Basics of high-power ultrafast fiber amplifiers

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Outline

Principles of fiber amplifiers

- Signal guiding, amplification
- Pump guiding and double-clad fibers
- Thermal aspects

Ultrafast fiber amplifiers

- Limiting effects in short pulse amplification
- LMA fibers and CPA amplification
- State of the art

Parabolic fiber amplifiers

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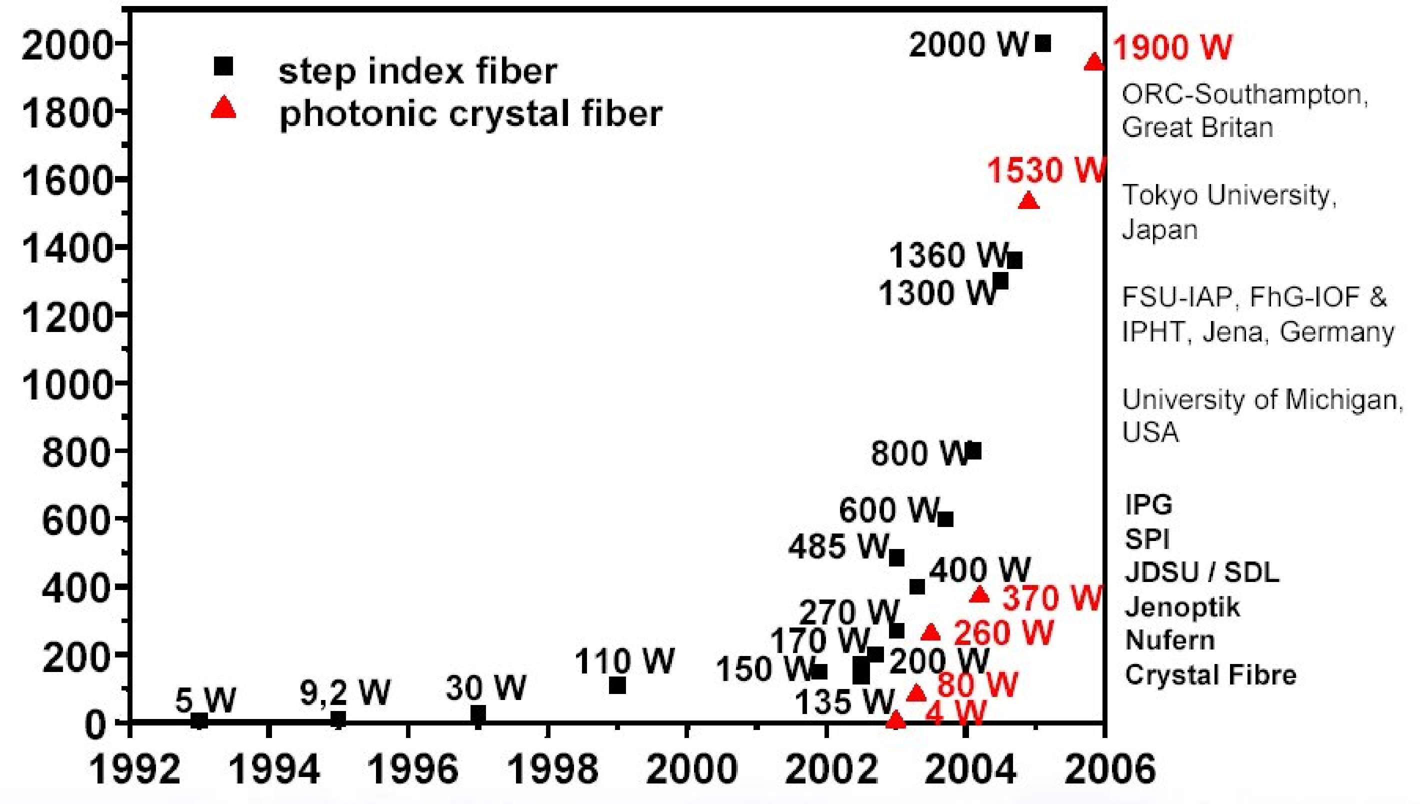
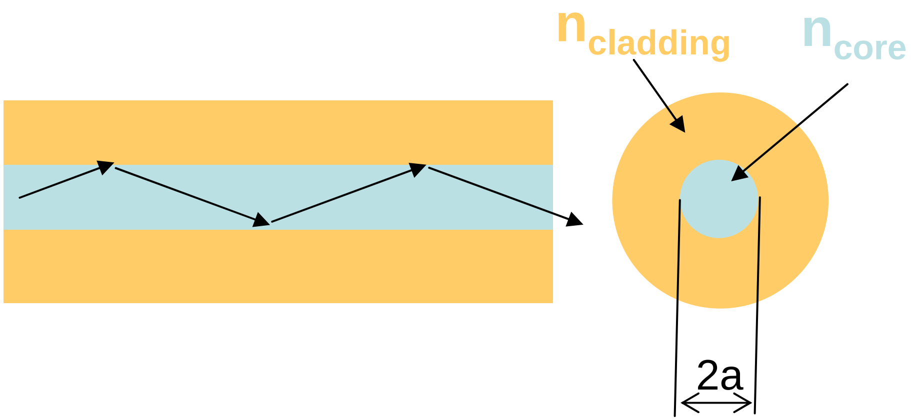
The explosion of fiber laser performances



CW fiber laser output power

Transverse monomode

Signal guiding

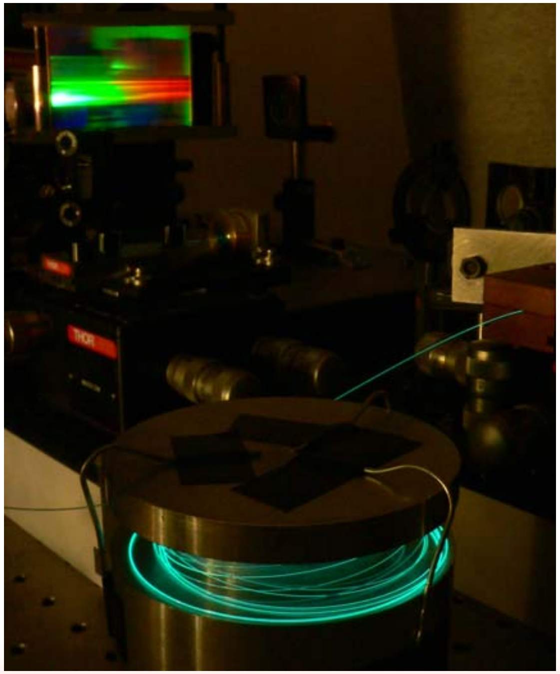


$$V_{SI} = \frac{2\pi}{\lambda} \cdot a \cdot \sqrt{n_{core}^2 - n_{cladding}^2}$$

single-mode condition: $V_{SI} < 2.405$

- Guiding by Total Internal Reflection
- Monomode operation : index contrast, mode diameter

Amplification in fibers

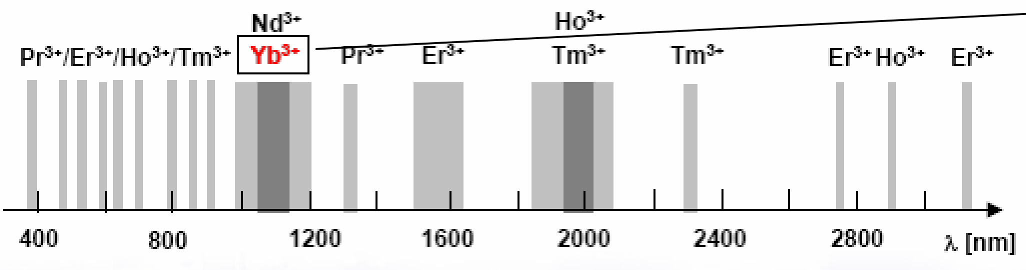


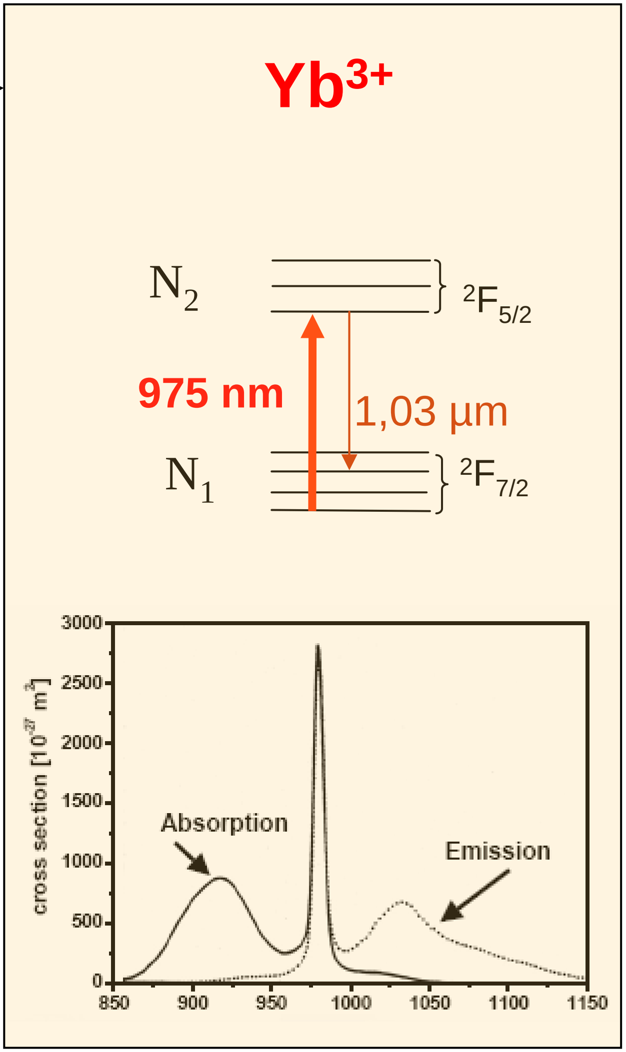
Advantages of fiber amplifiers

- High gain (interaction length and confinement)
- Immune against thermo-optical problems
- Excellent beam quality
- Integration in all-fiber systems

Ytterbium-doped fibers

Emission bands of rare-earth dopants





Advantages of the Yb dopant

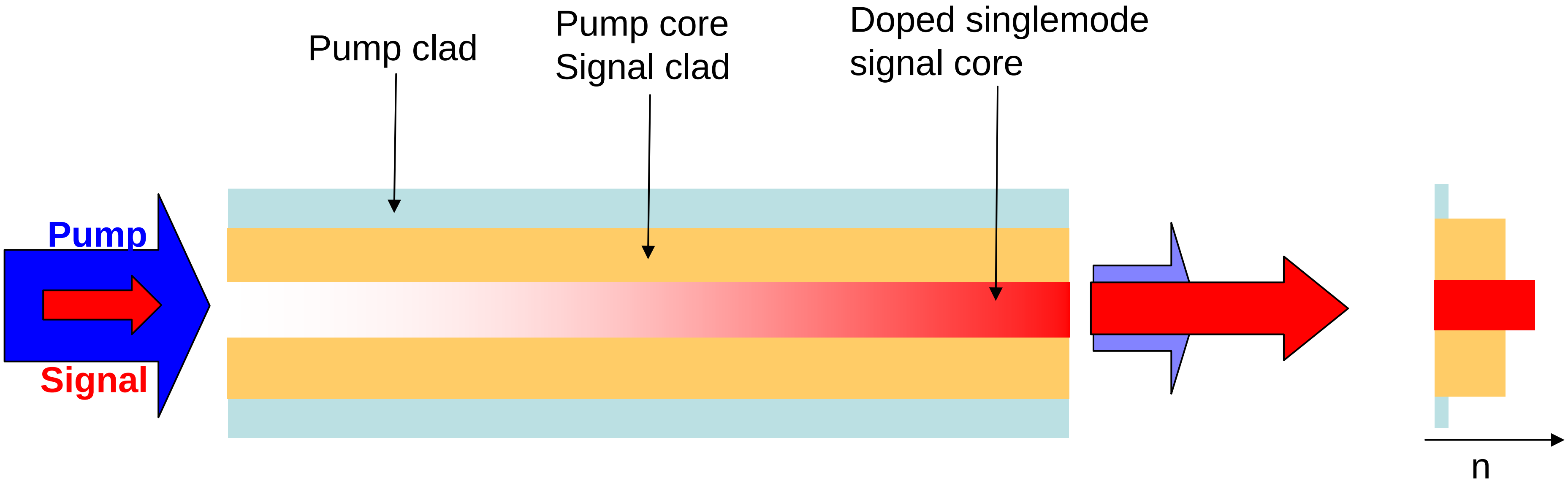
- No excited-state absorption
- Pumped by high-power diodes at 980 nm
- Broad emission bandwidth → short pulses
- Low quantum defect → high efficiency

  low thermal load

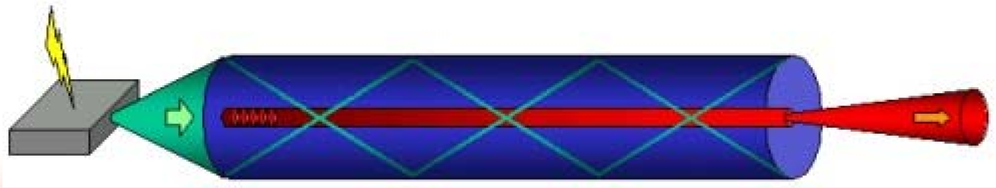
Double-clad fiber geometry

Problem : Pump must be diffraction-limited to be injected in singlemode core

Solution : Double clad fiber structure



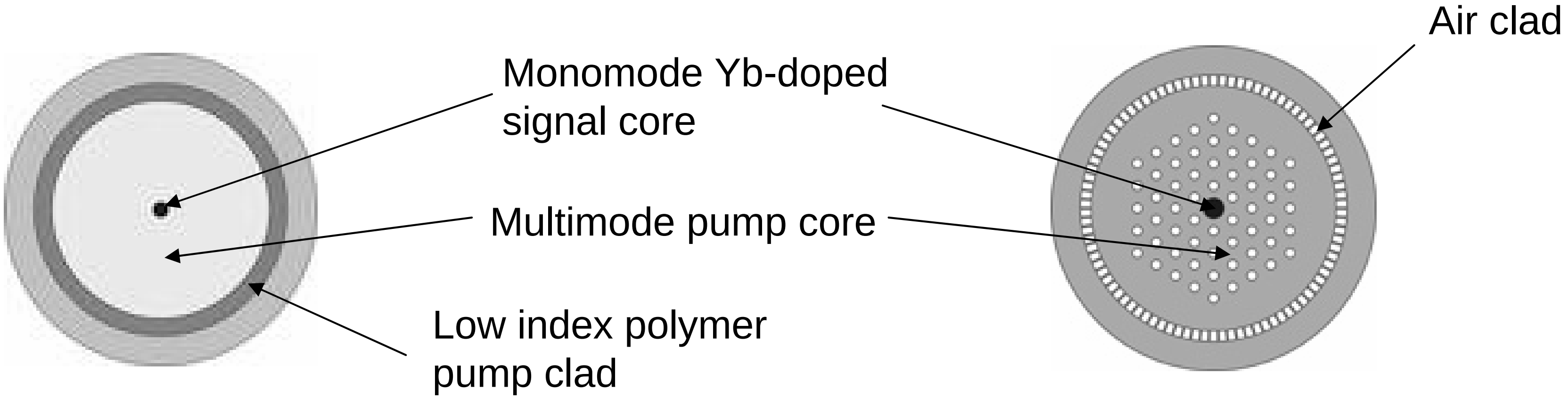
Highly efficient brightness conversion through stimulated emission



Double-clad fiber geometry

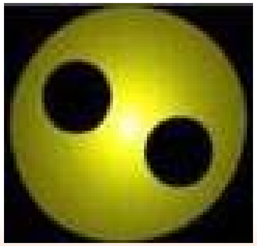
Geometry can be implemented through doping or microstructuration

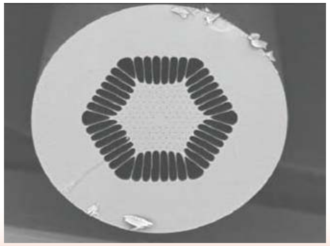
Double-clad fiber | Air-clad fiber



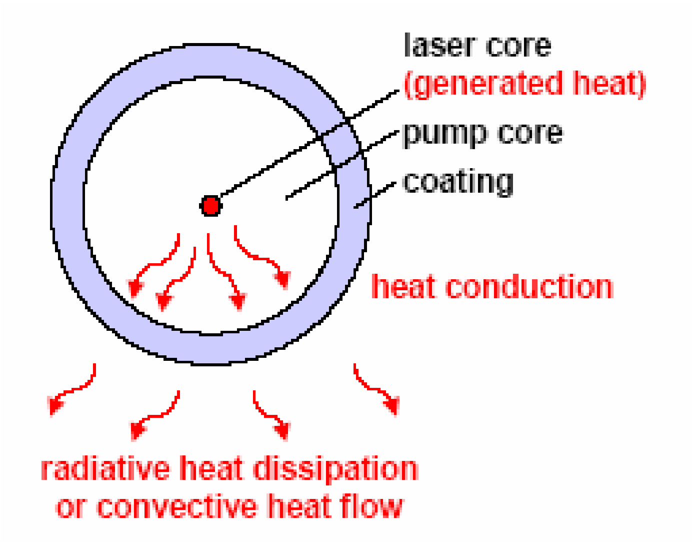
- Polymer pump clad
- Polarization-maintaining

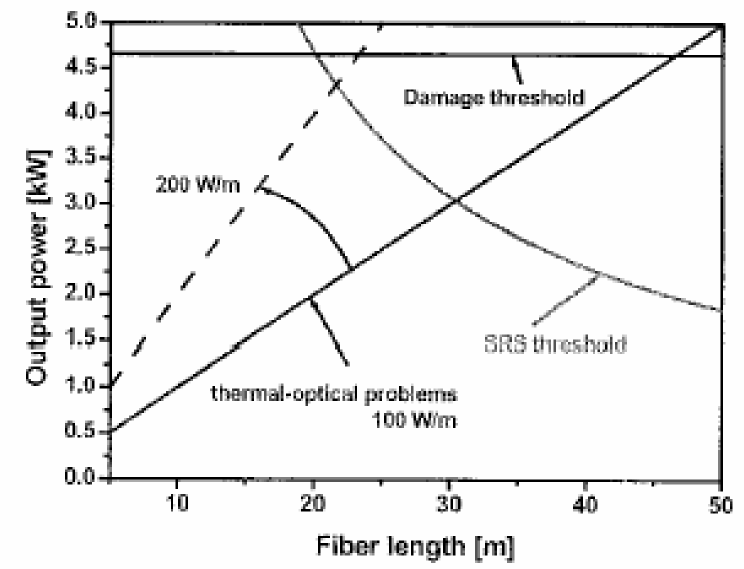
- Higher NA for pump core
- No pump radiation in the polymer clad
- Larger MFD while singlemode





Thermo-optical properties





- Long interaction length: Pump absorption distributed

  High surface to volume ratio

→ Multi kW monomode operation is possible

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Peak power limitation: optical damage

Fused silica

- Bulk damage (1 ns pulse) : 220 J/cm^2, 2.2 mJ for 35 µm MFD

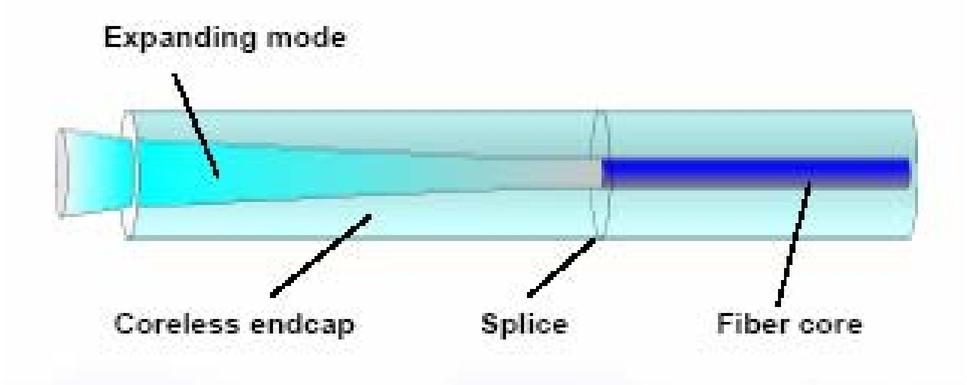
→ comparable to extractable energy

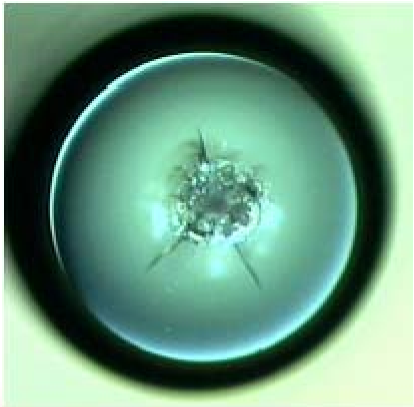
Surface damage (1 ns pulse) : 22 J/cm^2, 220 µJ for 35 µm MFD

→ coreless endcaps (beam expanders)

$$\varepsilon_{sd} \approx 22 \times (\Delta\tau)^{0.4}\ \mathrm{J/cm}^2$$

(ns) → $\Delta\tau$





Peak power limitation : nonlinear effects

- Interaction length, confinement, short pulses → nonlinear effects
- Spatial aspects: Self focusing (does not scale with MFD)

$$P_{crit} = \frac{\pi (0.61)^2 \lambda_0^{\ 2}}{8 n_0 n_2} \simeq 4\text{MW for silica @ 1050 nm}$$

- Temporal aspects: Nonlinear Schrödinger equation with gain

$$i \frac{\partial u}{\partial z} = \frac{\beta_2}{2} \frac{\partial^2 u}{\partial t^2} - \gamma \left(|u|^2 u - T_R \frac{\partial |u|^2}{\partial t} \right) + i \frac{g}{2} u$$

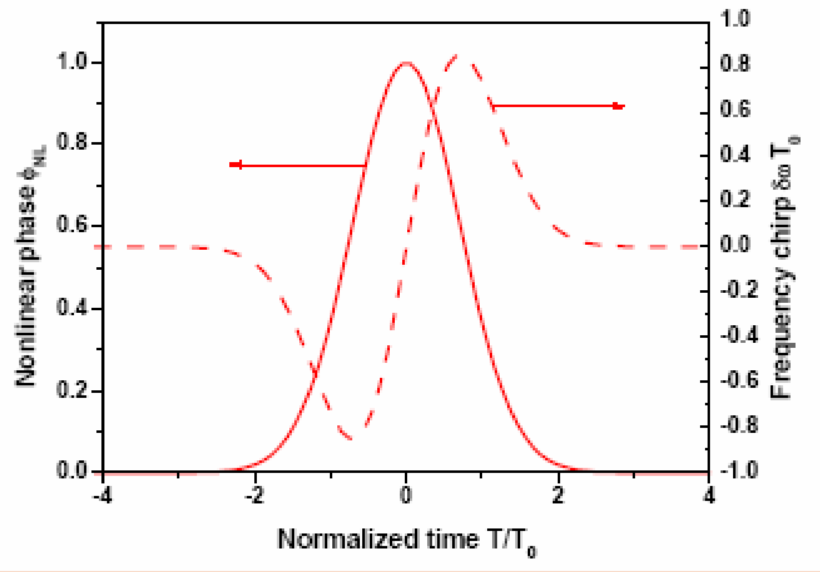
Dispersion   Self-phase modulation   Raman effect   Gain

Self-phase modulation

- Intensity-dependent refractive index $n(t) = n_L + n_2 I(t)$
- Nonlinear phase-shift $B = \int_0^L \gamma P_{peak}(z)\, dz$
- Frequency shift $\delta\omega(T) = -\frac{\partial \phi_{NL}(z,T)}{\partial T} \propto \frac{L}{A_{eff}}$

→ Spectral broadening

→ Nonlinear chirp, difficult to recompress



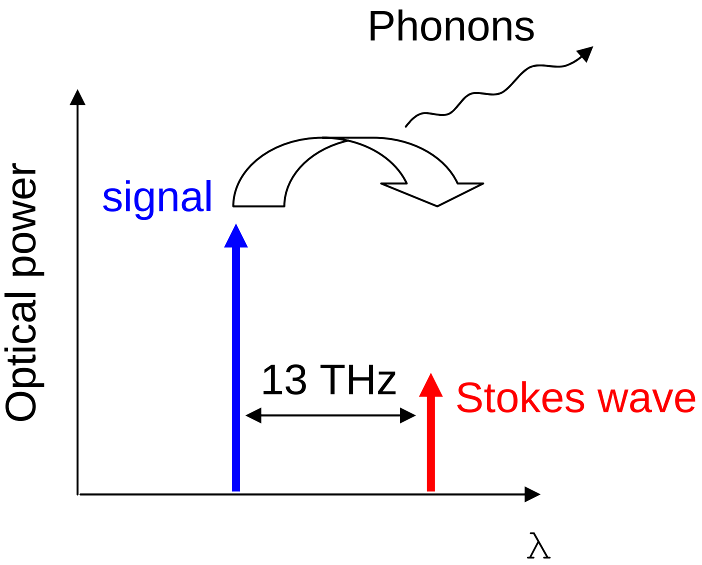
Raman effect

- Inelastic scattering of a signal photon to a stokes photon

- Energy transfer to acoustic modes

- Power threshold given by

$$P_{cr} \approx \frac{16A_{eff}}{g_R L_{eff}}$$

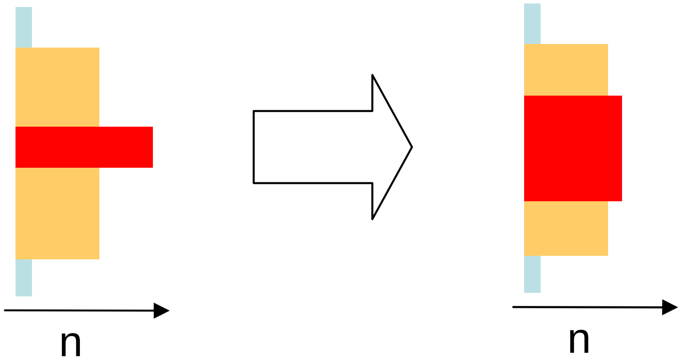


Large Mode Area (LMA) fibers

- Temporal nonlinearity
- Optical damage

} ↓ when MFD ↑

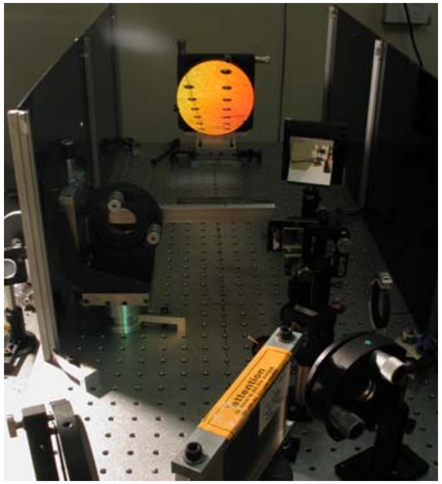
→ spread the intensity in space



- Index contrast ↓ to remain singlemode, Numerical aperture ↓
- LMA often multimode, fundamental mode selection through coiling
- Limited by bending loss

→ MFD ~ 25 µm conventional, 35 µm for microstructured fibers

Chirped-pulse amplification

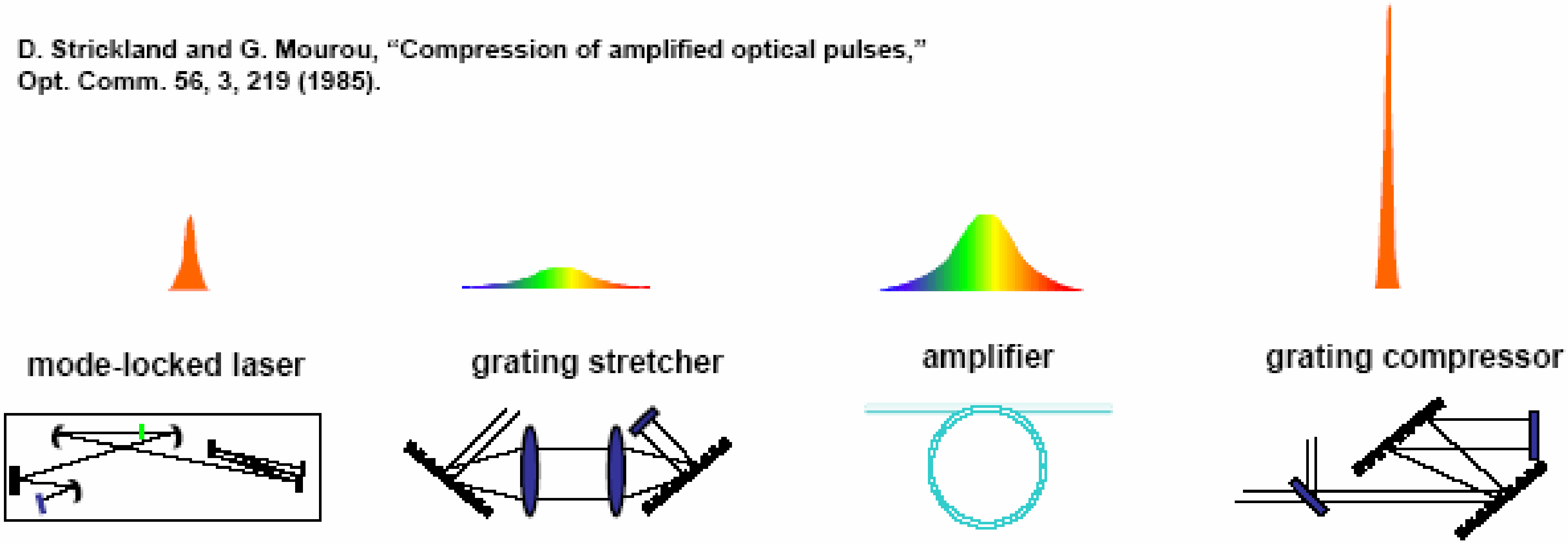


- Temporal nonlinearity
- Optical damage

} ↓ when peak power ↓

→ spread the intensity in time

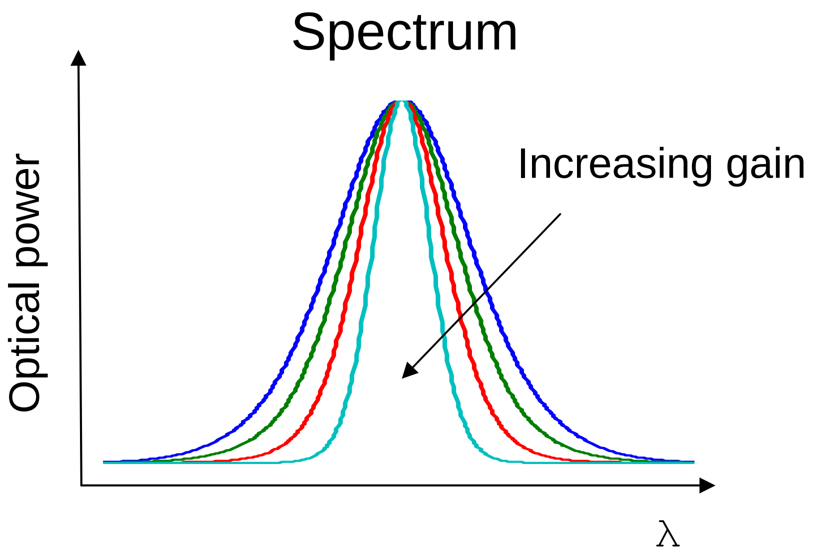
D. Strickland and G. Mourou, "Compression of amplified optical pulses," Opt. Comm. 56, 3, 219 (1985).



Other limitations

• Finite gain bandwidth of the medium causes gain narrowing

→ limits the pulsewidth (~100 fs for typical Yb fiber amplifier systems)



• Extractable energy $$E = \varepsilon_{sat} A_{eff} \ln(G_0)$$

~ mJ range for monomode LMA fibers

State of the art

- High average power femtosecond fiber amplifier

  Röser et al., Opt. Lett., vol. 30, no. 20 (2005) Jena group (J. Limpert)

  131 W 220 fs 73 MHz

- High energy femtosecond fiber amplifier

  Liao et al. CLEO 2006 postdeadline CPDB4 Michigan group (A. Galvanauskas)

  500 µJ 520 fs 5 kHz

- Review paper

Tunnermann et al., Topics in applied physics vol. 96, pp.35-53 (2004)

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Parabolic pulse principle

- Nonlinear pulse propagation with gain

$$i\frac{\partial u}{\partial z} = \frac{\beta_2}{2}\frac{\partial^2 u}{\partial t^2} - \gamma\left|u\right|^2 u + i\frac{g}{2}u$$

- $\beta_2 > 0$, $g > 0$ → Parabolic asymptotic solution

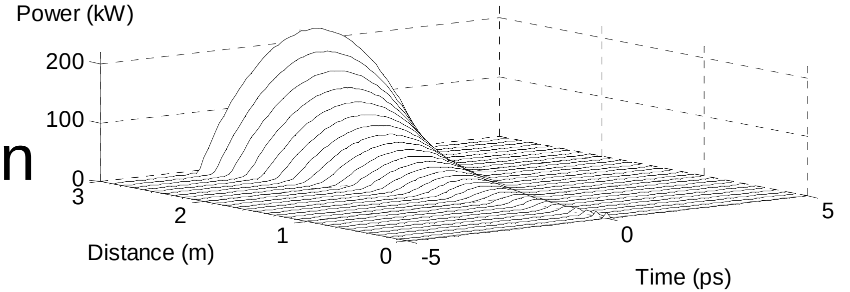
- Also known as « similariton » because of its self-similar propagation properties

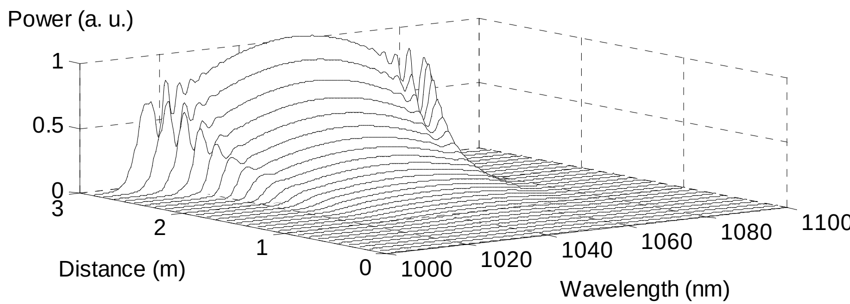
- Limited by higher-order effects : Raman, Finite gain bandwidth, Third-order dispersion

Parabolic amplification

Advantages of parabolic amplifiers

- Stable nonlinear pulse propagation
- Asymptotic regime
- Spectrum is generated and
- Linear (recompressible) chirp
- No stretcher



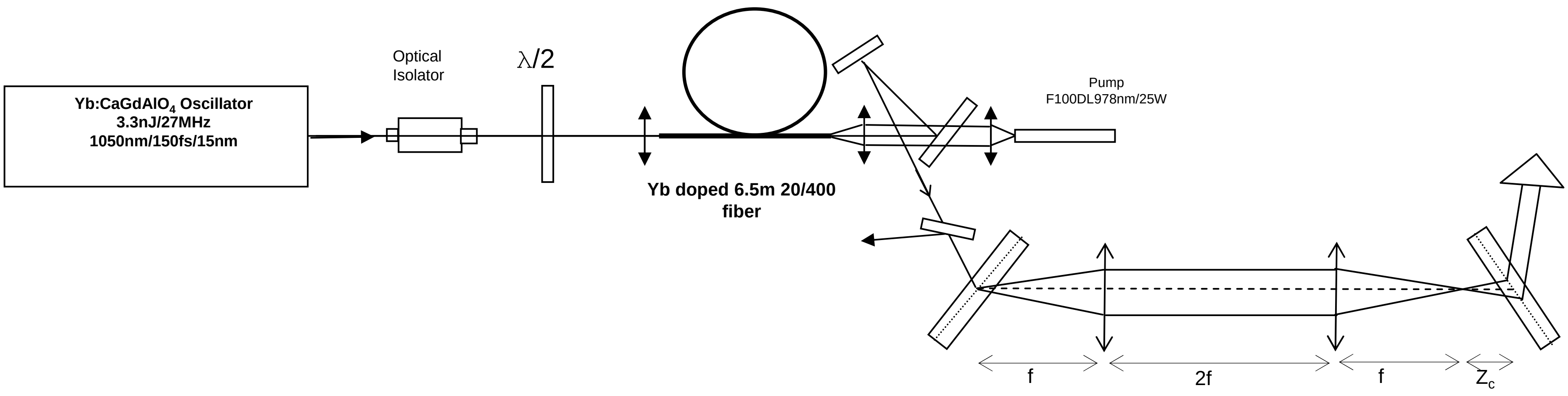


Drawbacks

- Limited to ~1 µJ with current fibers

Input : gaussian 100 fs 1nJ
Output : parabolic 5 ps 1 µJ
(ideally recompressible down to 50 fs)

Experimental results



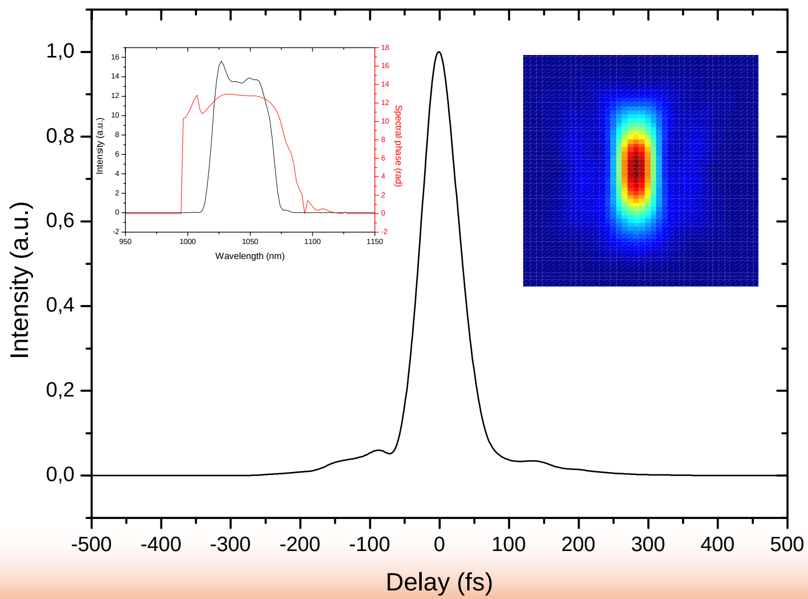
FWHM pulsewidth : 63 fs

Pulse energy : 0.28 µJ

Peak power : 4 MW

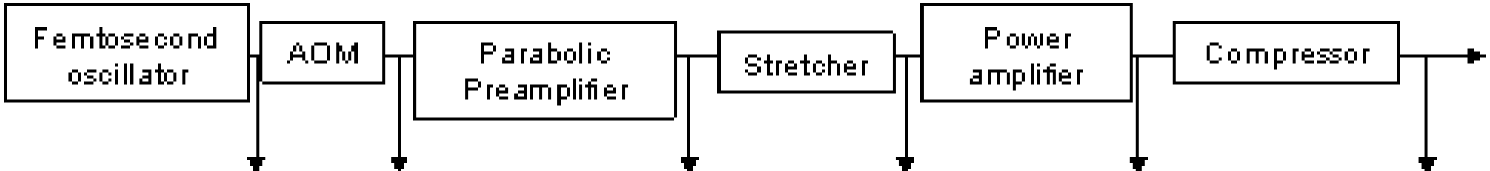
Average power : 7.5 W

Rep rate : 27 MHz



HiPoLYFF project source

• High-harmonic generation with a high repetition rate femtosecond fiber-based source



Repetition rate	100 MHz	1 MHz	1 MHz	1MHz	1 MHz	1 MHz
Pulse width	100 fs	100 fs	10 ps (50 fs bandwidth)	1 ns (50 fs bandwidth)	1 ns (50 fs bandwidth)	50 fs
Average power	100 mW	1 mW	2 W	1 W	200 W	100 W
Pulse energy	1 nJ	1 nJ	2 µJ	2 µJ	200 µJ	100 µJ
Peak power	10 kW	10 kW	200 kW	2 kW	200 kW	1 GW