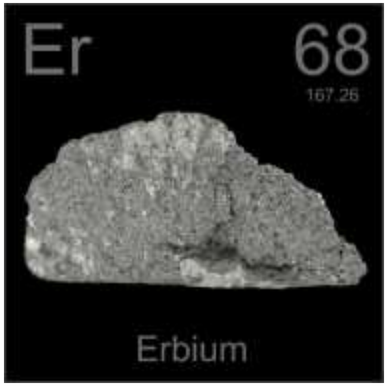
- Virtually alignment free
- Robustness
- Weakly affected by the environment
- Stability

CONS

- Careful design (you cannot optimize it)
- (Low power)
- (dispersion managment)

Possible Gain Media

Yb: 1030 nm



Er: 1550 nm

Tm/Ho: ~2000 nm

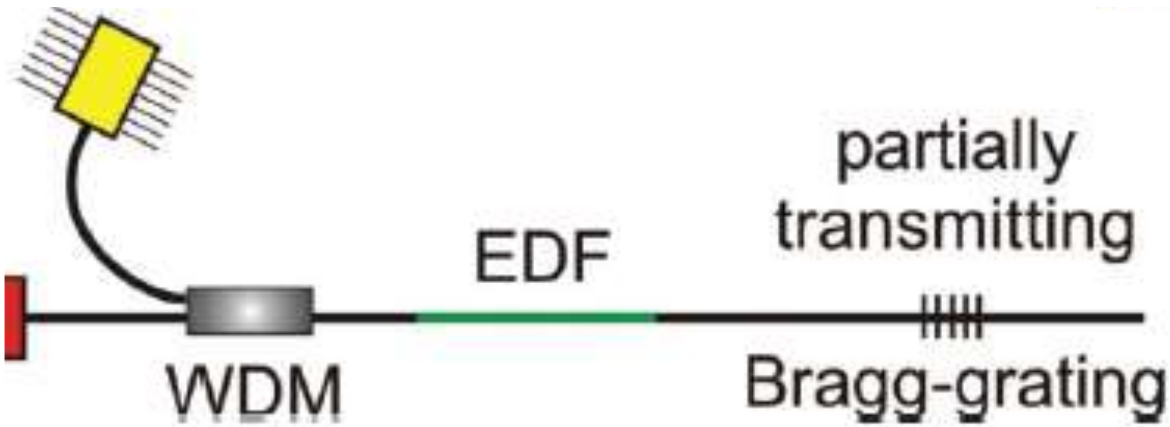
…

In general: rare earth ions in silica matrix

CW vs femtosecond

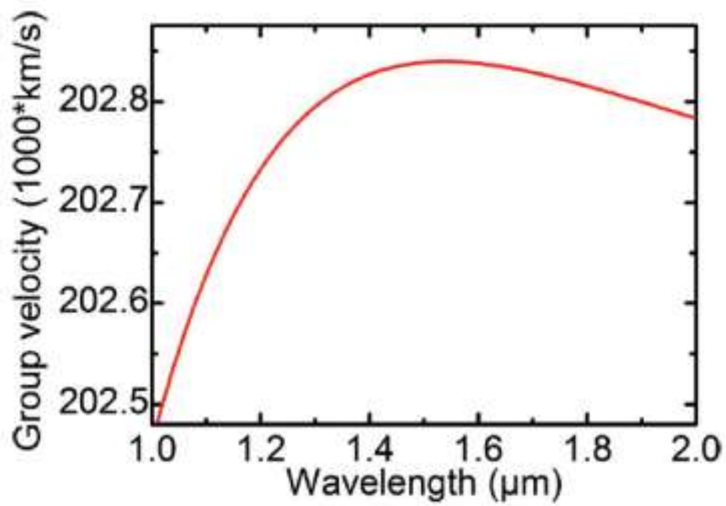
CW laser
diode

Mirror

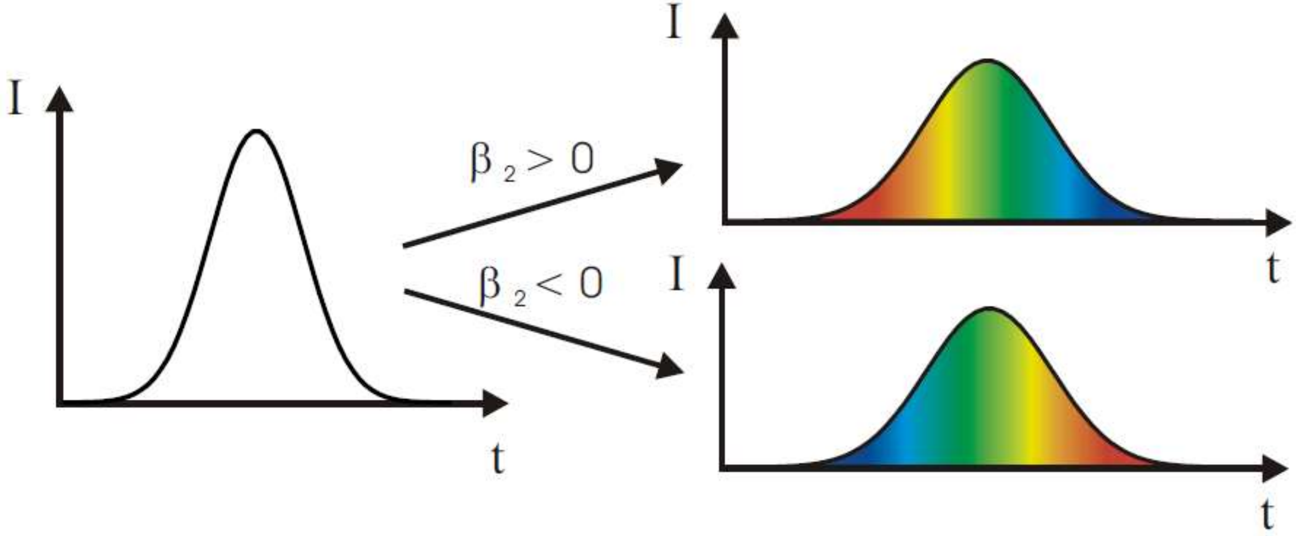


Femtosecond laser
-> short pulses
-> frequency comb

PROBLEM: dispersion



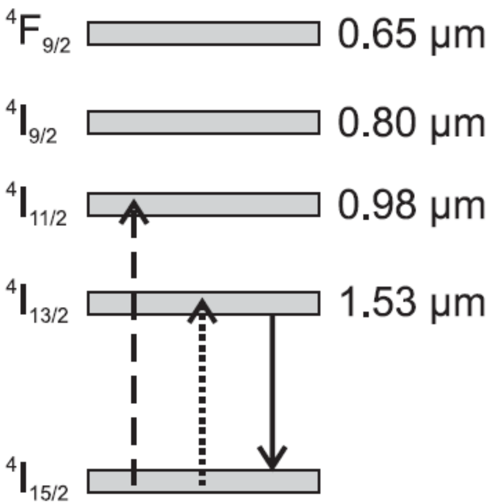
Linear propagation of short pulses

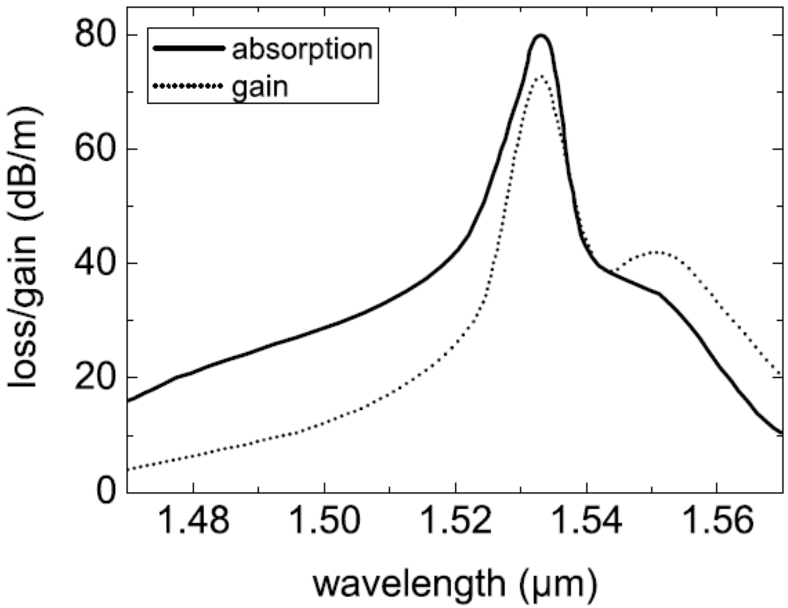


Examples

Er:fiber laser

Er^{3+} ions as gain medium



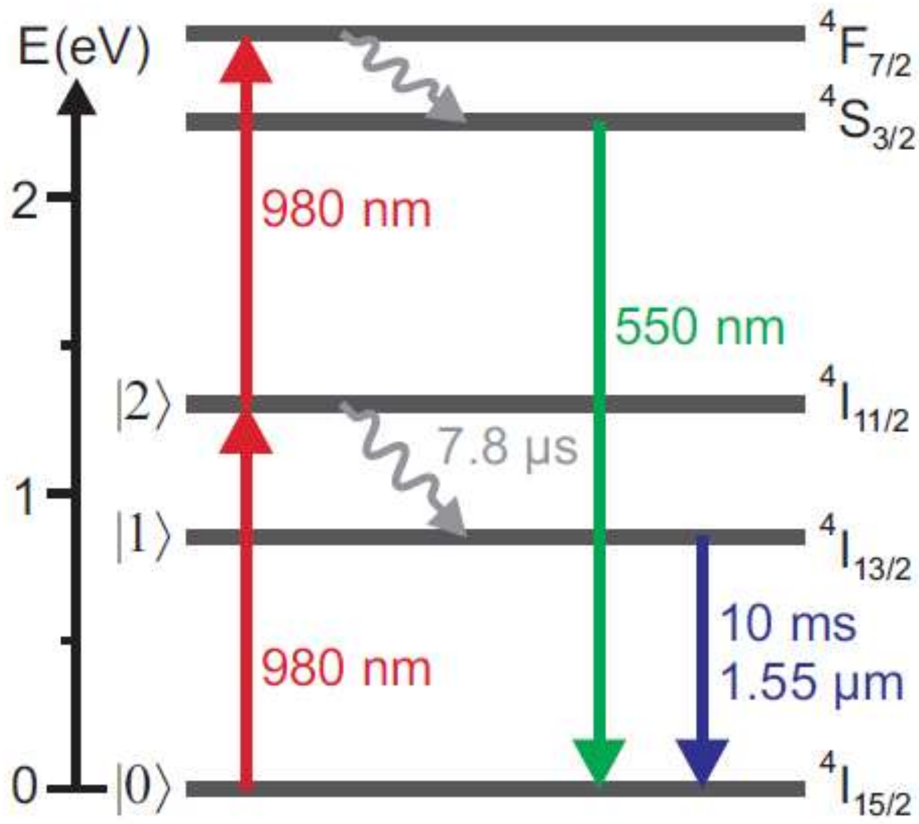


1550 high transparency window for fused silica

True 3-level system

Lasing at 1550 requires significant population inversion!!

Er^{3+} ions more details

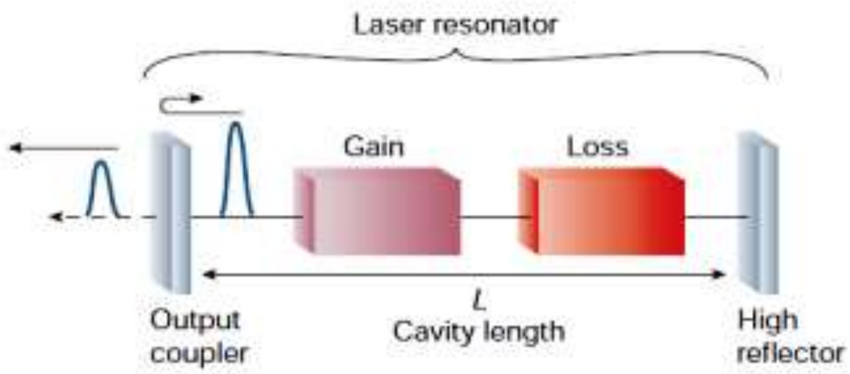


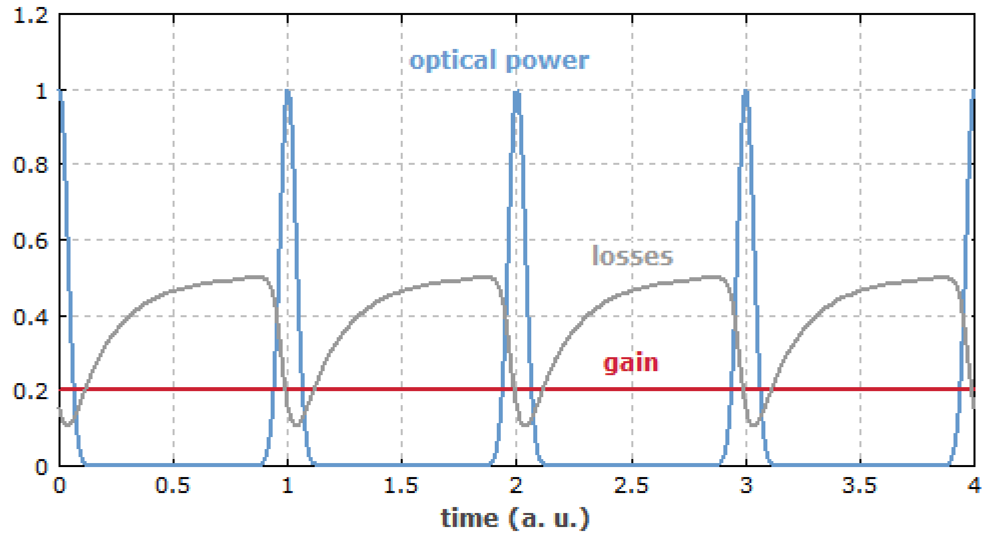
3 level system

Lifetime of the lasing level is fairly long: 10 ms

Green fluorescence

Mode locking operations in a fiber laser

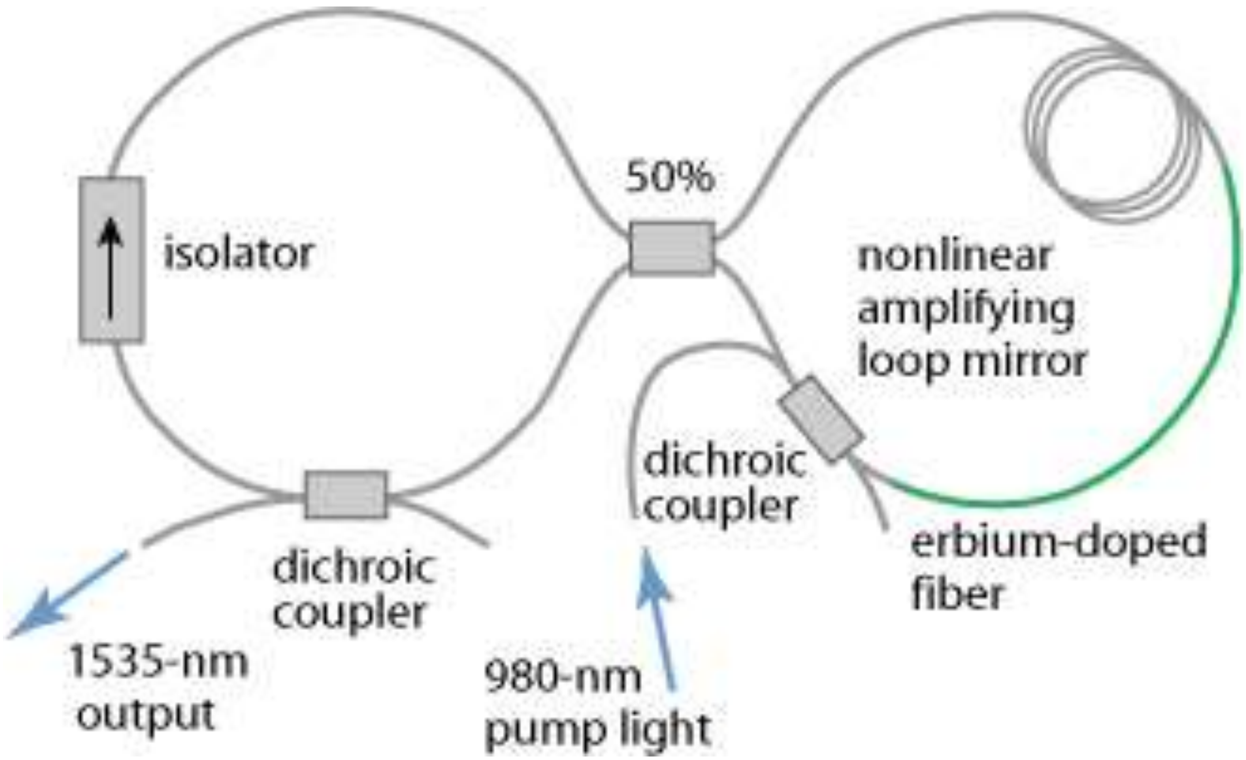




Three approaches:

- Active modulation
- Instantaneous Nonlinearity
- Ultrafast saturable absorber

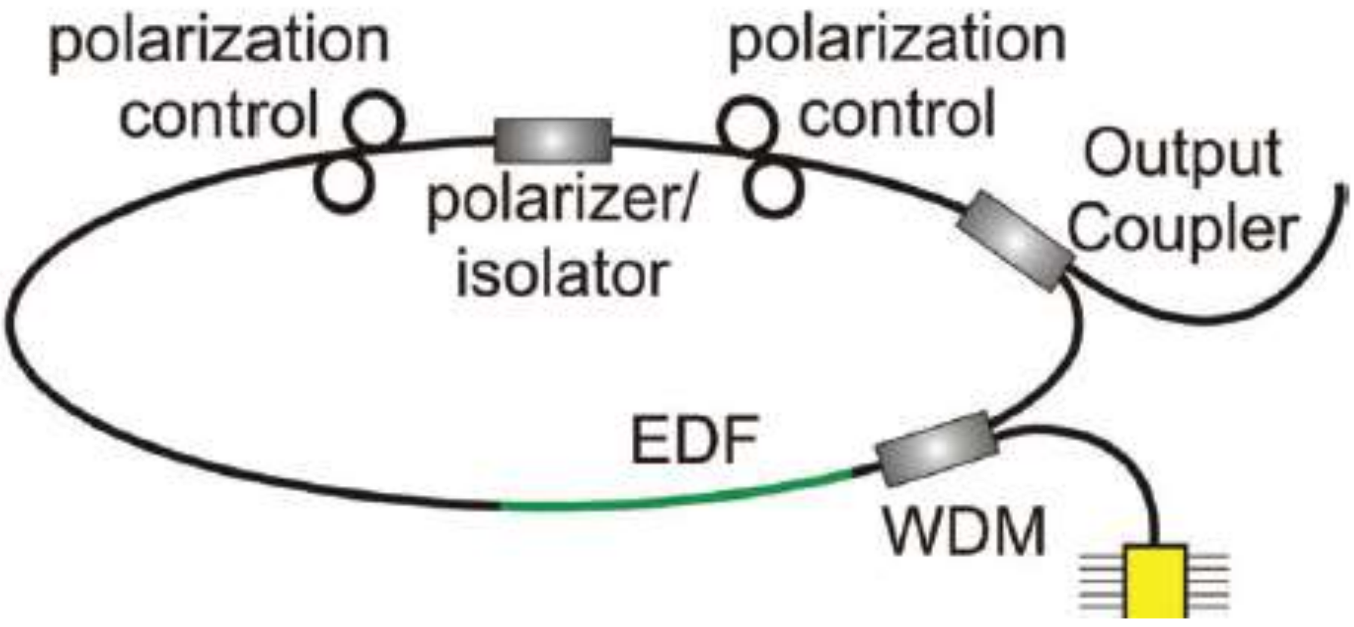
Femtosecond fiber laser 1: figure of 8



Asymmetry in the path between clockwise and counterclockwise propagation

The isolator is the lossy component

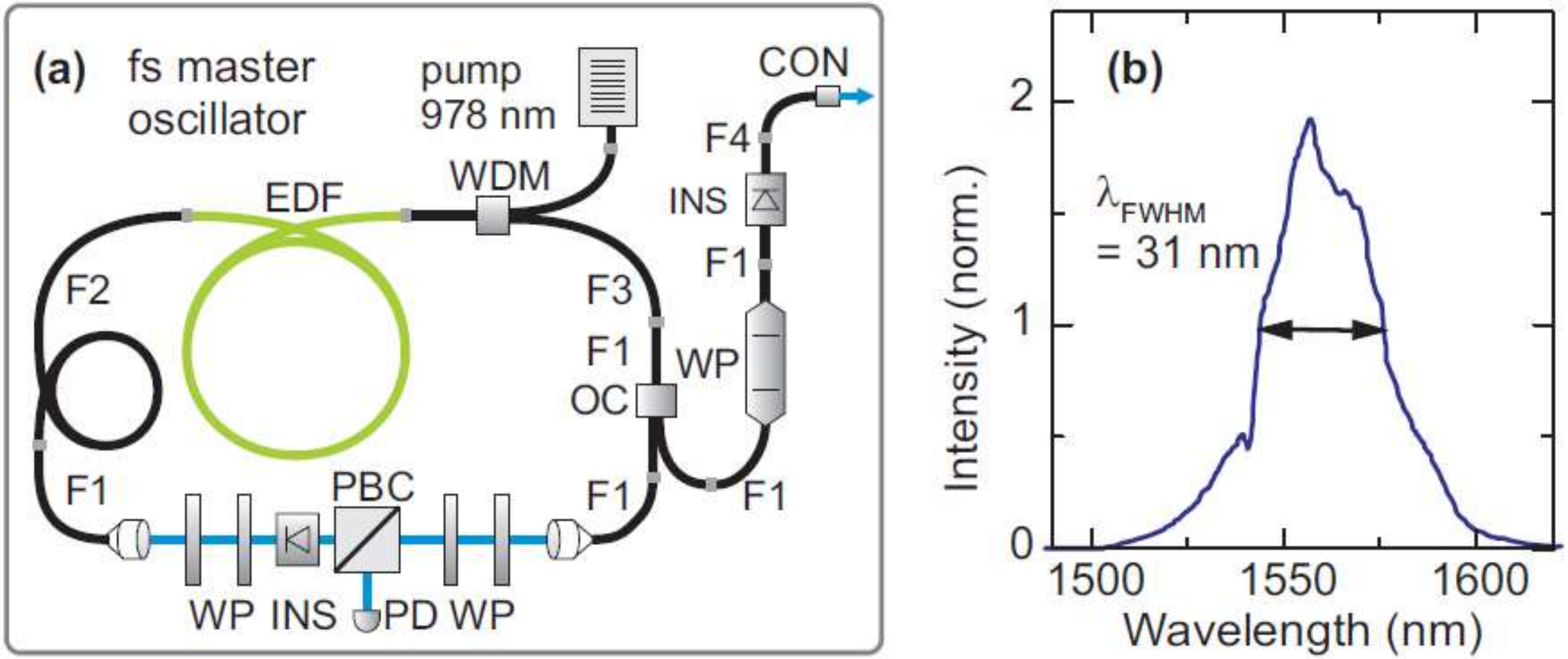
Femtosecond fiber laser 2: Polarization Rotation



Nonlinearity: XPS

Typically it requires outcoupling to free space within the oscillator

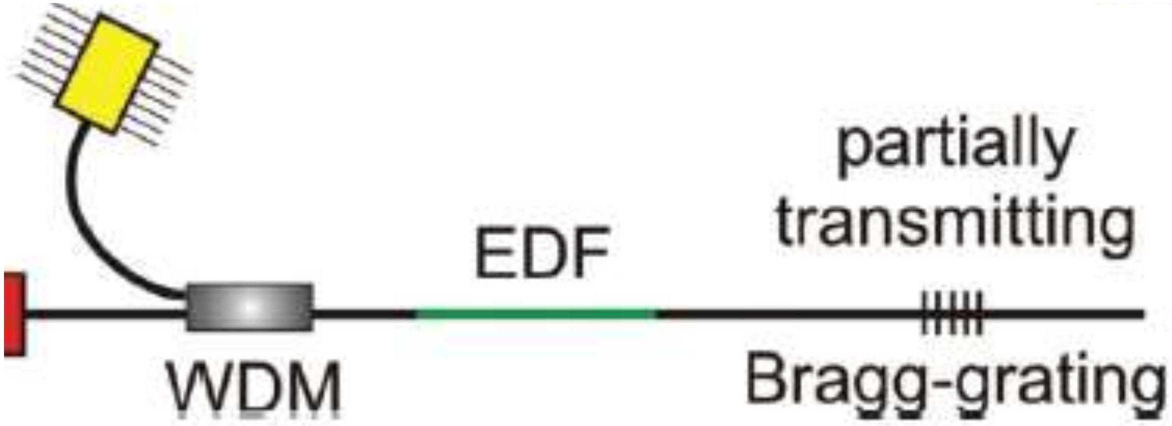
Femtosecond fiber laser 2: Polarization Rotation



Fiber	$GVD_{1.55\ \mu m}$ (ps^2/km)	Length (mm)
F1	-19.7	528
F2	-4.76	2340
F3	0.9	393
EDF	19	680

Femtosecond fiber laser 3: Saturable Absorber

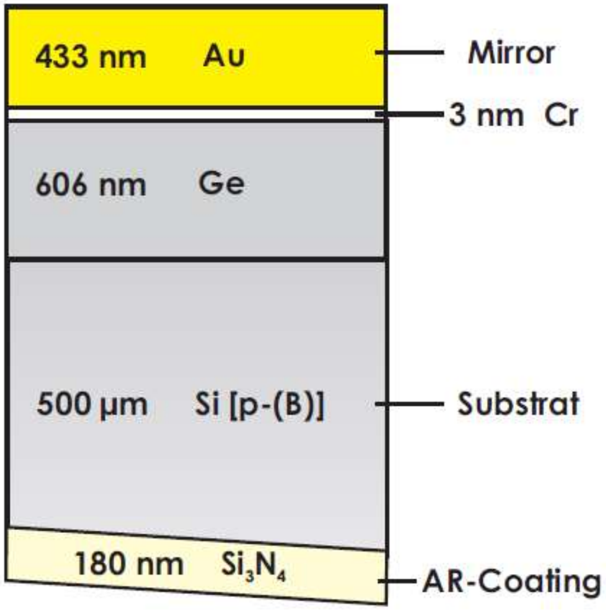
Saturable
Absorber
Mirror

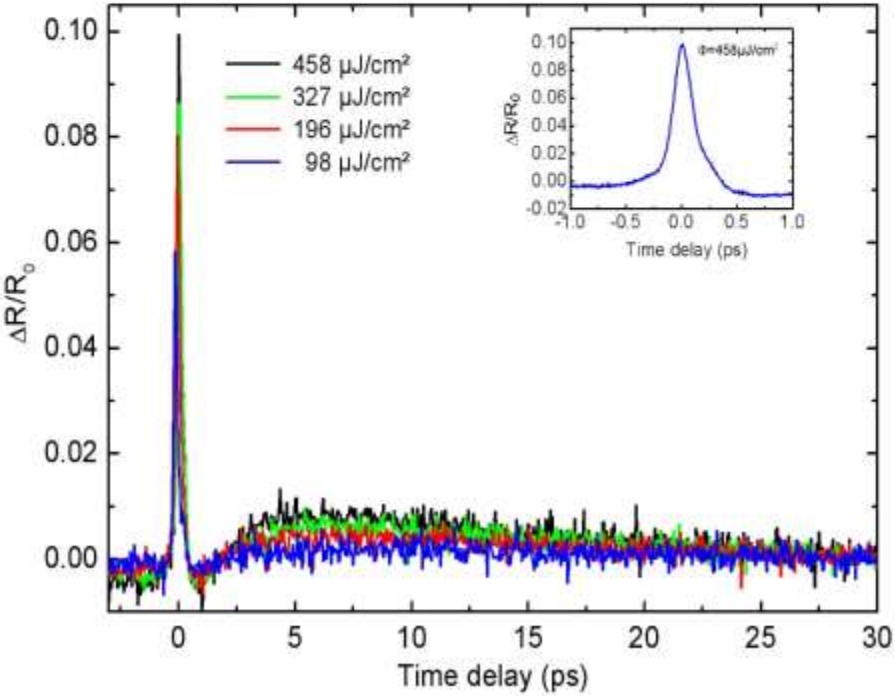


SAM works as a mirror only if the optical power in the cavity is sufficiently high

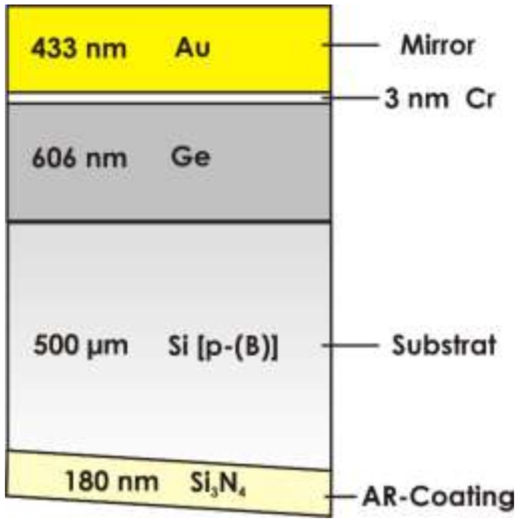
It has to show a dynamical behavior and recover the “lossy” condition really quickly

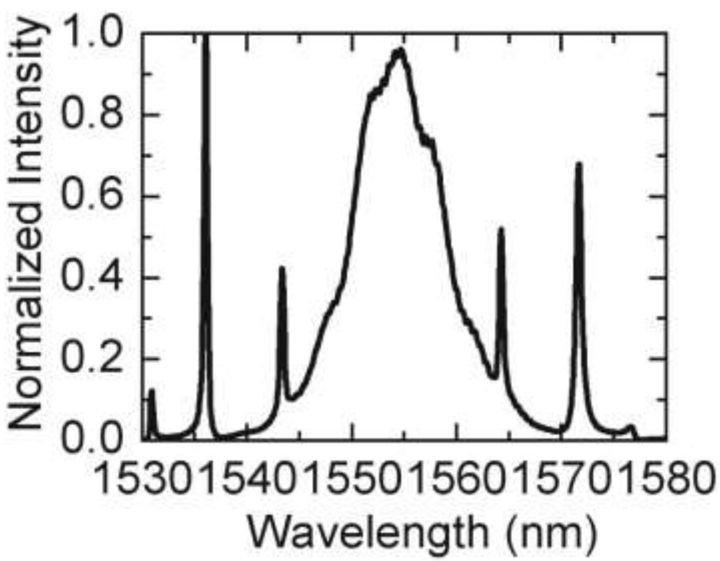
Femtosecond fiber laser 3: Saturable absorber

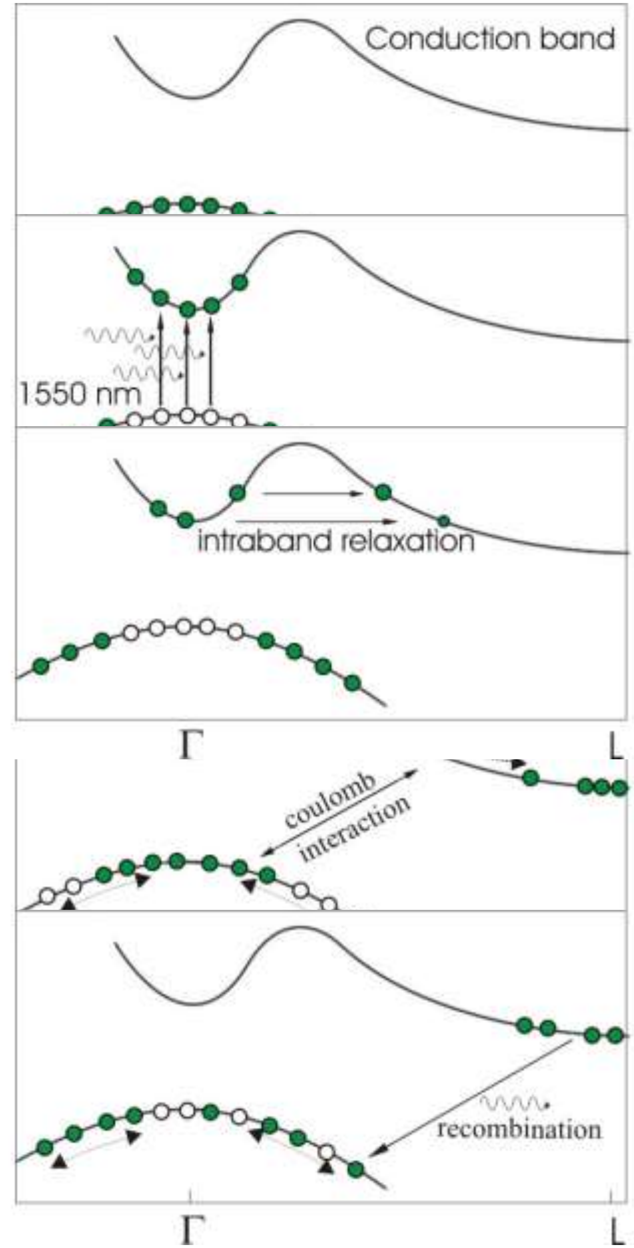




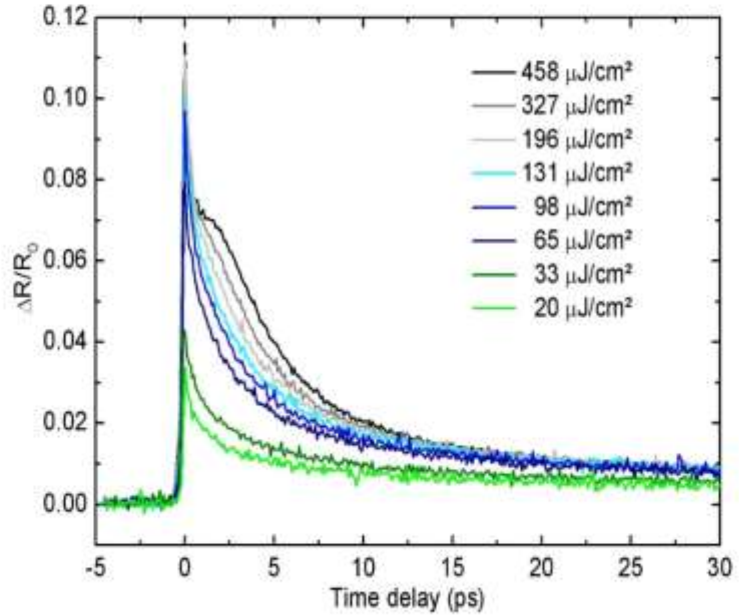
Germanium Saturable Absorber Mirror

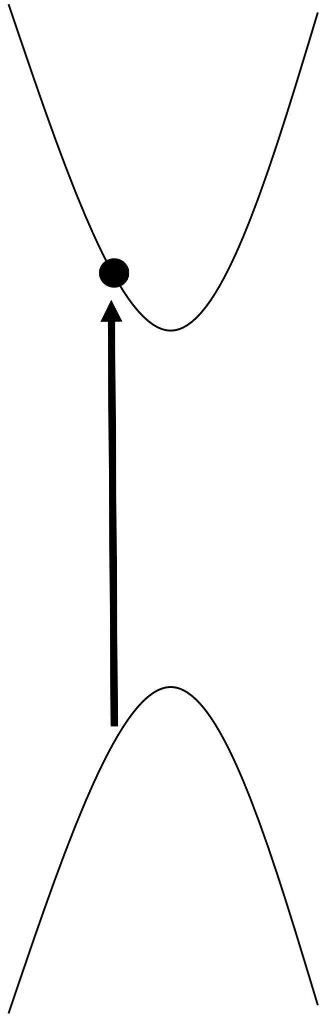




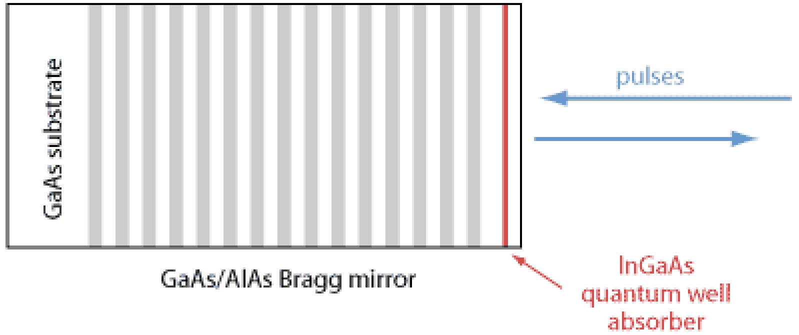


InGaAs Saturable Absorber Mirror



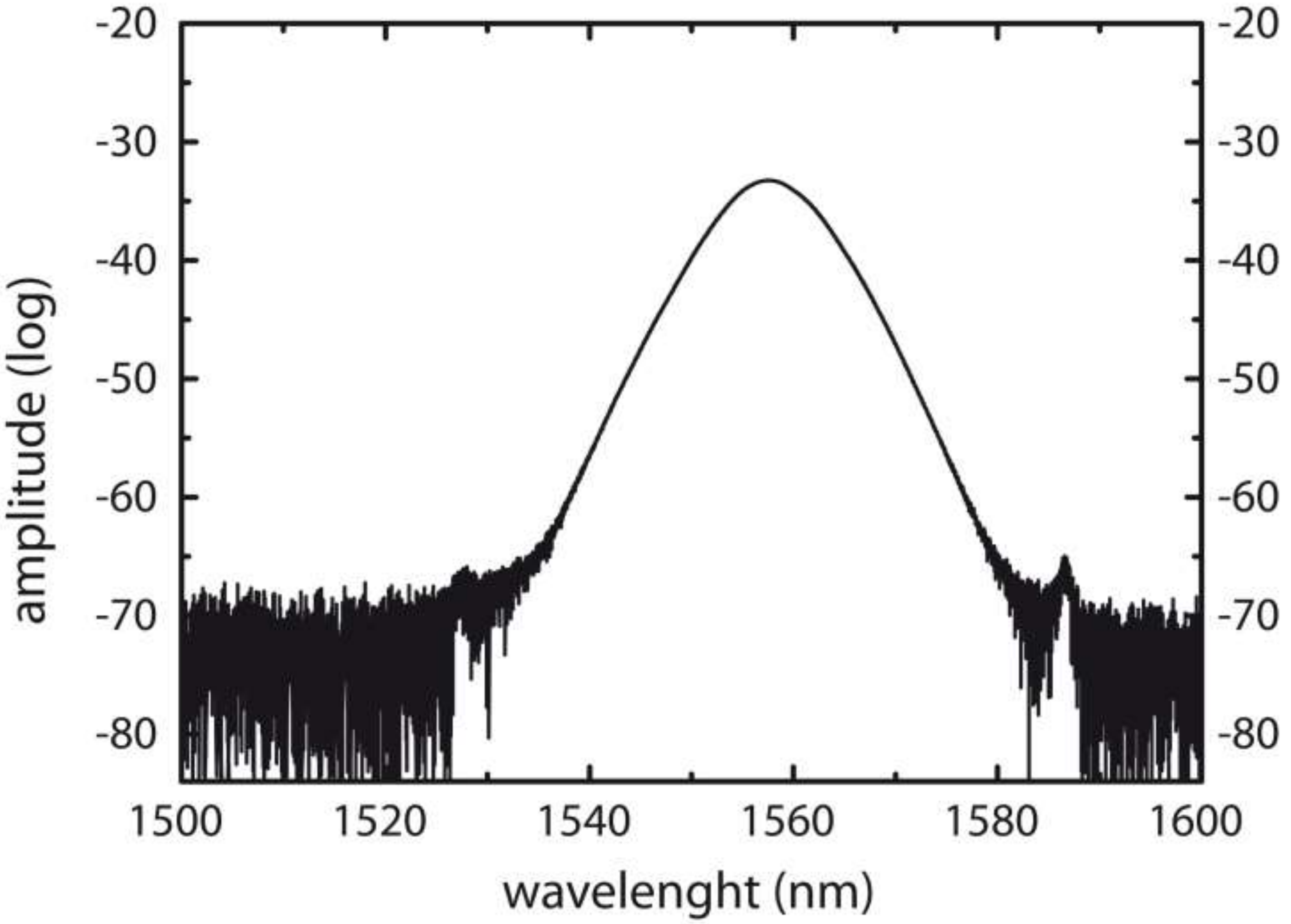


Direct gap semiconductor



GaAs at the center of the Brillouin zone

InGaAs Saturable Absorber Mirror



Solitonic Oscillator

Solitonic propagation condition

$$P_0 t_0^2 = \frac{|\beta_2|}{\gamma}$$

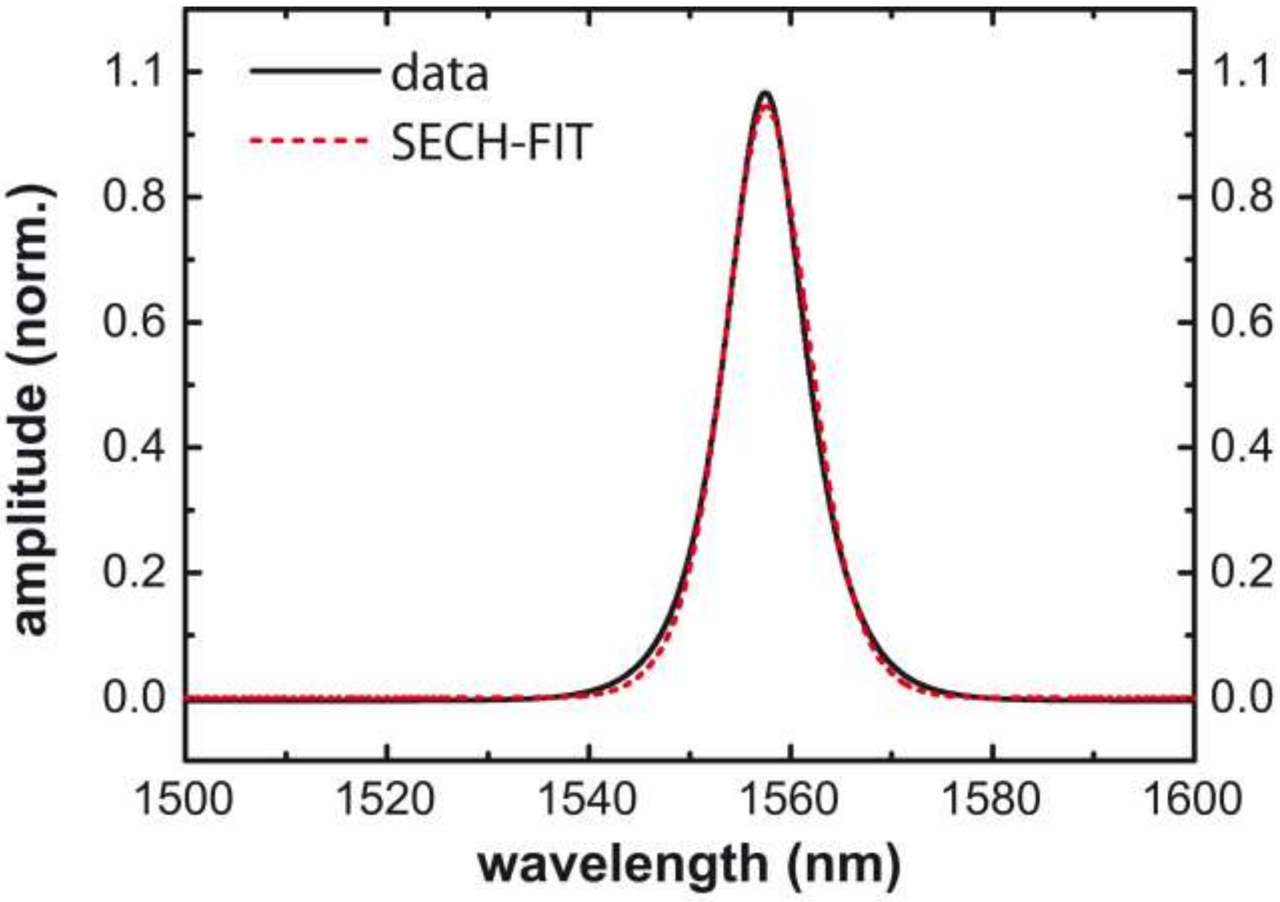
Where

$$\gamma = \frac{n_2 \omega_0}{c A_{\text{eff}}}$$

The pulse temporal profile is:

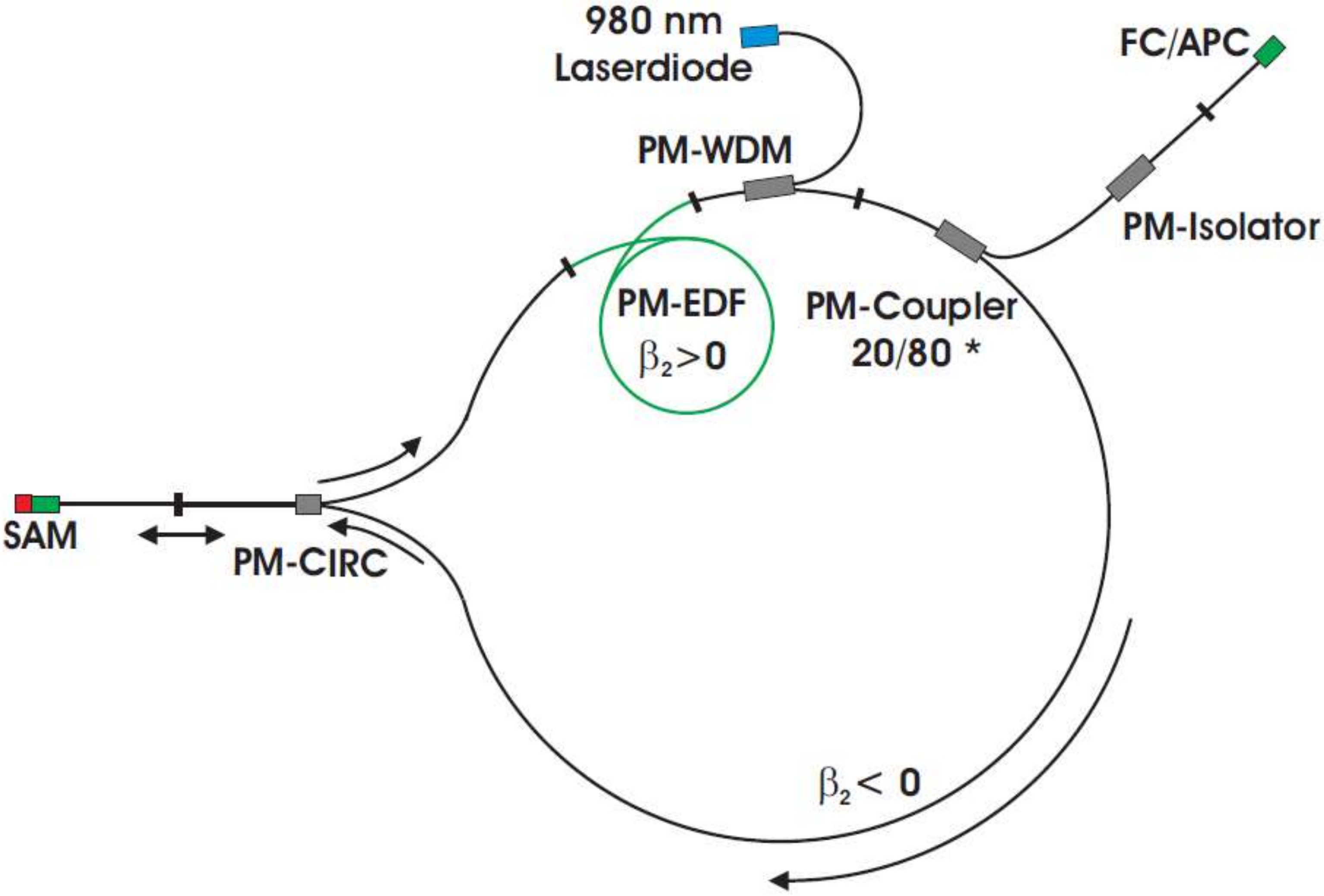
$$P(t) = P_0 \,\text{sech}^2 \left(\frac{t}{t_0} \right)$$

Solitonic Oscillator

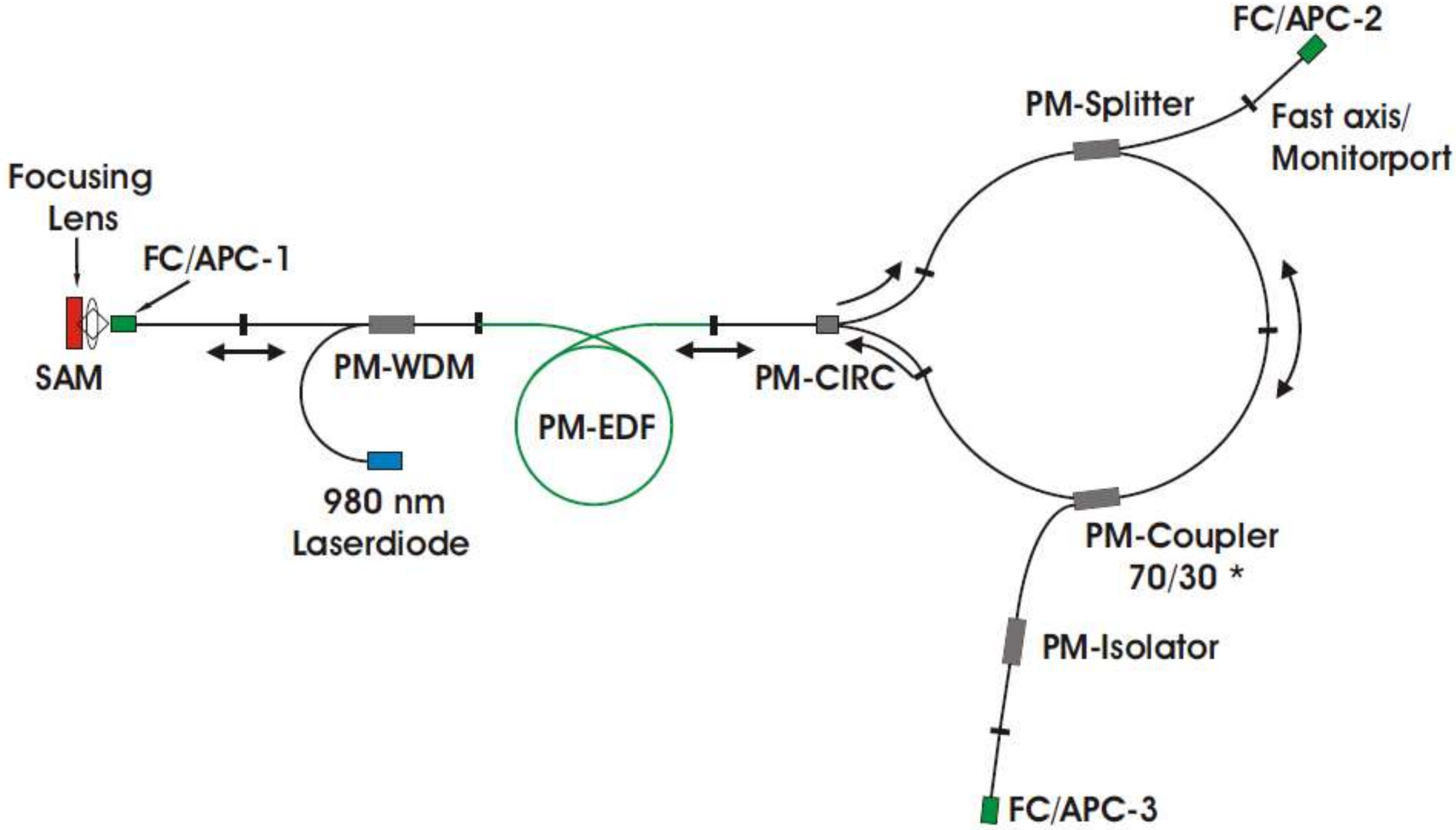


Transform Limit pulse duration of approximately 300 fs
Output power 2/3 mW

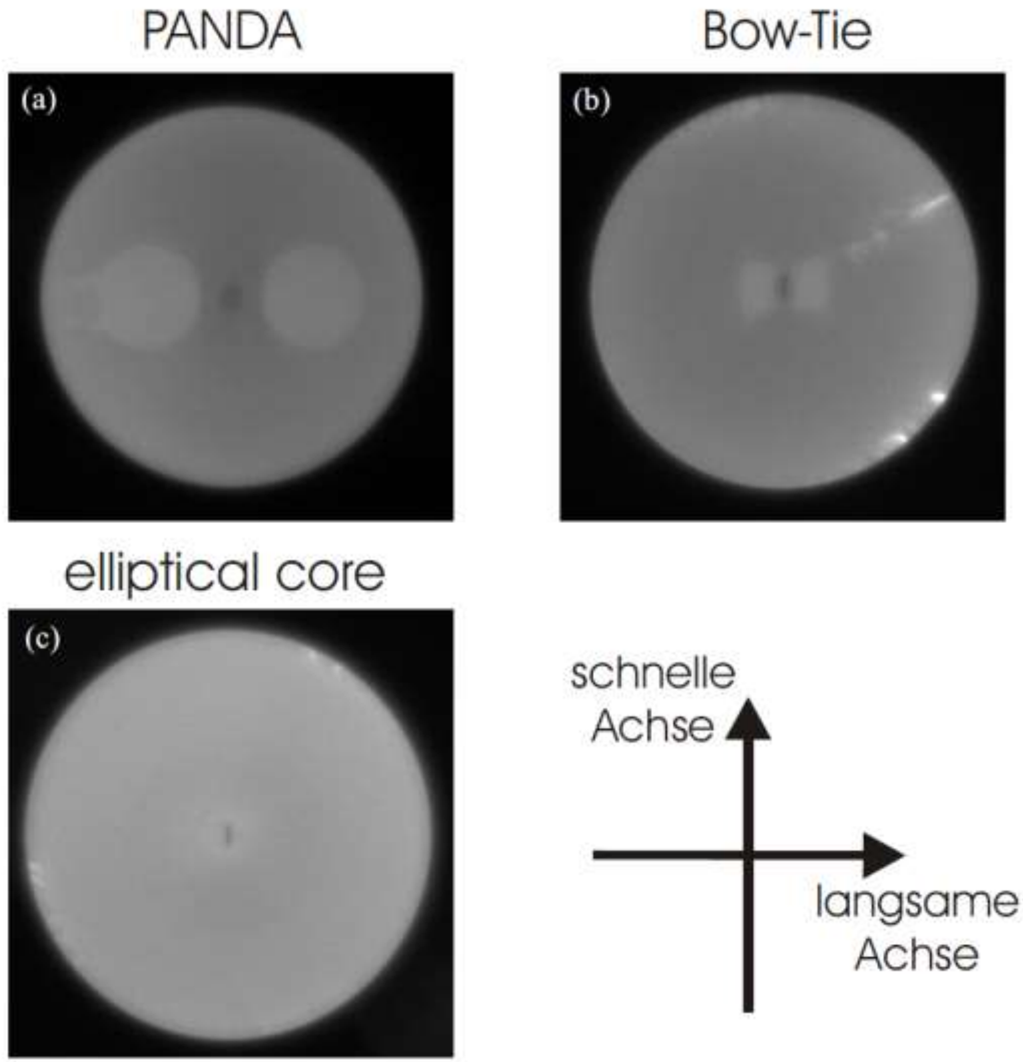
Femtosecond fiber laser 3: Saturable absorber



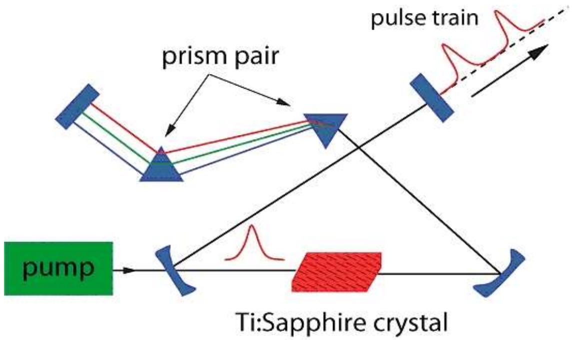
Femtosecond fiber laser 3: Saturable absorber



Femtosecond fiber laser: polarization



Discussion



VS

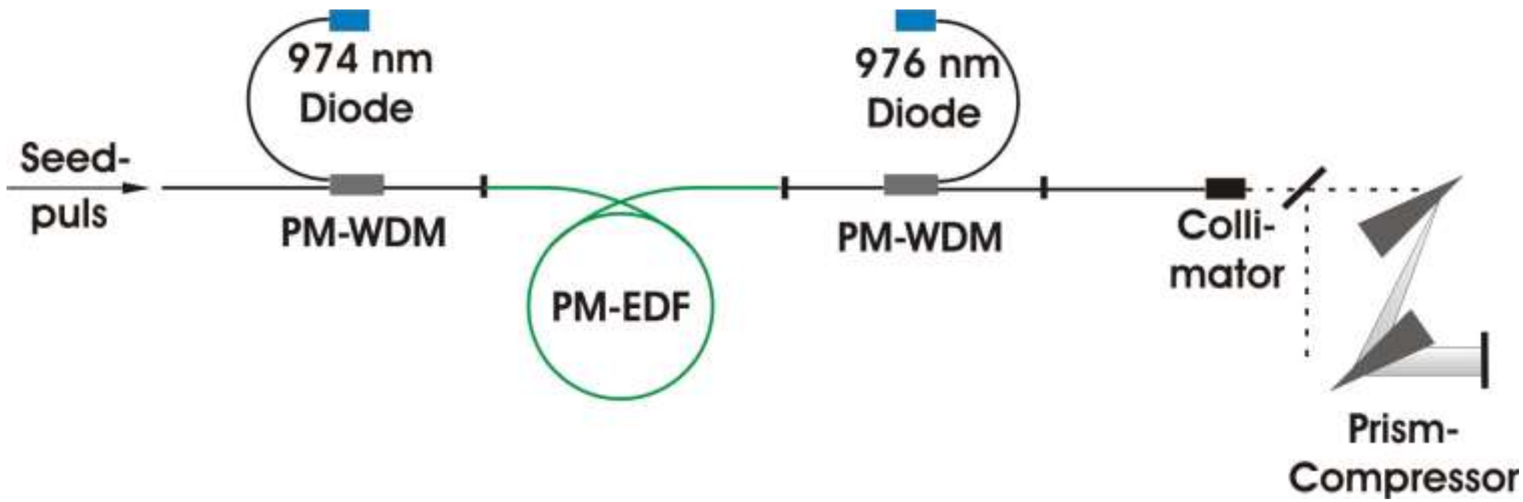
Noise performances (Shot noise)

Environmental robustness

Optimization

Pulse energy

Femtosecond Er:Fiber-Amplifier



Single pass amplifier

2.5 m long gain medium (Er:PM-Fiber) with normal dispersion

980 nm pump light injected from both sides (each with 700 mW)

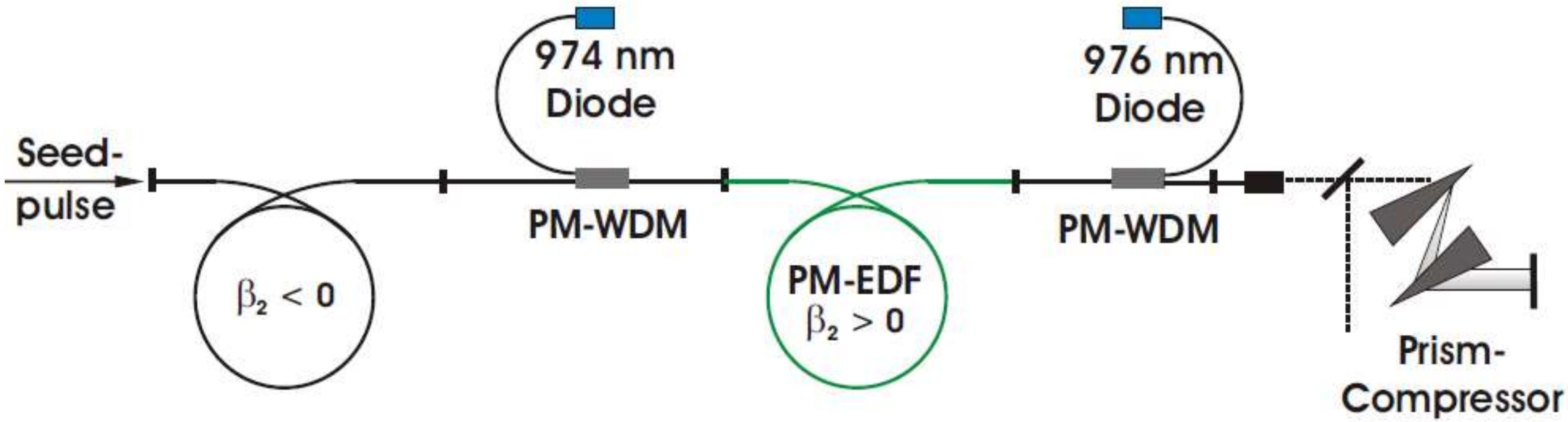
Amplification up to 330 mW, $\rightarrow$ Pin/Pout ≈ 500

Spectral broadening due to SPM (Self Phase Modulation) and other nonlinear effects in EDF and collimator fiber

Recompression of the pulse in a silicon prism compressor

Nonlinear amplifier: dispersion managment

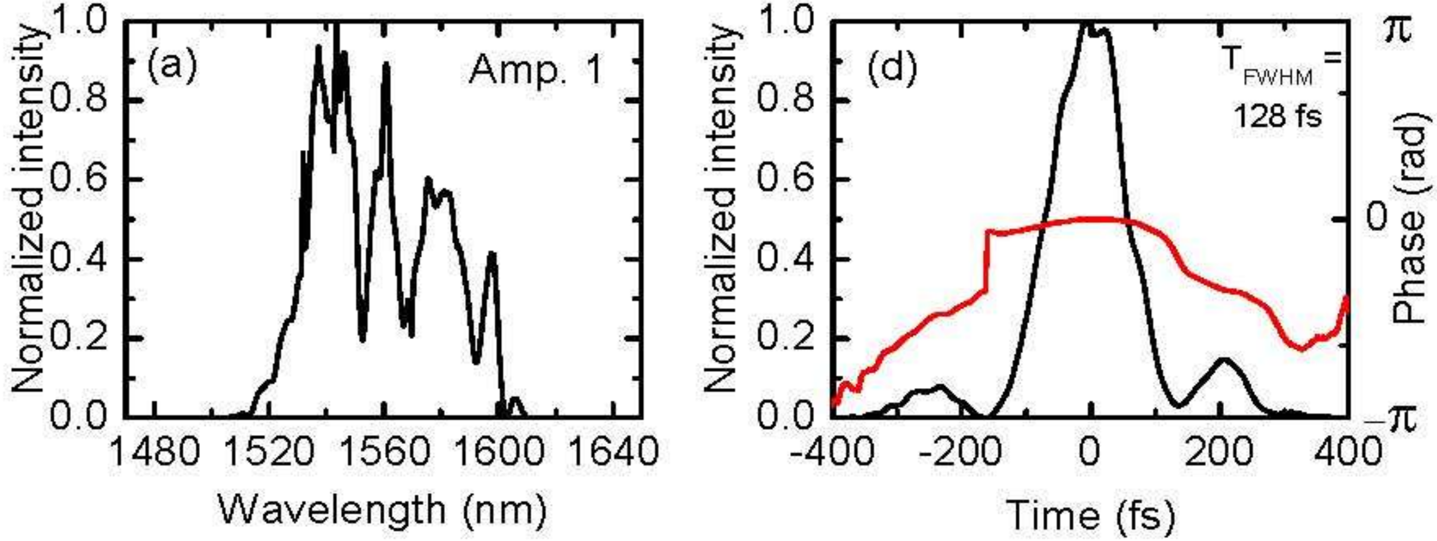
Optimization of the nonlinearity during amplification by a pre-stretching fiber



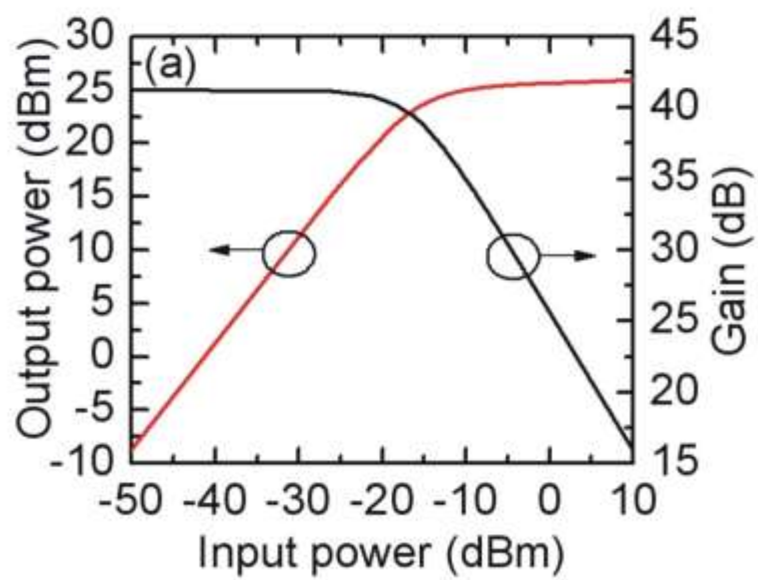
Also the pump diode coupling is a degree of freedom

1 co-propagating, 1 counterpropagating to optimize the inversion profile in the EDF

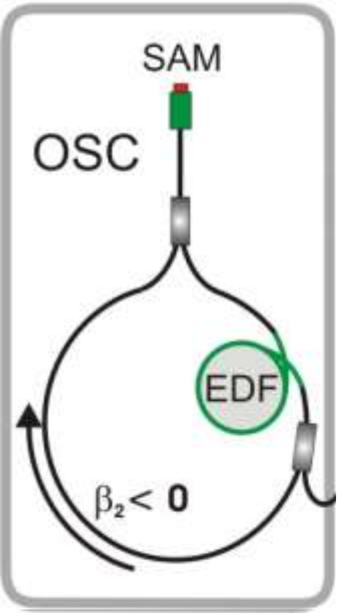
Amplifier

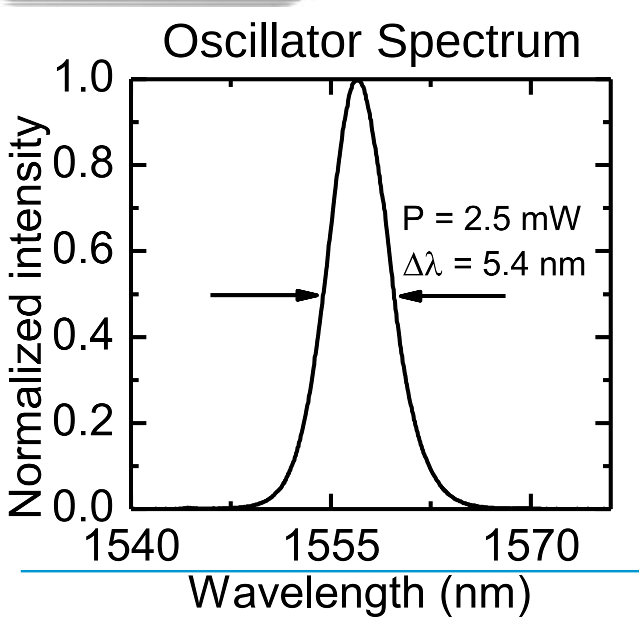


Bandwidth $\Delta\lambda$ = 70 nm
Pulse duration T_{FWHM} = 130 fs
Degree of Polarisation > 98%
330 mW before compressor and
305 mW after compressor
Pulse energy: 8 nJ
Almost perfect synchronisation possible (43 as)



General Setup





attosecond timing jitter:
F. Adler, et al.,
Opt. Lett. **32**, 3504 (2007)

tailored spectra:
A. Sell, G. Krauss et al.,
Opt. Express **17**, 1070 (2009)

Variable Pulse Compression

Compression in silicon prism sequence

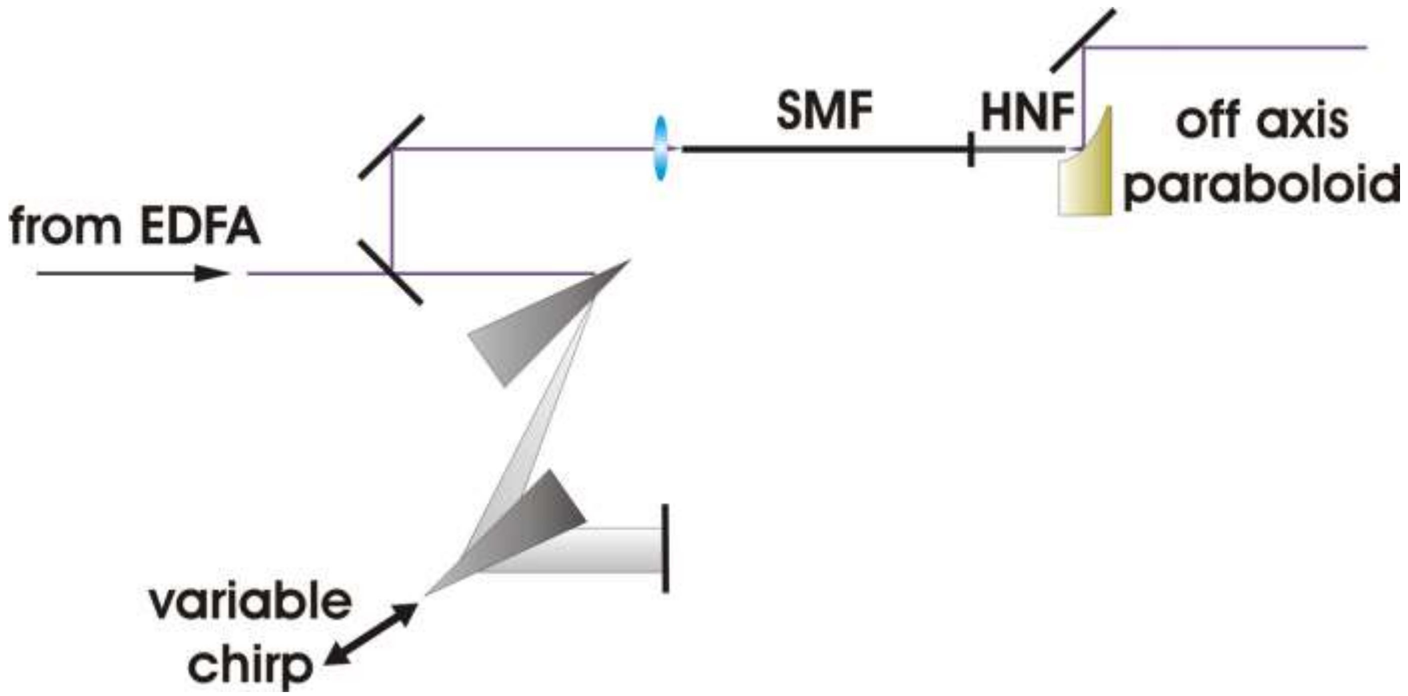
→ variable prechirp

Pumping of highly nonlinear fiber

→ tunability of dispersive wave and soliton

Collimation with off-axis parabolic mirror

→ no chromatic aberration



Nonlinear Pulse Propagation

Quantitative modeling without free parameters:

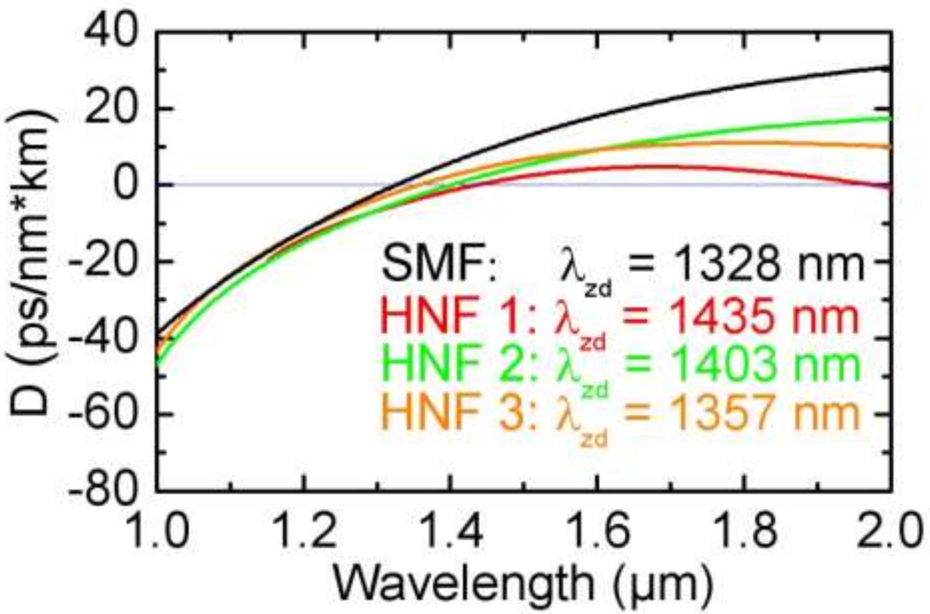
Gain/absorption

Dispersion up to 6th order (measured via white-light interferometry)

Instantaneous Kerr nonlinearity

Retarded Raman effect

Amplitude and phase spectra of pump (measured via FROG)



→ **Central design tool with predictive power**

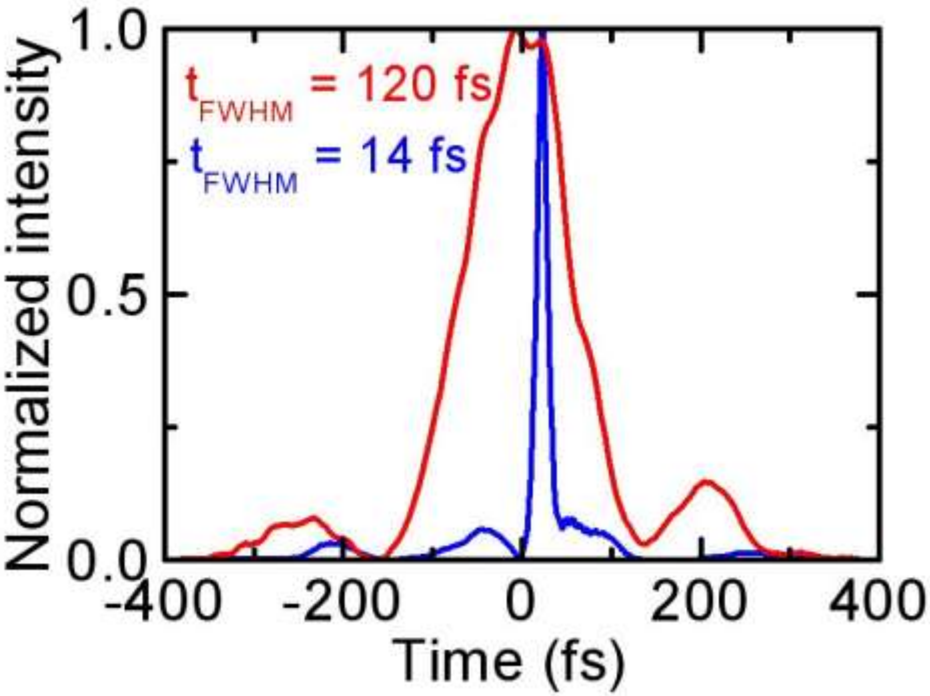
$$\partial_z A(z,t) = \left[-\frac{\alpha}{2} - i\frac{\beta_2}{2}\partial_\tau^2 + i\frac{\beta_3}{6}\partial_\tau^3 \pm \ldots \right] A(z,\tau) + \gamma \left(i - \frac{\partial_\tau}{\omega_0} \right) \left[A(z,\tau) \int_{-\infty}^{\infty} \left| A(z,\tau) \right|^2 R(\tau-\tau_1) d\tau_1 \right]$$

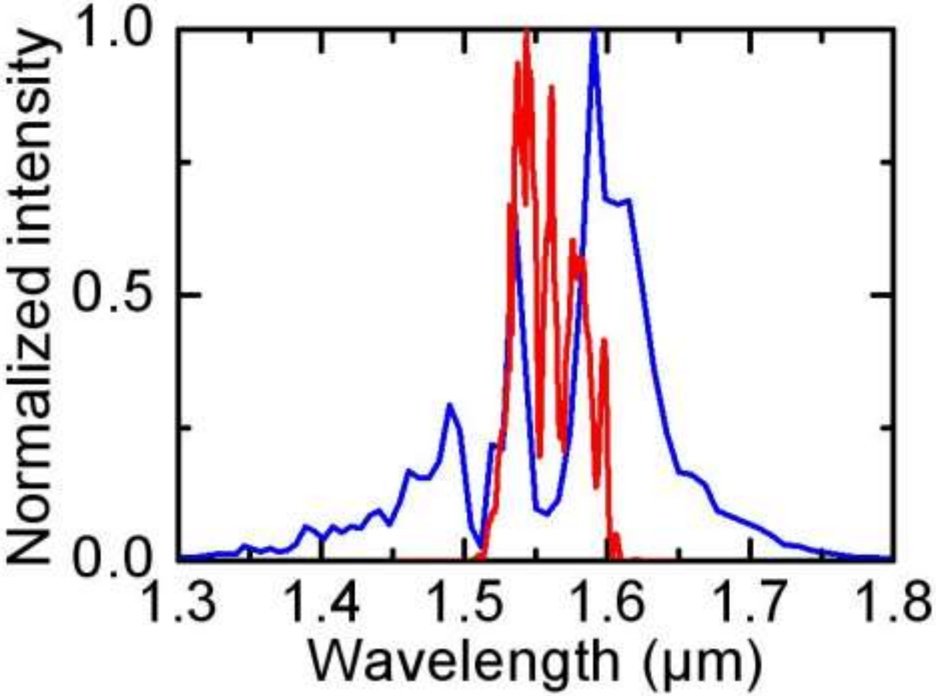
Tailored Spectra in Highly Nonlinear Fibers I

Two-stage process

1st step: soliton compression in standard telecom fiber
(l ≈ 10 cm, $Ø_{Core}$ = 10.5 µm)

Spectrum broadens and pulse is compressed to 14 fs





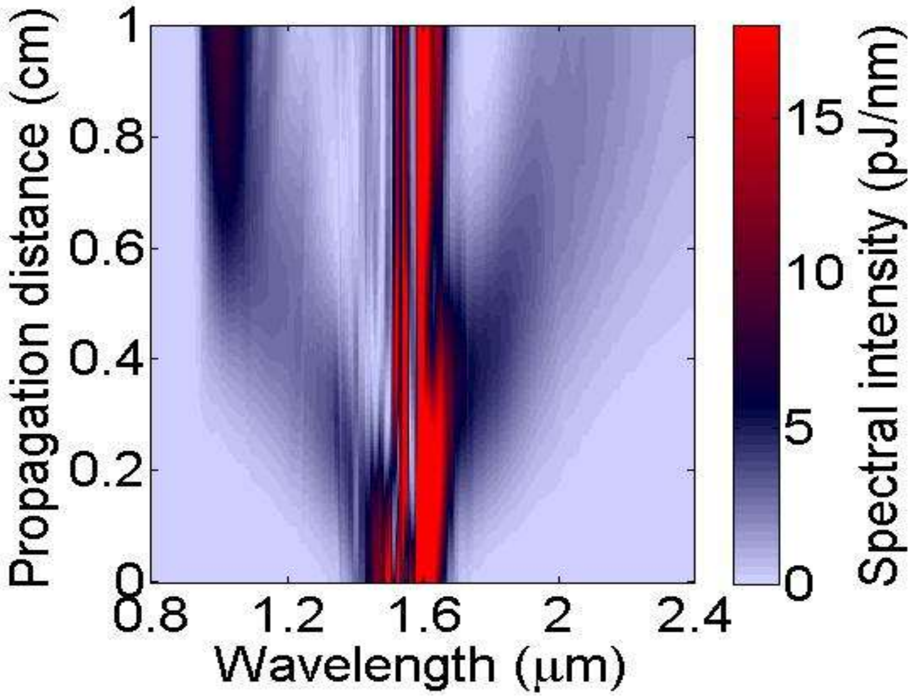
Tailored Spectra in Highly Nonlinear Fibers II

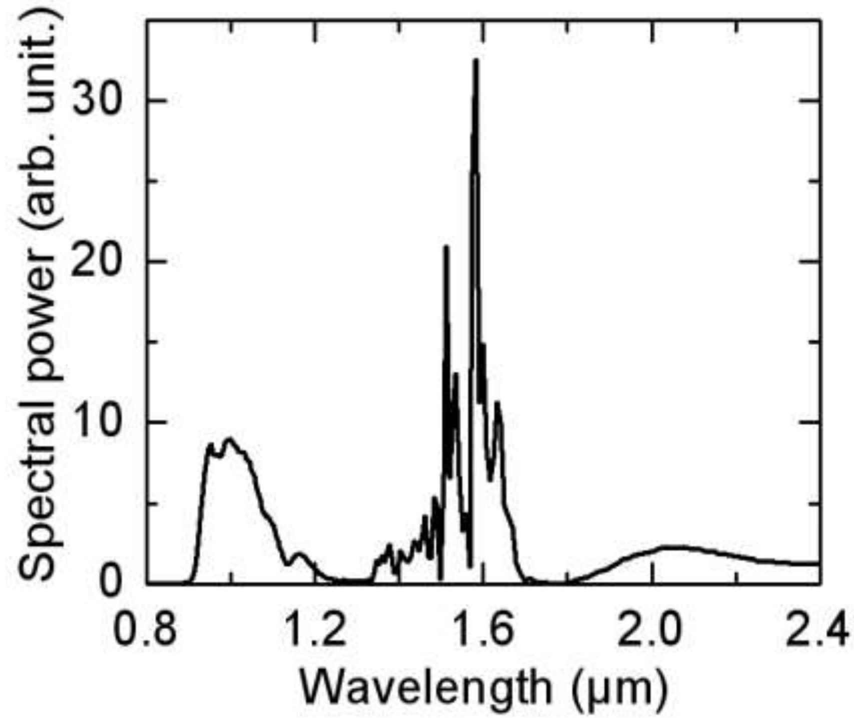
2nd step: four-photon interactions in HNF ($Ø_{Core}$ = 4 µm)

Spectrum splits into two components:

Soliton

Dispersive wave





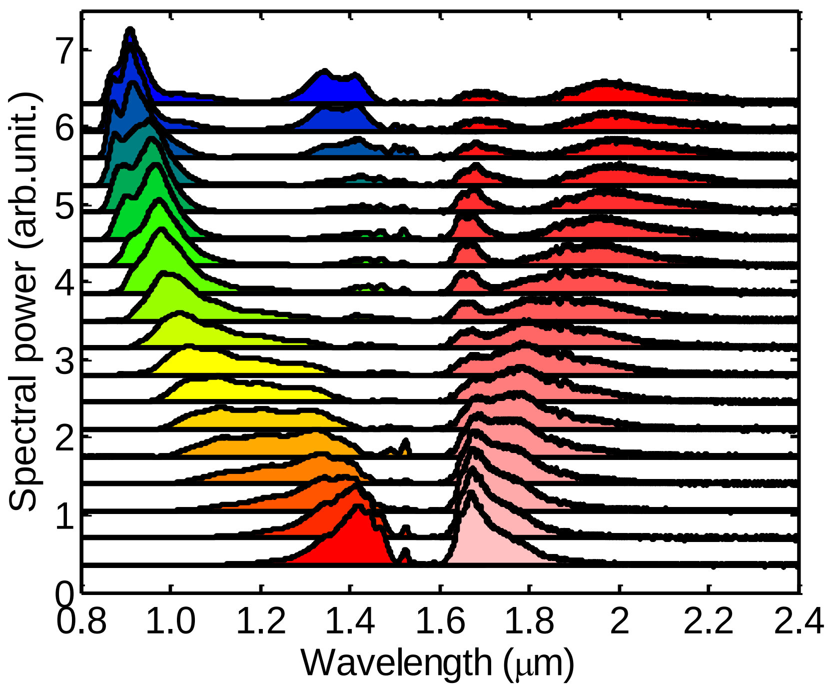
Tuning via Prechirp

Control of nonlinear frequency shift: prechirp of pump (determines minimum pulse duration before HNF)

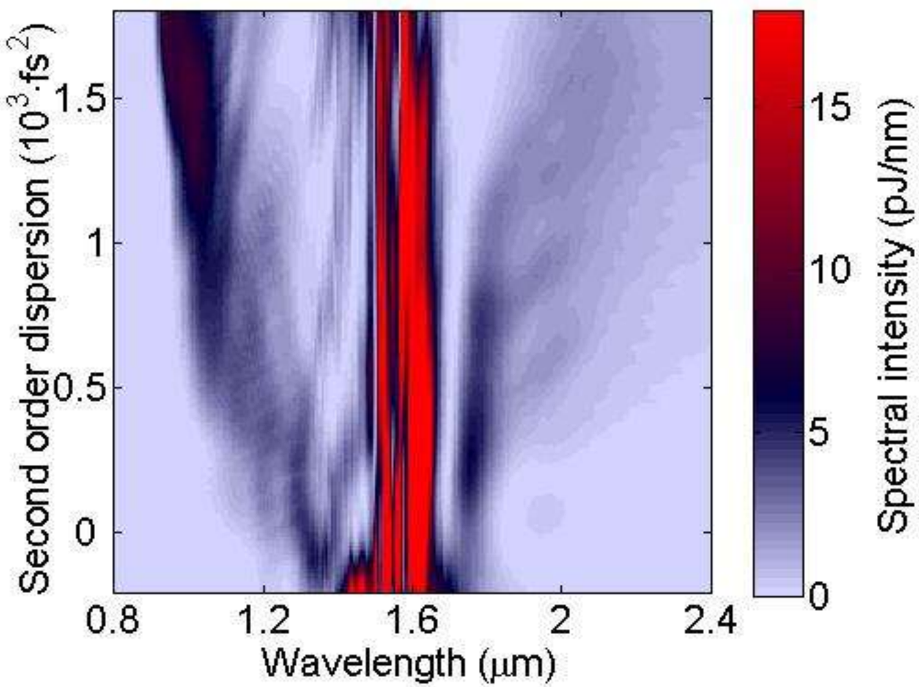
P_{out} > 30 mW (dispersive wave) and > 50 mW (soliton)

Spectral range covered: 800 nm to 2400 nm

time evolution in precompression fiber



spectral evolution in HNF



Ultrabroad Spectra I

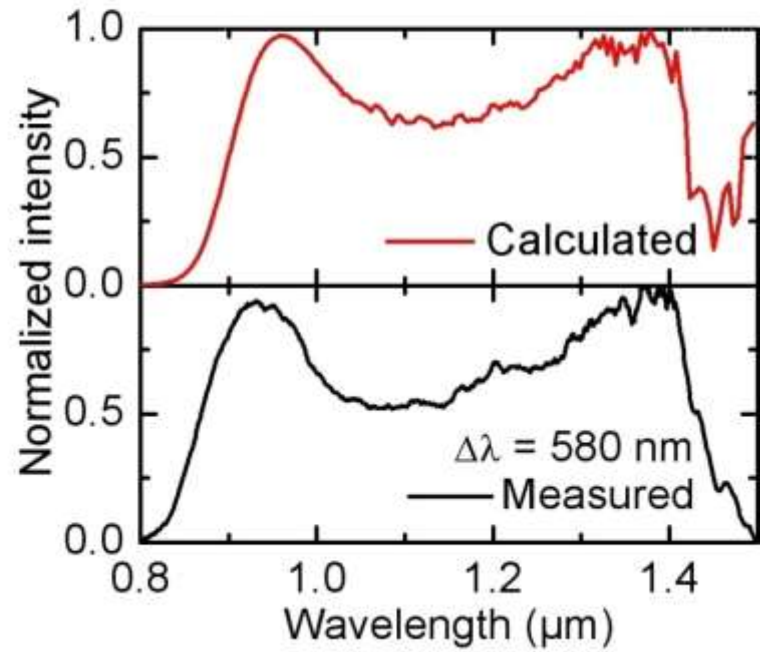
Optimized dispersion profiles for ultrabroadband and unstructured spectra

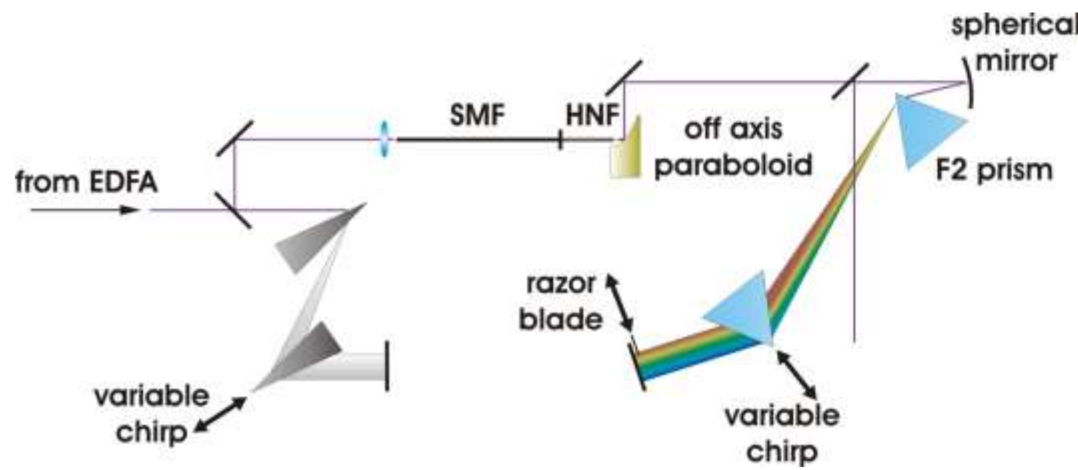
Quantitative agreement between simulation and experiment

Maximum spectral width in dispersive wave: $\Delta\lambda = 580$ nm

$P_{out} = 23$ mW

Compression in glass prism compressor





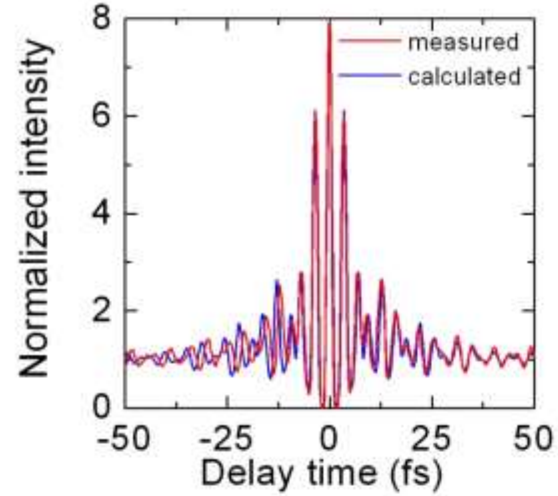
7.8 fs Dispersive Wave

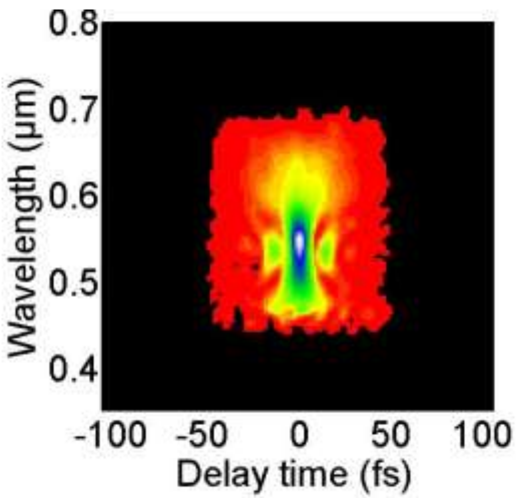
Retrieved pulse duration: t_p = 7.8 fs
$\rightarrow$ two optical cycles

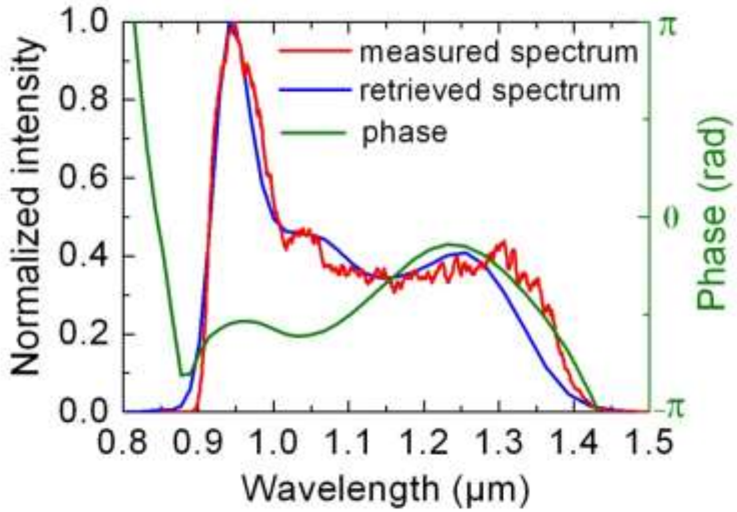
Bandwidth limit: 7.0 fs

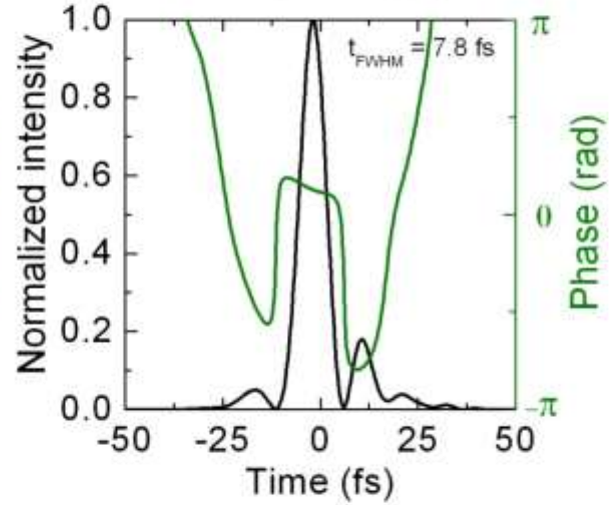
Good agreement between measured and retrieved spectrum

Perfect match between measured and calculated autocorrelation





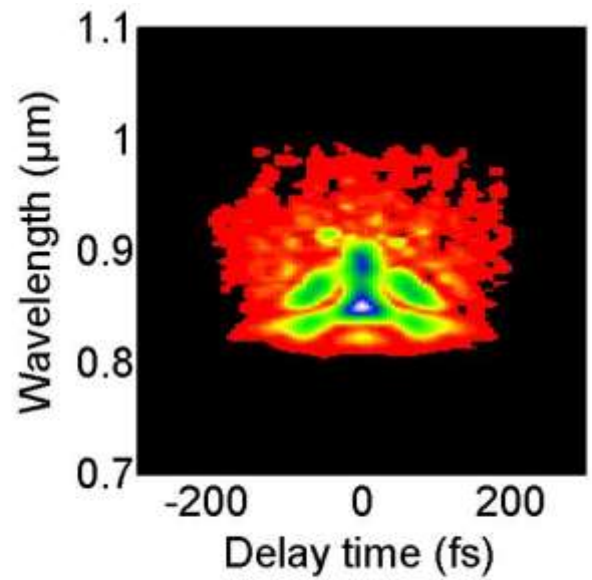


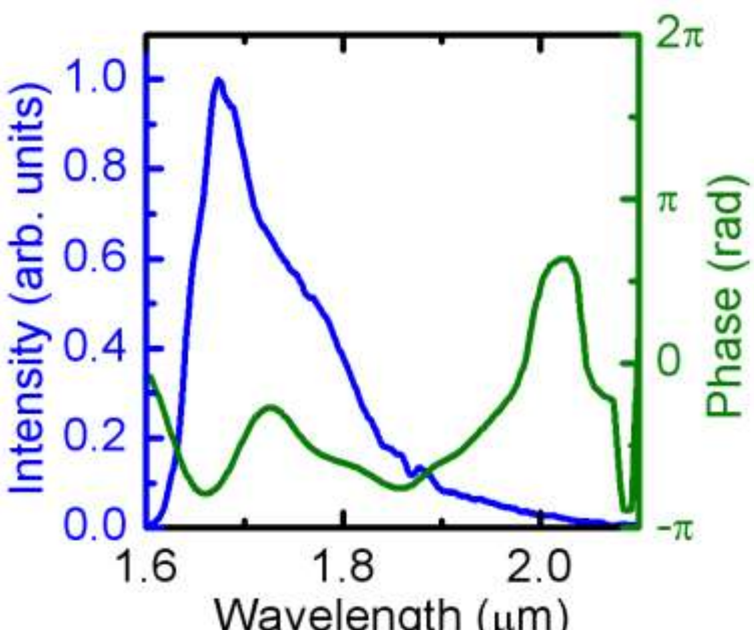


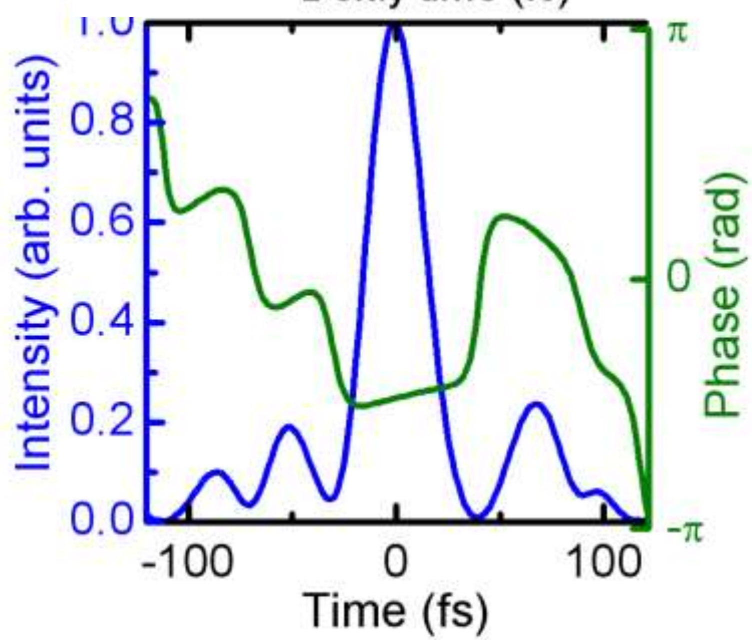
A. Sell, *et al.* Opt. Express **17**, 1070 (2009)

Few-Cycle Soliton from HNF 2

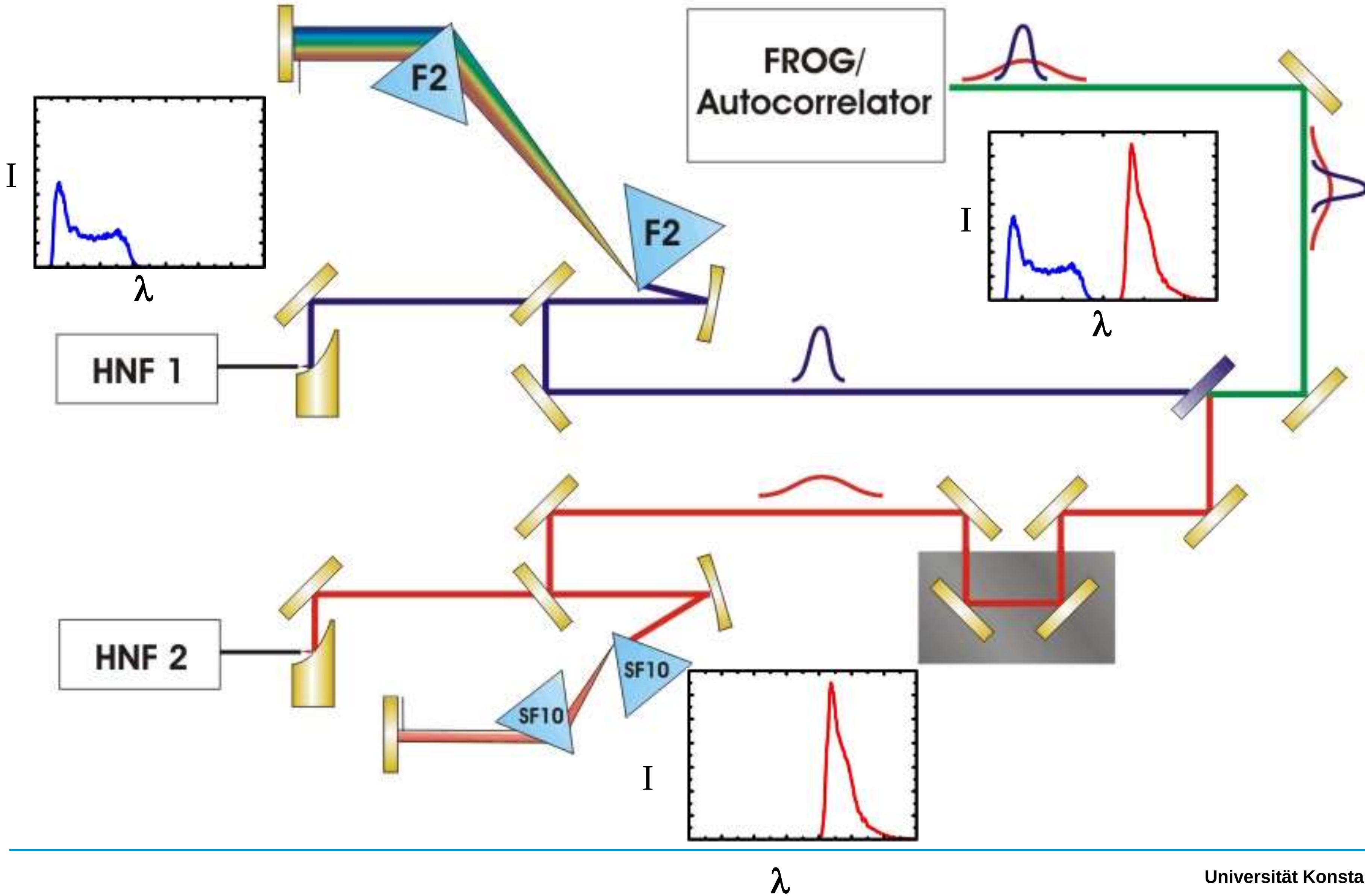
- Retrieved pulse duration: t_p = 31 fs
- 5 optical cycles
- Fourier limit: 23 fs
- Average output power: 55 mW



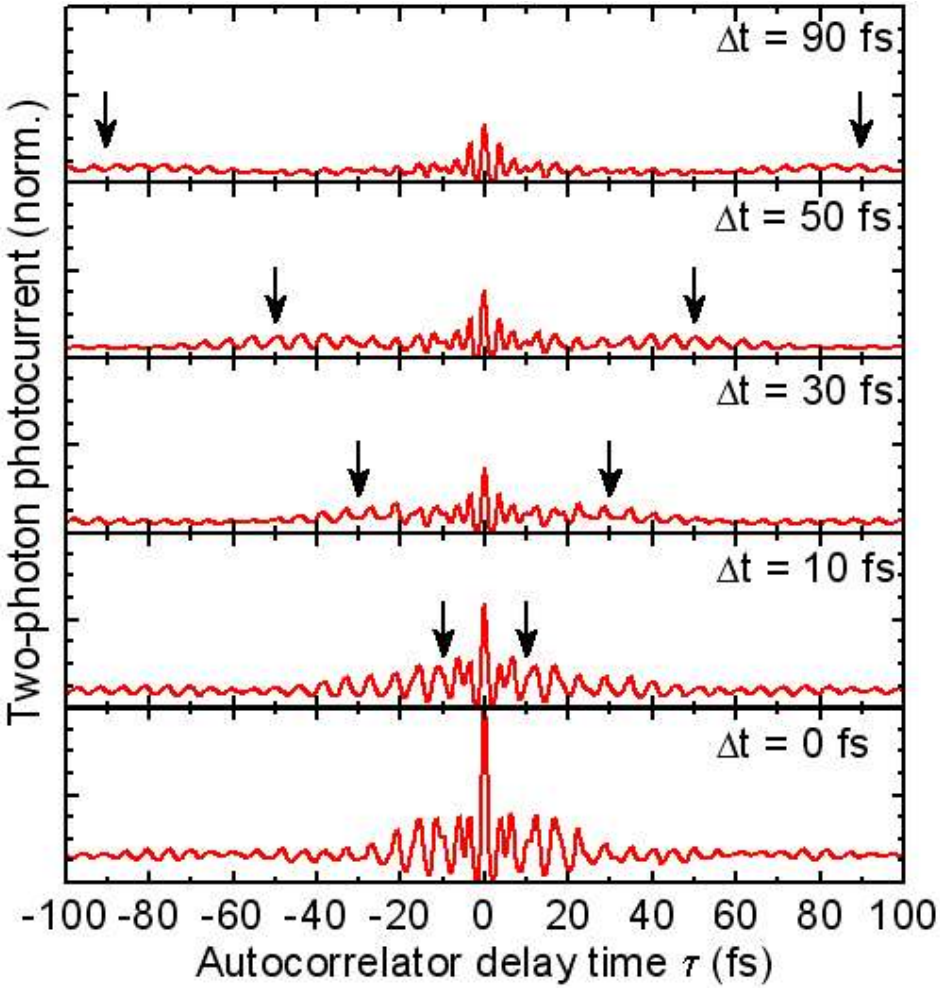




Single-Cycle Setup



Single-Cycle Pulse Synthesis



Large delay times Δt: second-order auto- and cross-correlations

Decreasing Δt:

Cross- correlation shifts towards center

Amplitude of central fringe increases strongly

Maximum amplitude for Δt = 0

Single-Cycle Pulse Characterization

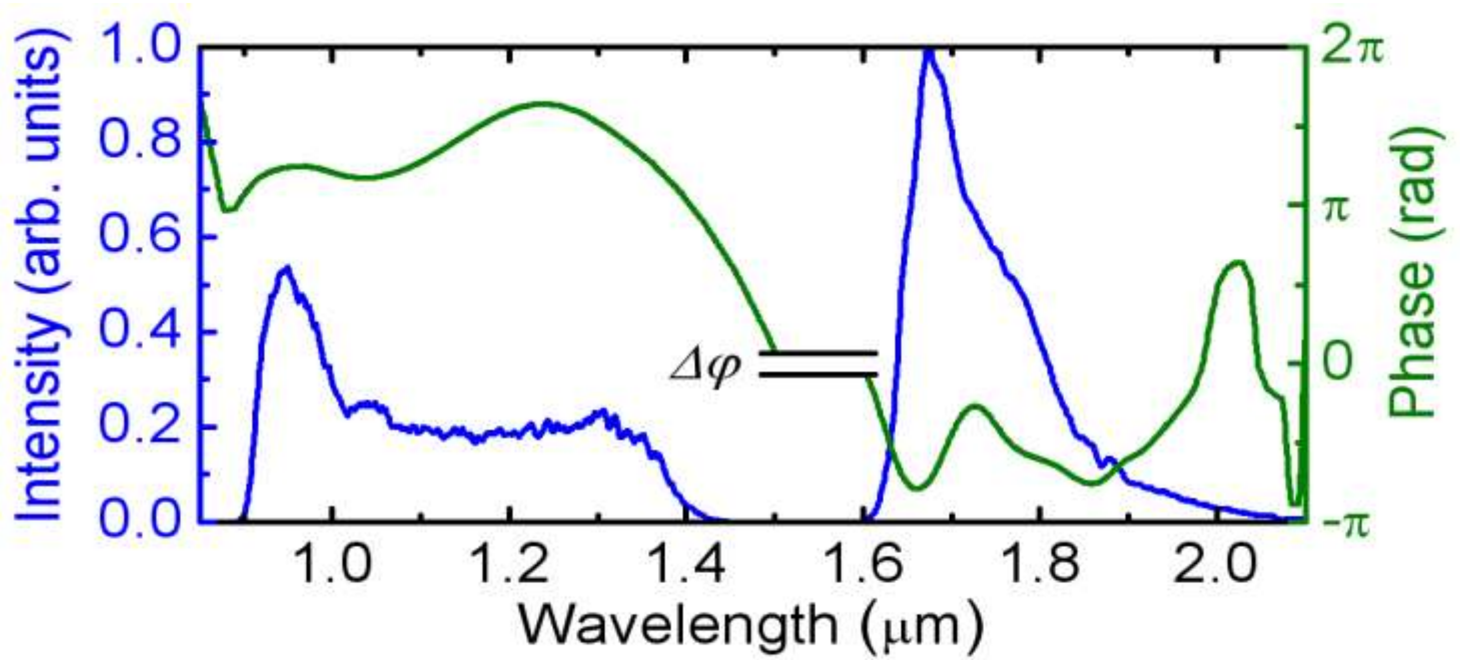
Separate FROG analysis of spectral amplitude and phase of soliton and dispersive wave

Amplitude ratio: linear spectrum

Two missing parameters left for total characterization:

Linear slope (time delay Δt)

Relative phase $\Delta\varphi$ between dispersive wave and soliton



Single-Cycle Pulses: Results

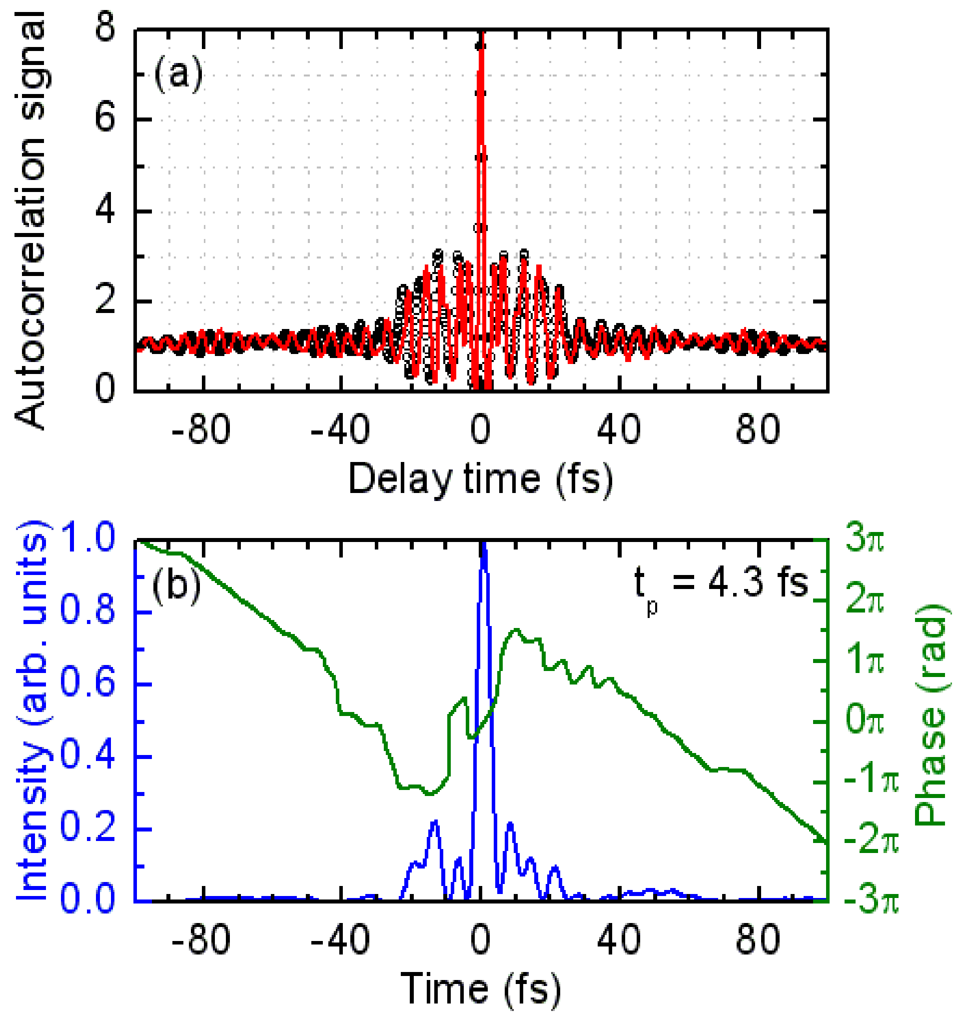
Determination of phase spectrum from FROG traces and least-square fit of $\Delta\varphi$ and Δt to second-order autocorrelation

Temporal amplitude and phase via Fourier transform

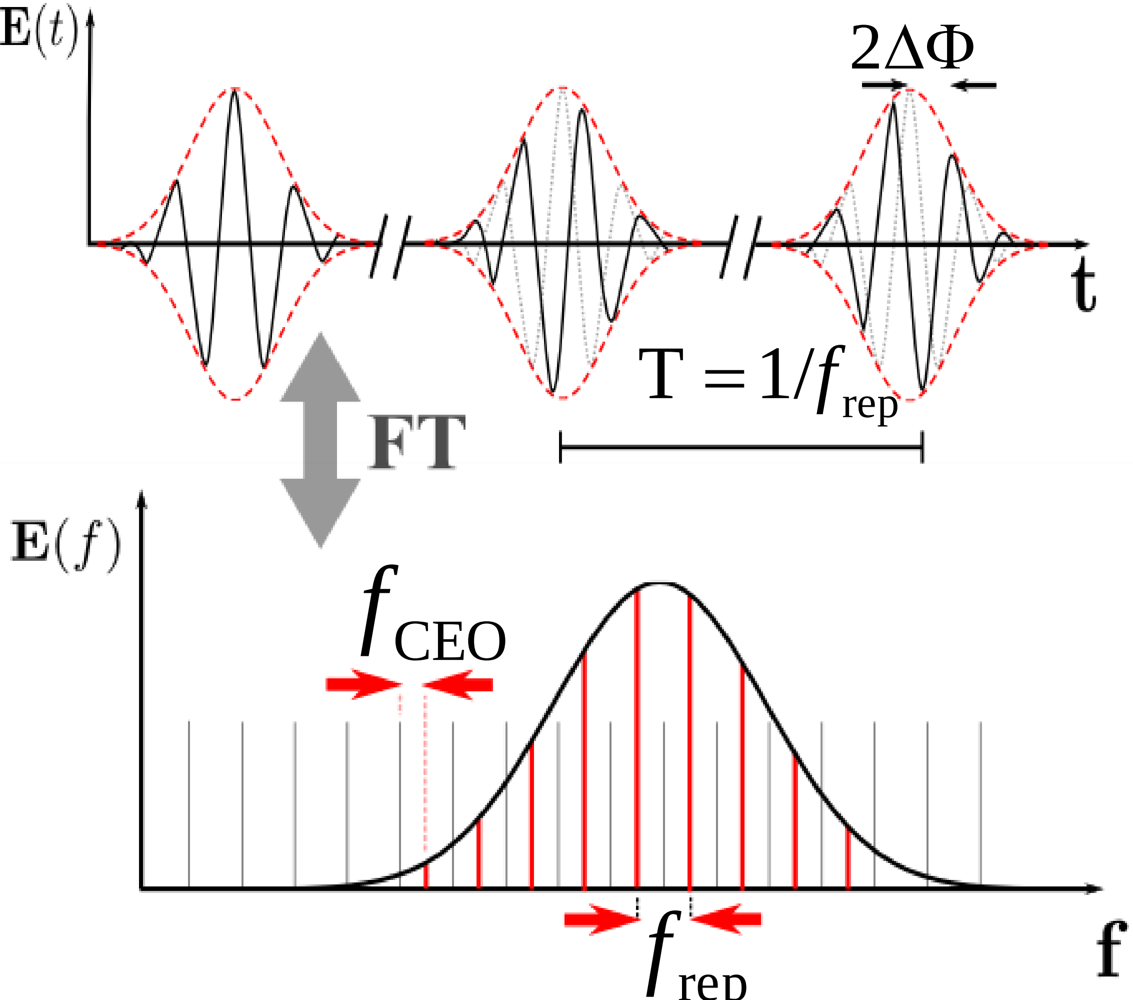
Retrieved pulse duration: t_p = 4.3 fs

Pulse energy: E_p = 1 nJ

→ Single cycle of light in the telecom wavelength regime



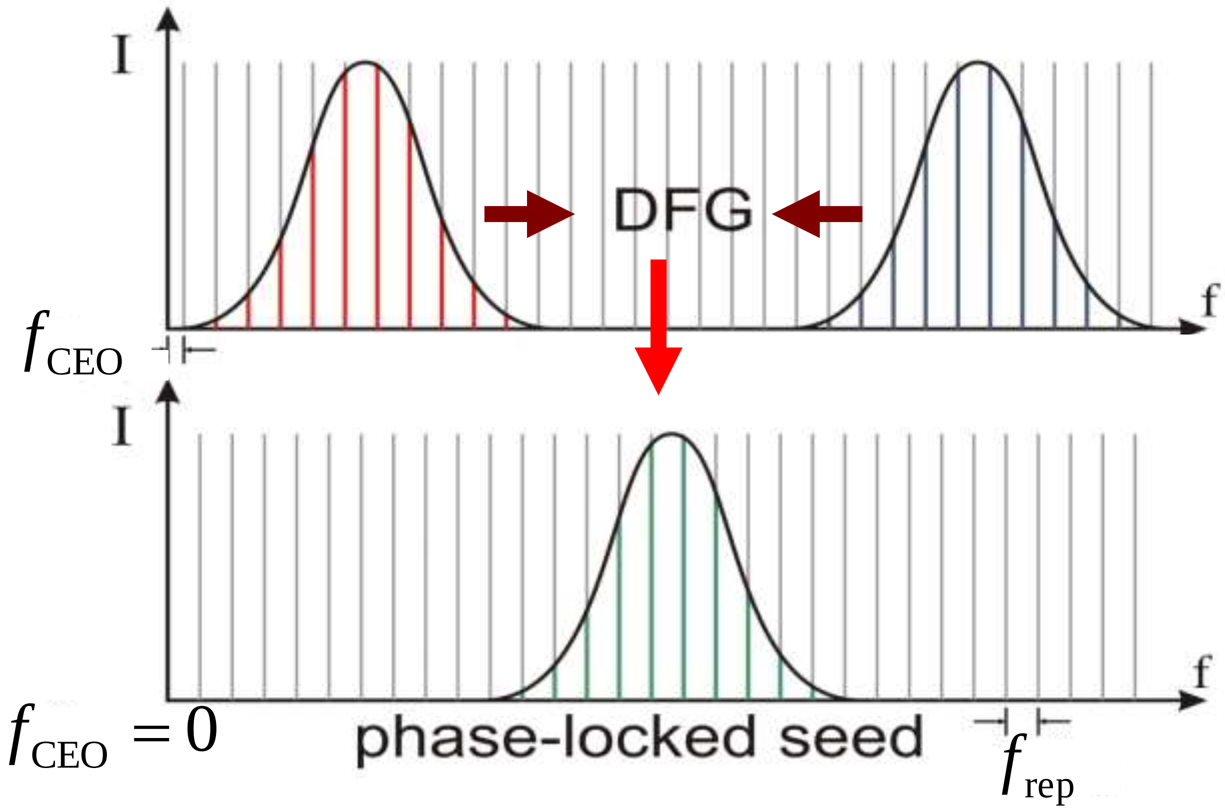
Carrier-Envelope Phase Control



$$f_n = f_{CEO} + n f_{rep}$$

- frequency spectrum consists of equidistant lines with CEO-frequency offset
- slippage of carrier envelope phase due to group and phase velocity mismatch
- control of CEO-frequency essential for:
  - nonlinear physics
  - metrology

Passive CEP Stabilization: Input Spectra

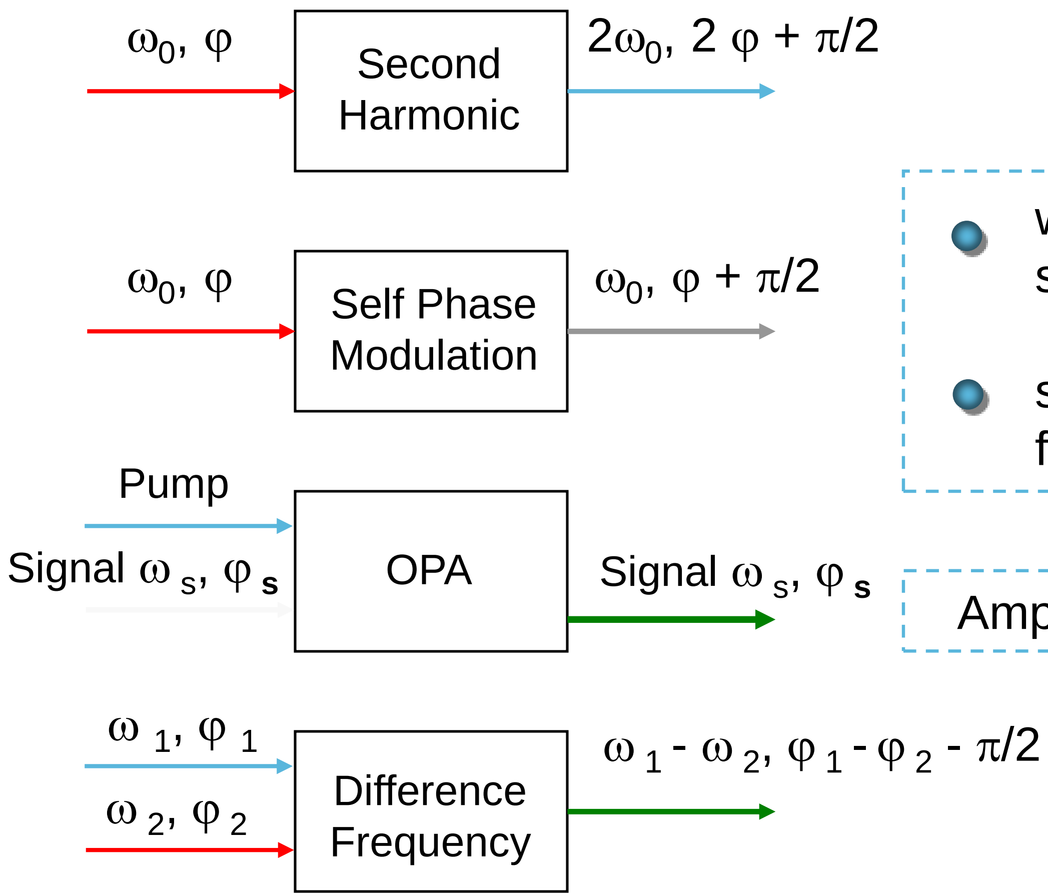


Idea: generation of phase-stable pulses at 1550 nm via DFG, from ultrabroadband HNF spectrum

goal: seed source with carrier-envelope offset frequency set to zero and subsequent amplification

⇒ **passive phase locking of fs-Er:fiber technology at full repetition rate of 40 MHz**

CEP and nonlinear processes



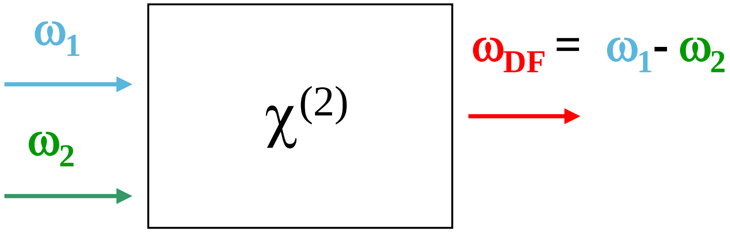
- white light generation in a sapphire plate
- supercontinuum by a hollow fiber

Amplification does not affect CEP

Difference Frequency Generation

$$\omega_{DF} = \omega_1 - \omega_2$$

$$\varphi_{DF} = \varphi_1 - \varphi_2 - \pi/2$$



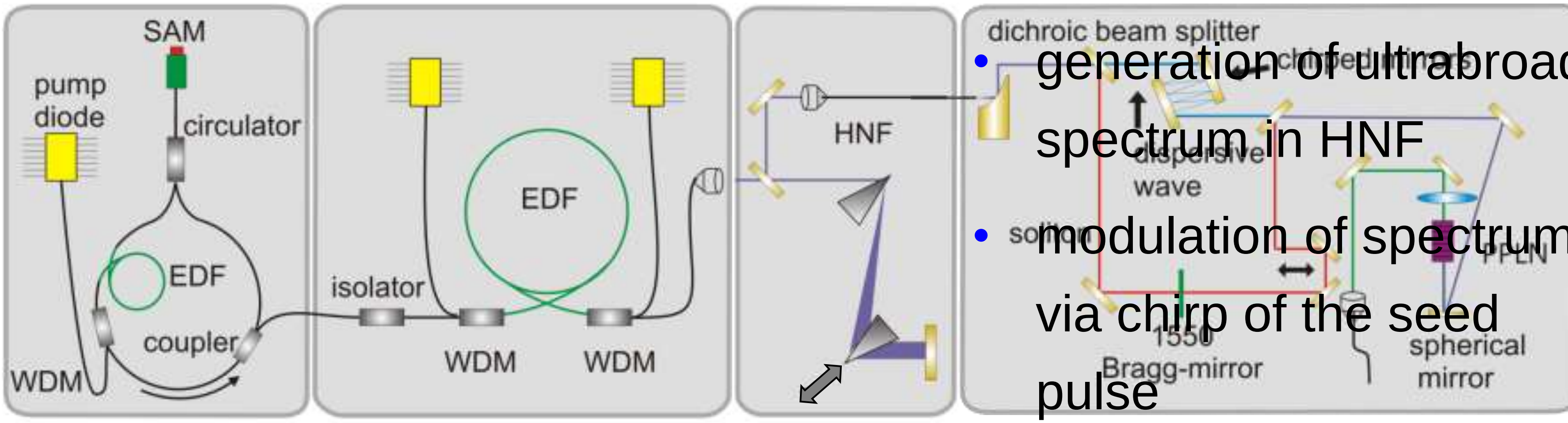
- Difference-frequency generation (DFG) allows:
  - ✓ manipulation of the CEP
  - ✓ generation of MIR light

if fields are **phase-locked**:

$$\varphi_1 = \varphi_2 + \Delta\varphi \Rightarrow \varphi_{DF} = \Delta\varphi - \pi/2 \text{ (const.)}$$

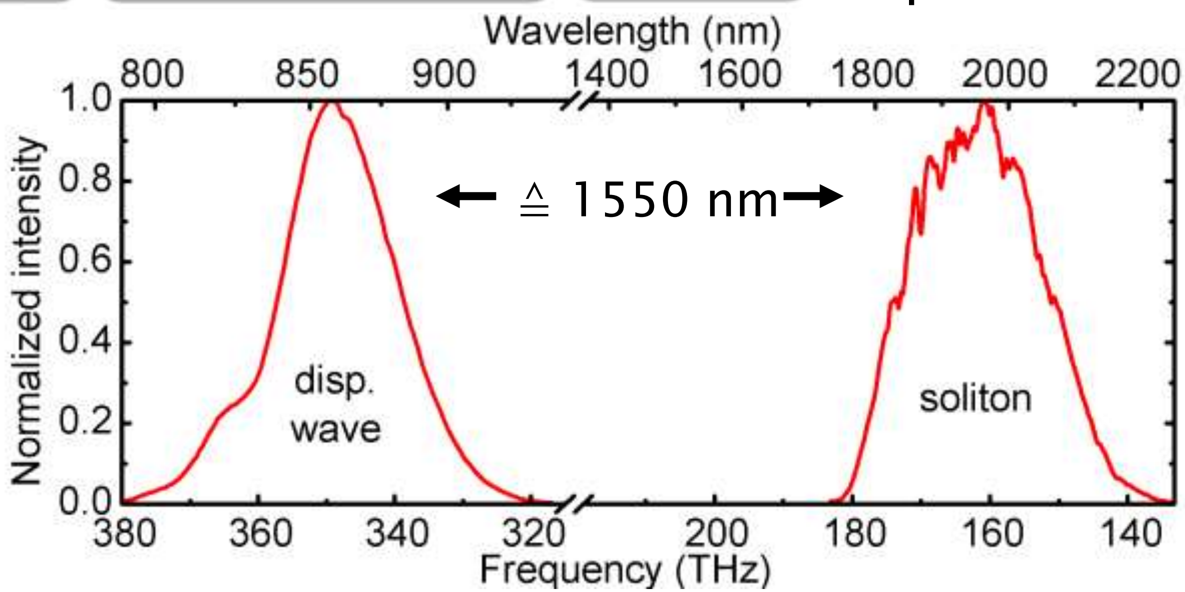
- DFG between two pulses carrying the same CEP leads to **automatic** phase-stabilization of the DF pulse

General Setup



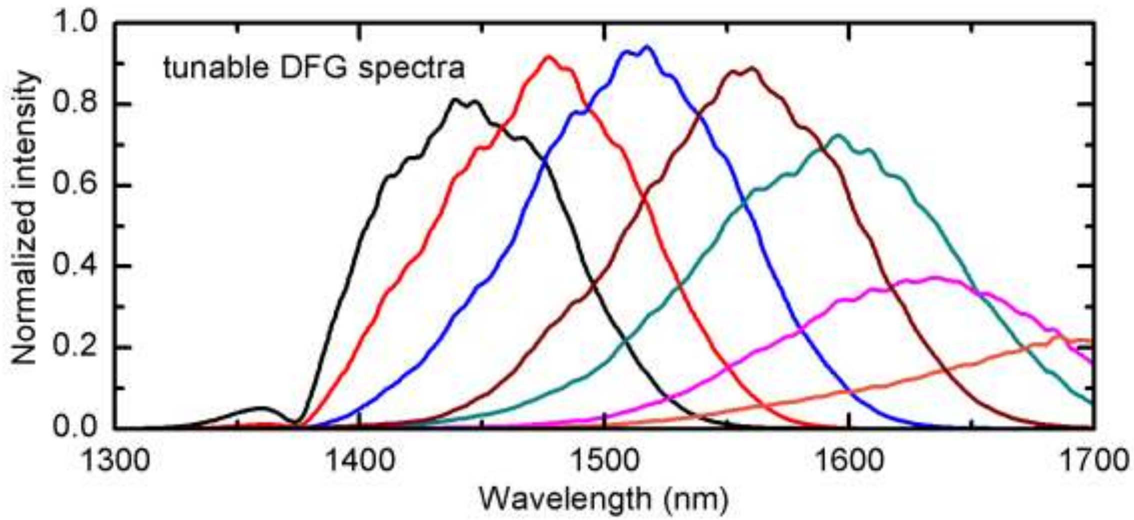
- generation of ultrabroad spectrum in HNF
- modulation of spectrum via chirp of the seed pulse

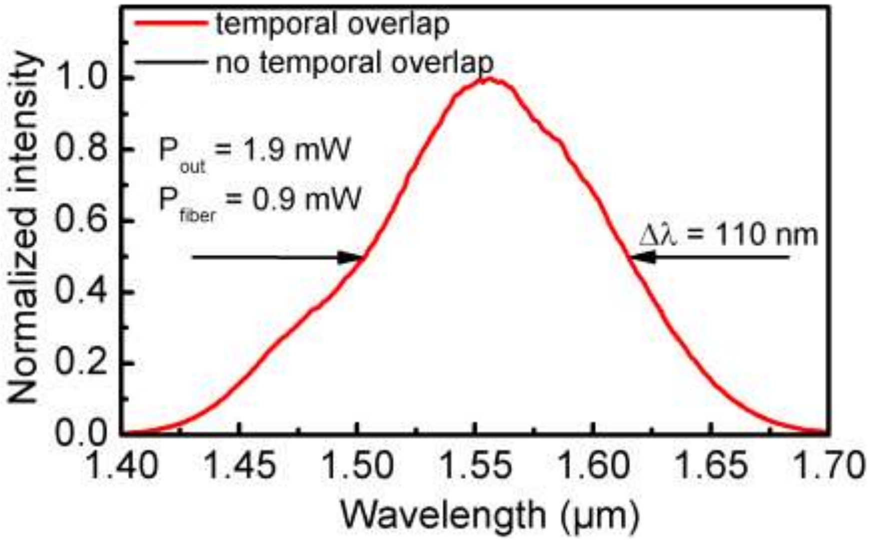
- sep ession
- diffe



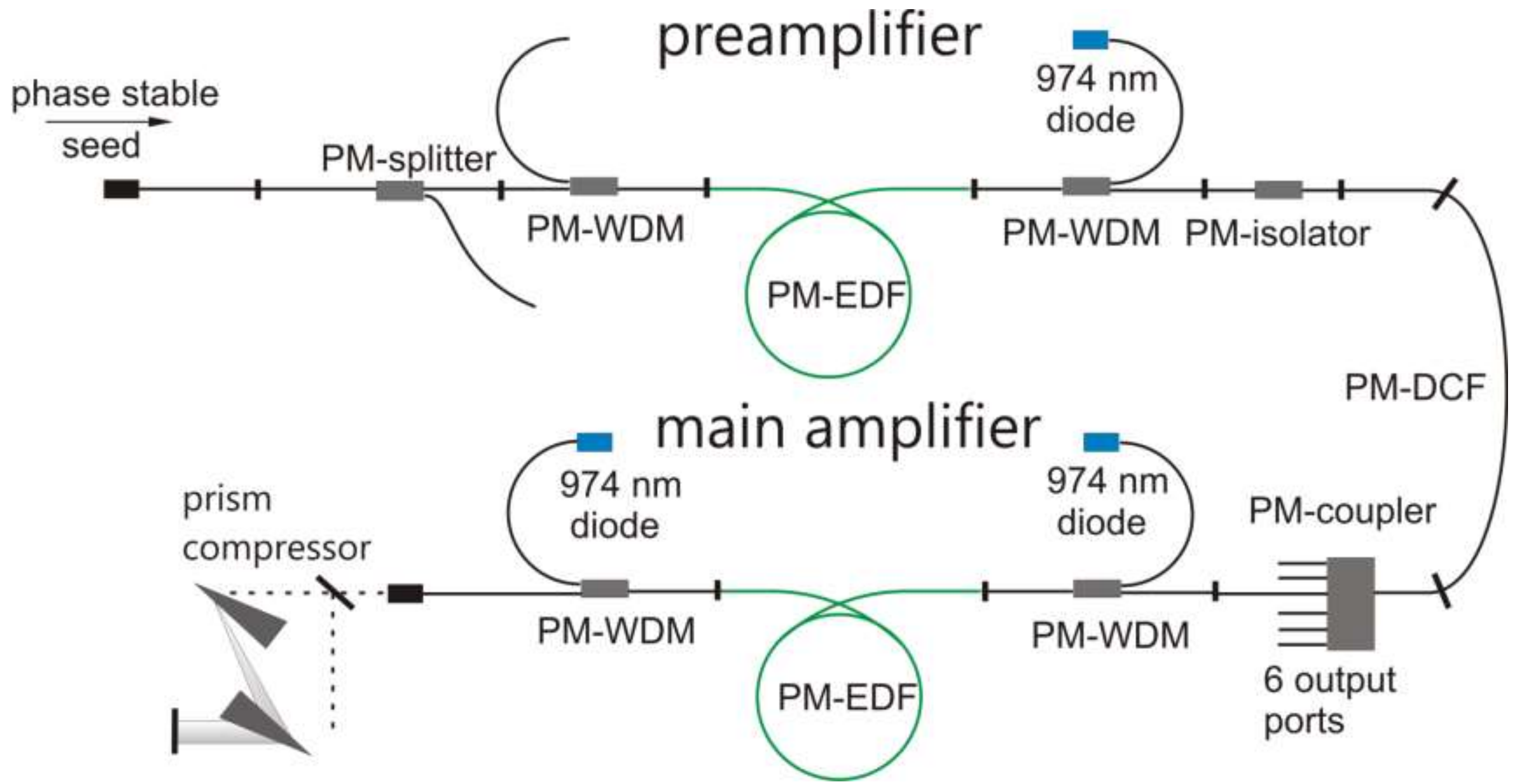
Phase-locked Pulses at 1550 nm

- DFG tunable from 1400 nm – 1600 nm
- broadband DFG output
- complete background suppression with two 1550 nm Bragg-mirrors





Reamplification of Phaselocked Seed

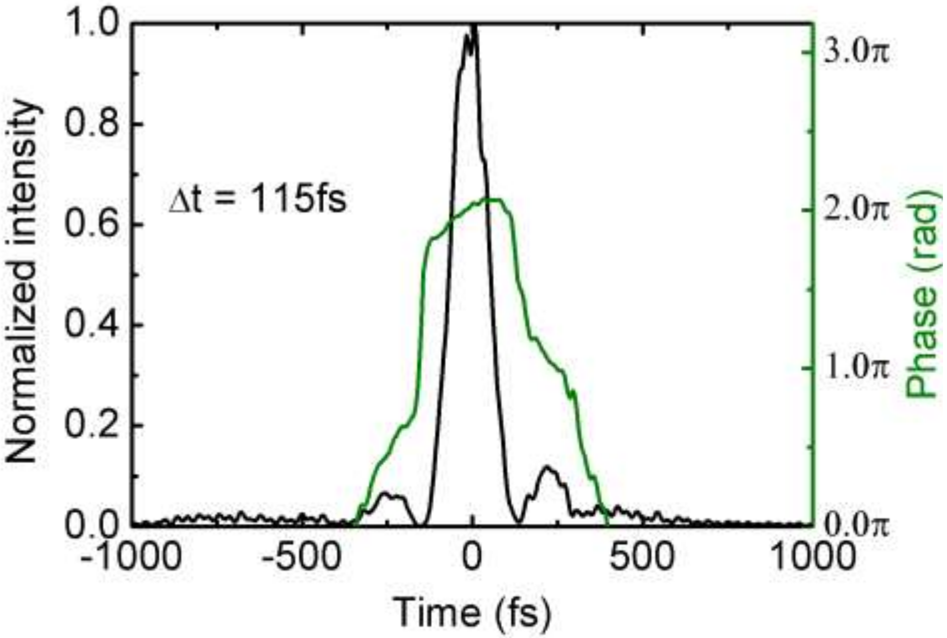


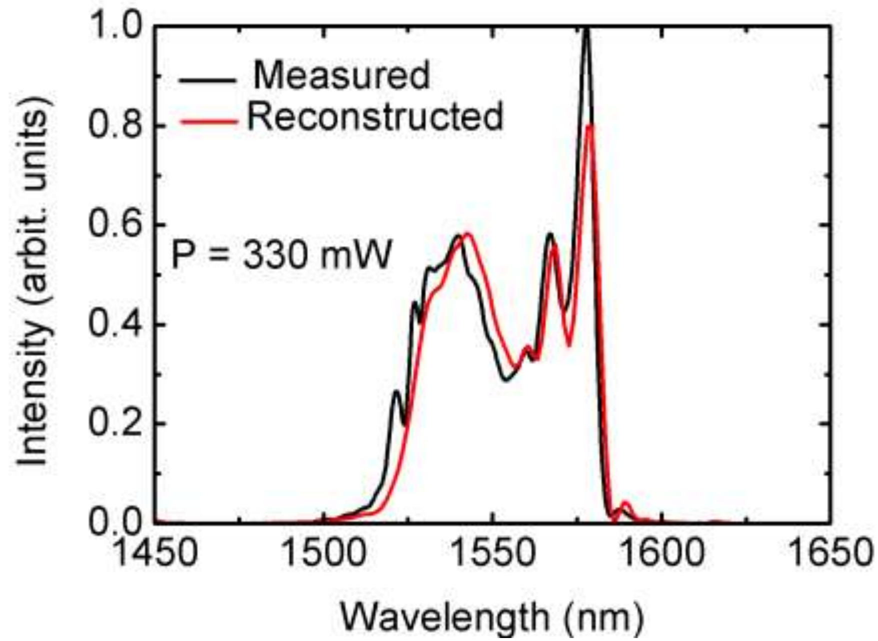
6 synchronized output ports after preamp

high power fiber amplifiers for extreme nonlinear optics

frequency comb applications

Output Performance of Amplifiers





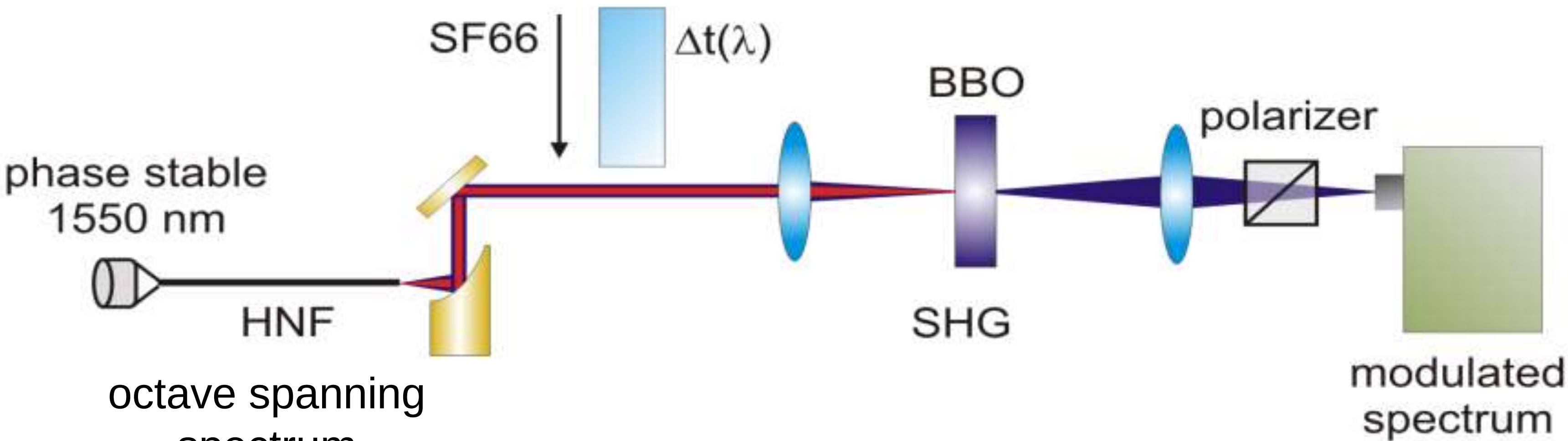
average power P = 2.1 mW @ each port after preamplifier

average power P = 330 mW after main amplifier

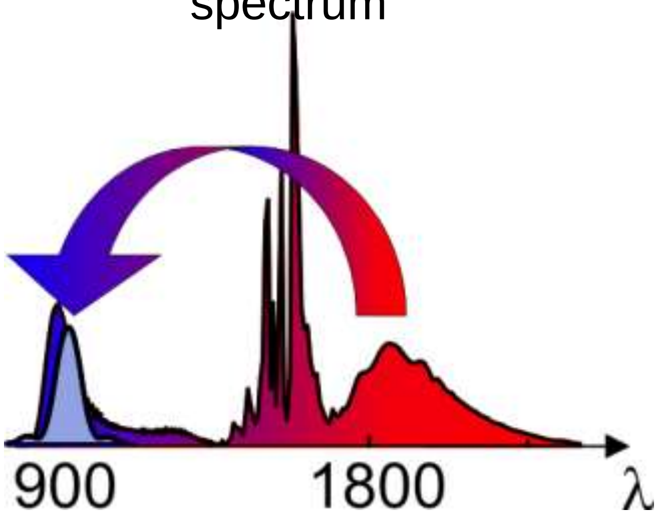
pulse duration t_p = 115 fs after prism compressor

inherently phase-locked 8 nJ pulses at full 40 MHz repetition rate

Characterization of Absolute Phase Stability



octave spanning
spectrum



$$\left\langle \left(\sin(\omega t + \varphi) + \sin(\omega(t-\tau) + 2\varphi + \pi/2) \right)^2 \right\rangle$$

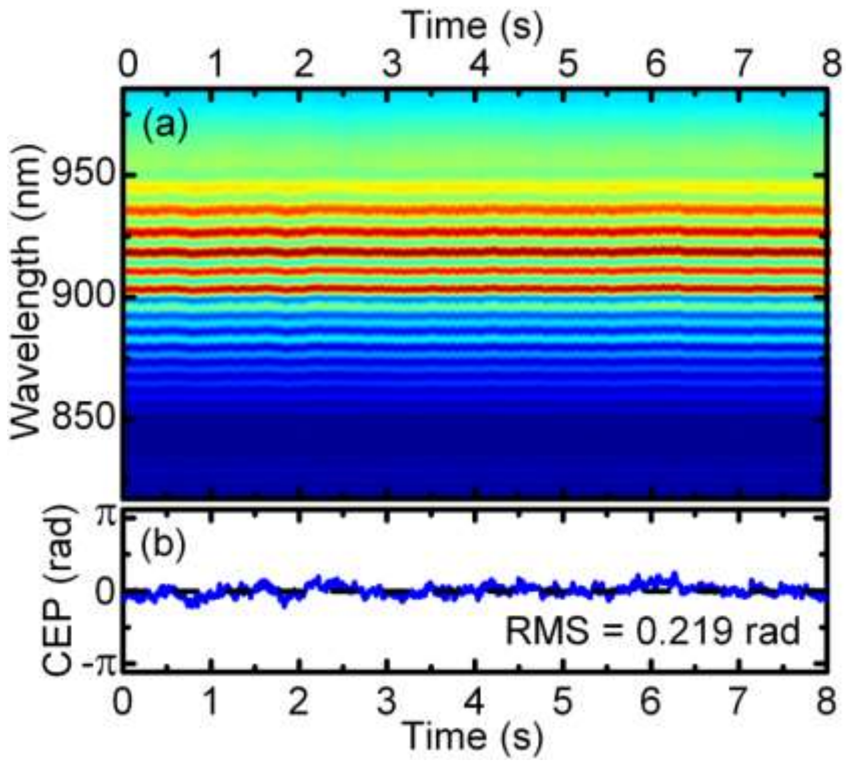
spectrum modulated by: $1 + \sin(\omega\tau - \varphi)$

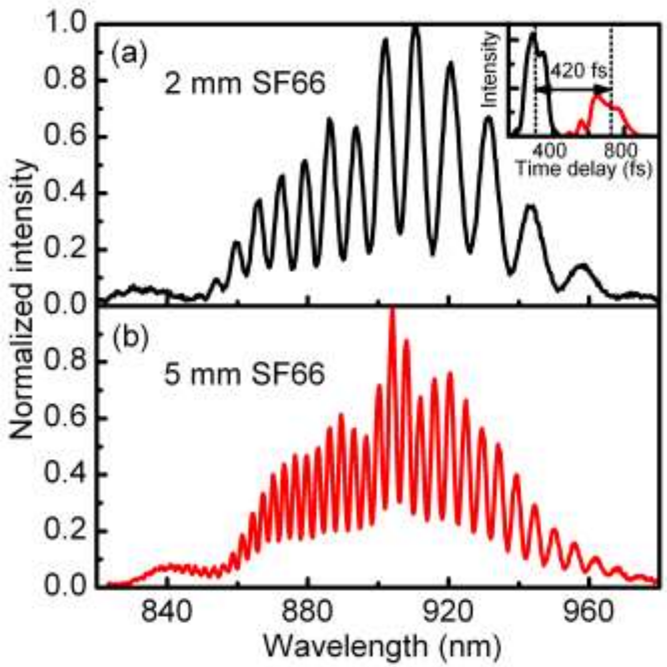
CEP stable → stationary inteference fringes

Long-term Stability of Passive Phase Lock

- integration time of 4 ms implies average over 160,000 pulses

- good fringe visibility indicates extremely good short-term stability





- acquisition of 1000 spectra over 8 s
- RMS of phase amounts to 0.219 rad
- excellent long-term stability for time-domain applications

Seeding Yb and Tm amplifiers

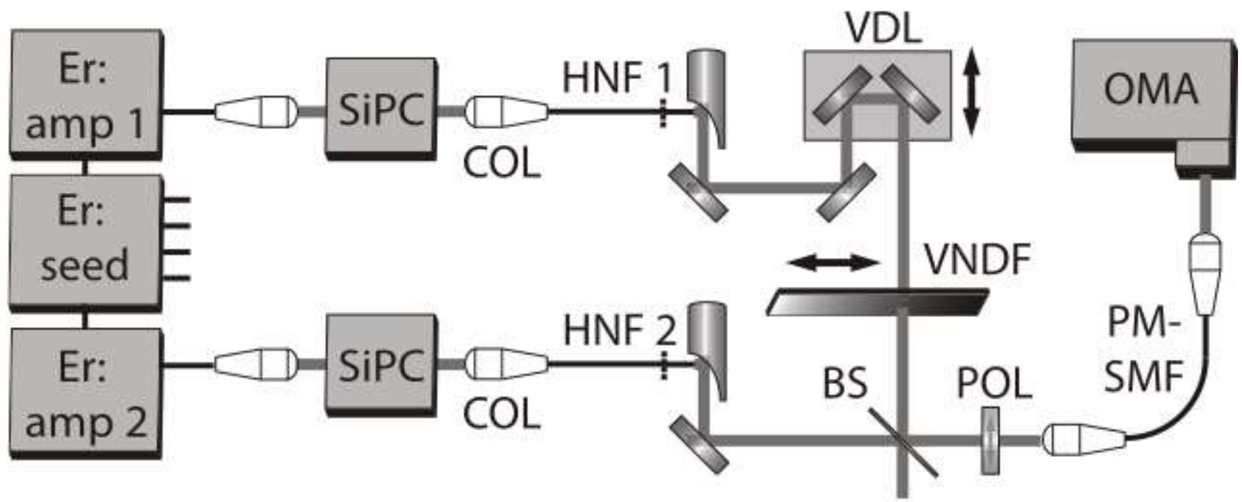
Seed high power fiber laser starting with a compact Er:fiber system.

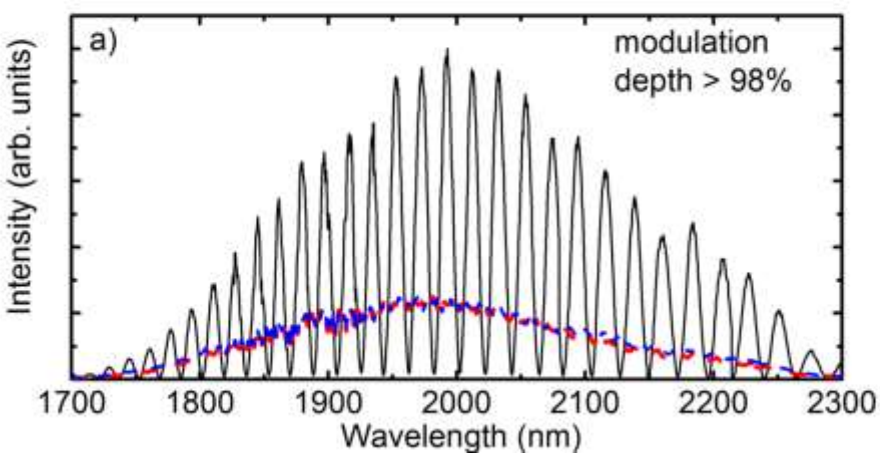
Yb	**Tm**
1064 nm	1950 nm
Power scalable up to a multiW regime	Broad gain bandwidth
Mature technology	Particularly promising for future application
Dispersive wave	Soliton

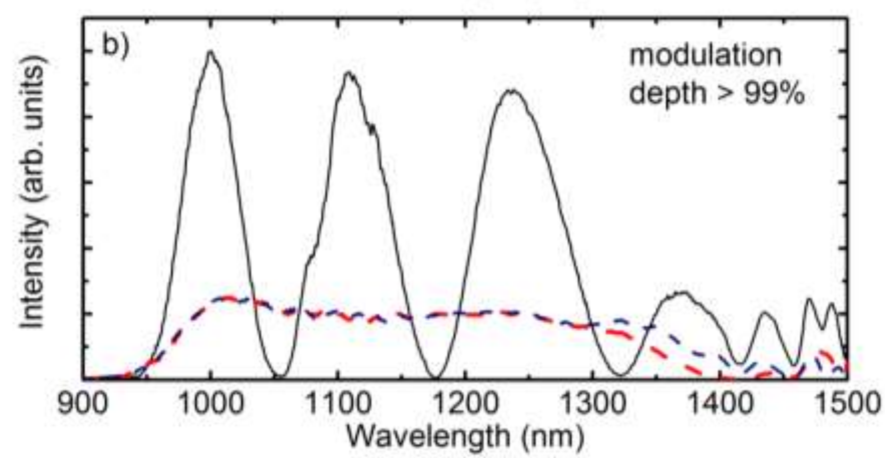
Problem: supercontinuum coherence at the output of standard PCFs

Supercontinuum coherence

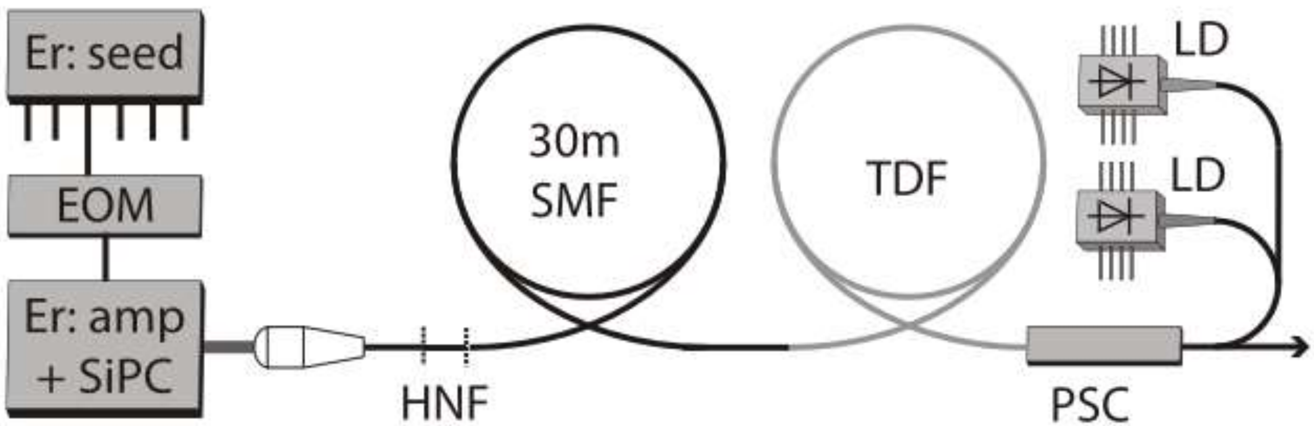
Interference between the SCs generated by two distinct branches of the system







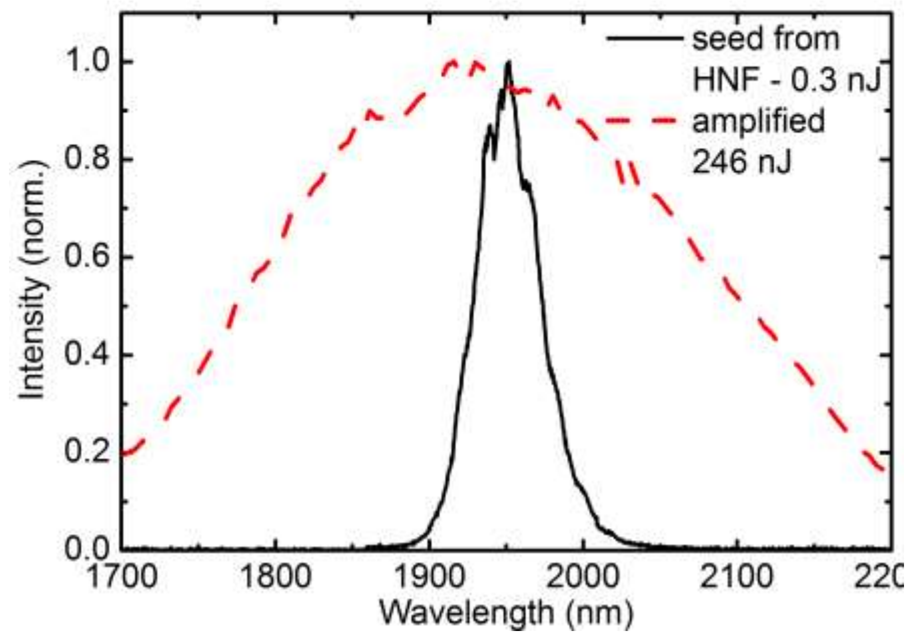
First proof of Tm:amplifier



10 MHz
Tm:amplifer

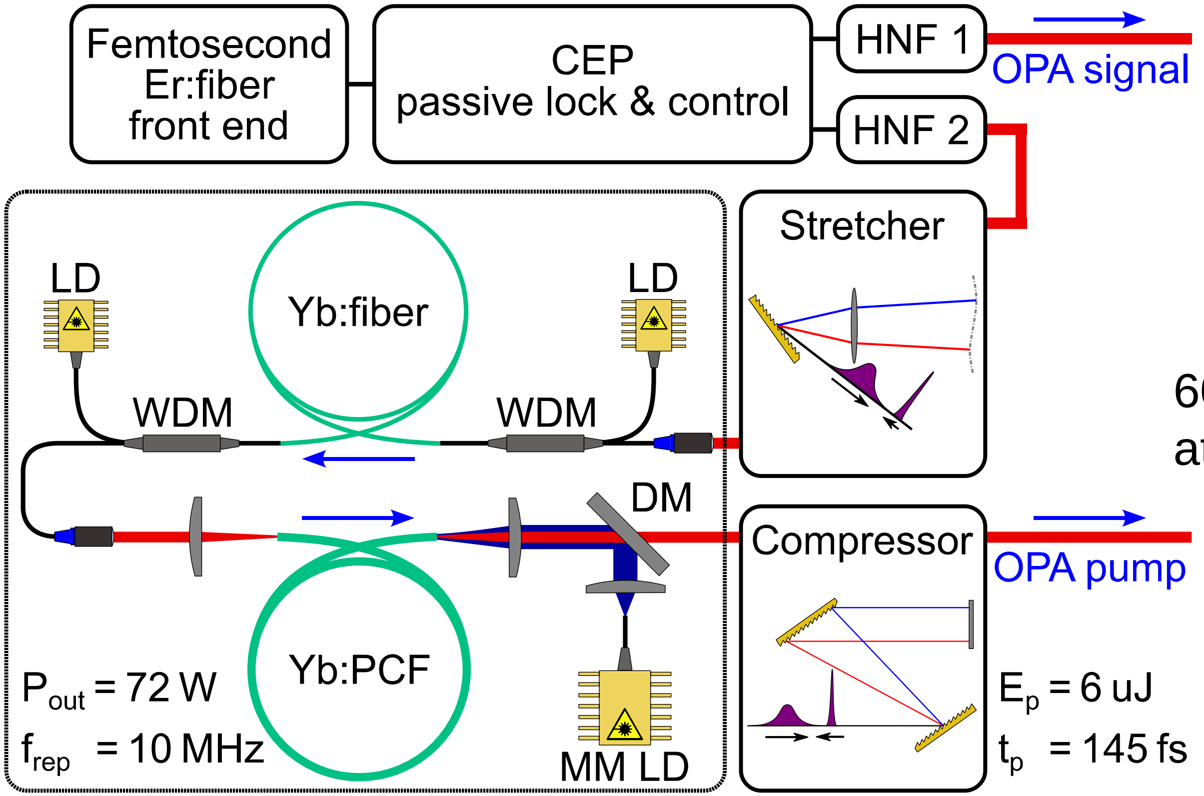
9 W pump
power

Amplification at 1950 nm with 2.46 W output average power



High repetition rate for maximum sensitivity

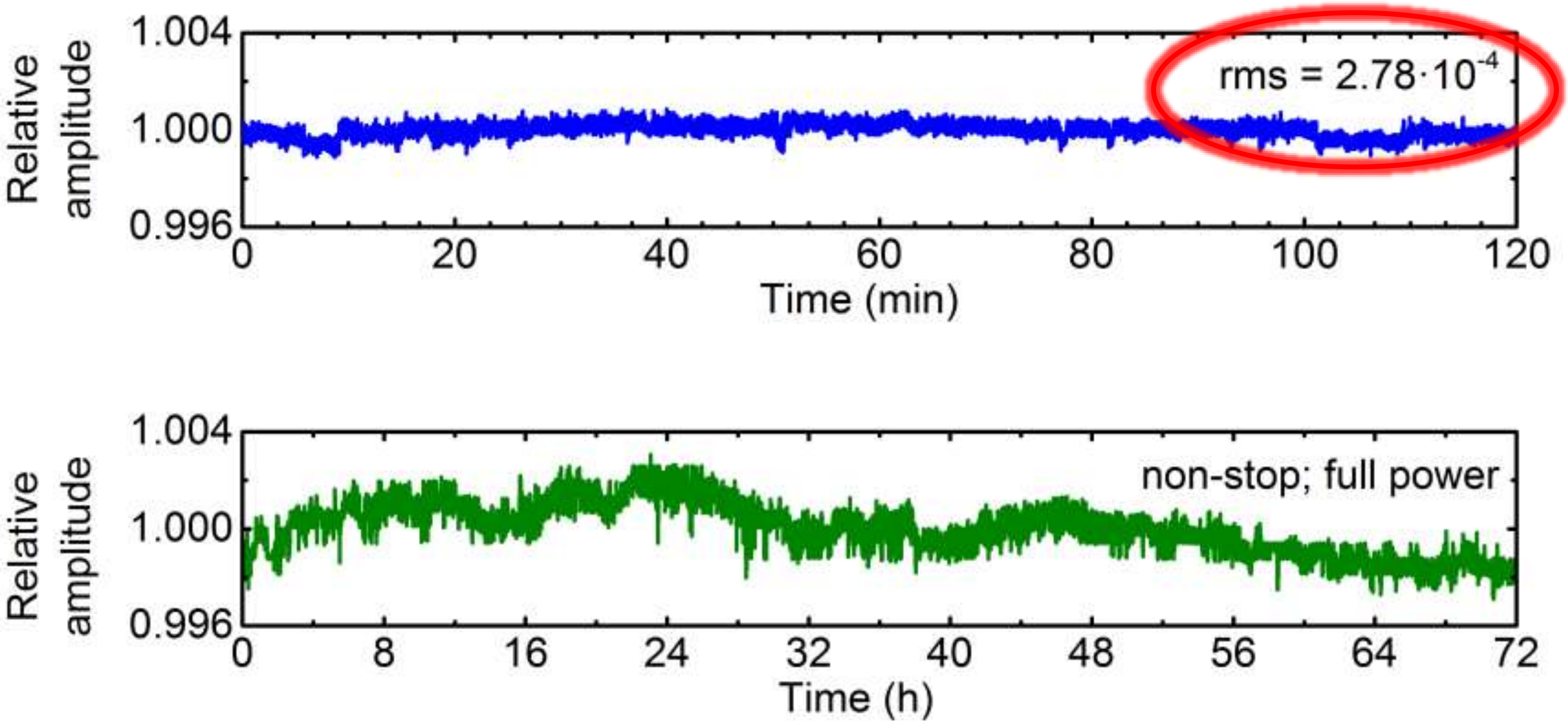
Er:fiber femtosecond laser seeding a high power Yb:fiber amplifier



60 W total output power at 10 MHz repetition rate

Multibranch design for advanced ultrafast applications

Noise Performance and Long-Term Stability



peak-to-peak fluctuation: < ± 0.3% during 72 h of operation at full power

White Light Generation

- 2.5 W from Yb:fiber amplifier (less than 5% of the available power at 10 MHz!)
- Focused into 3 mm YAG

➔ 2 octave spanning spectrum