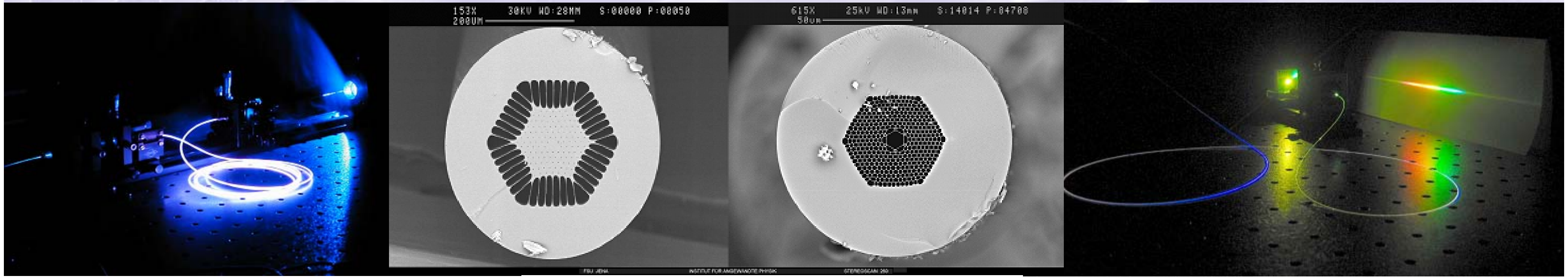


High power fiber lasers and amplifiers

Jens Limpert

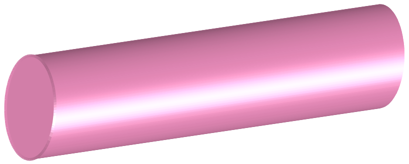
Friedrich-Schiller University Jena, Institute of Applied Physics, Jena, Germany
and
Fraunhofer Institut of Applied Optics and Precission Engeniering, Jena, Germany

Outline of the talk

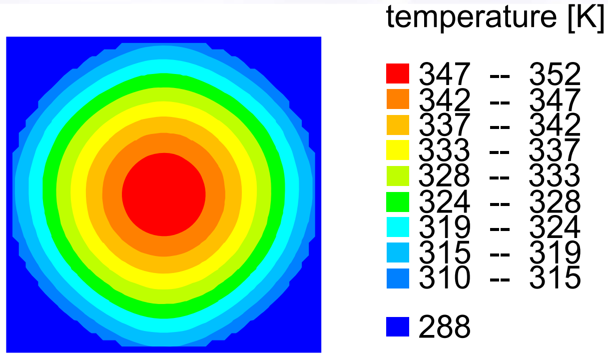
High power fiber lasers and amplifiers

- **Properties of Fiber Lasers**
- **Advanced Fiber Designs**
- **Selected Experiments of High Power Fiber Lasers**
- **Conclusion and Outlook**

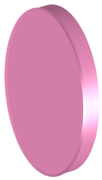
Solid-State Laser Concepts



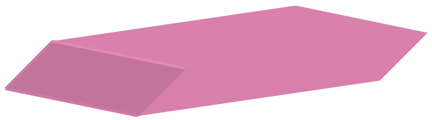
rod



➔ **power dependent thermal lensing and thermal stress-induced birefringence**



disk



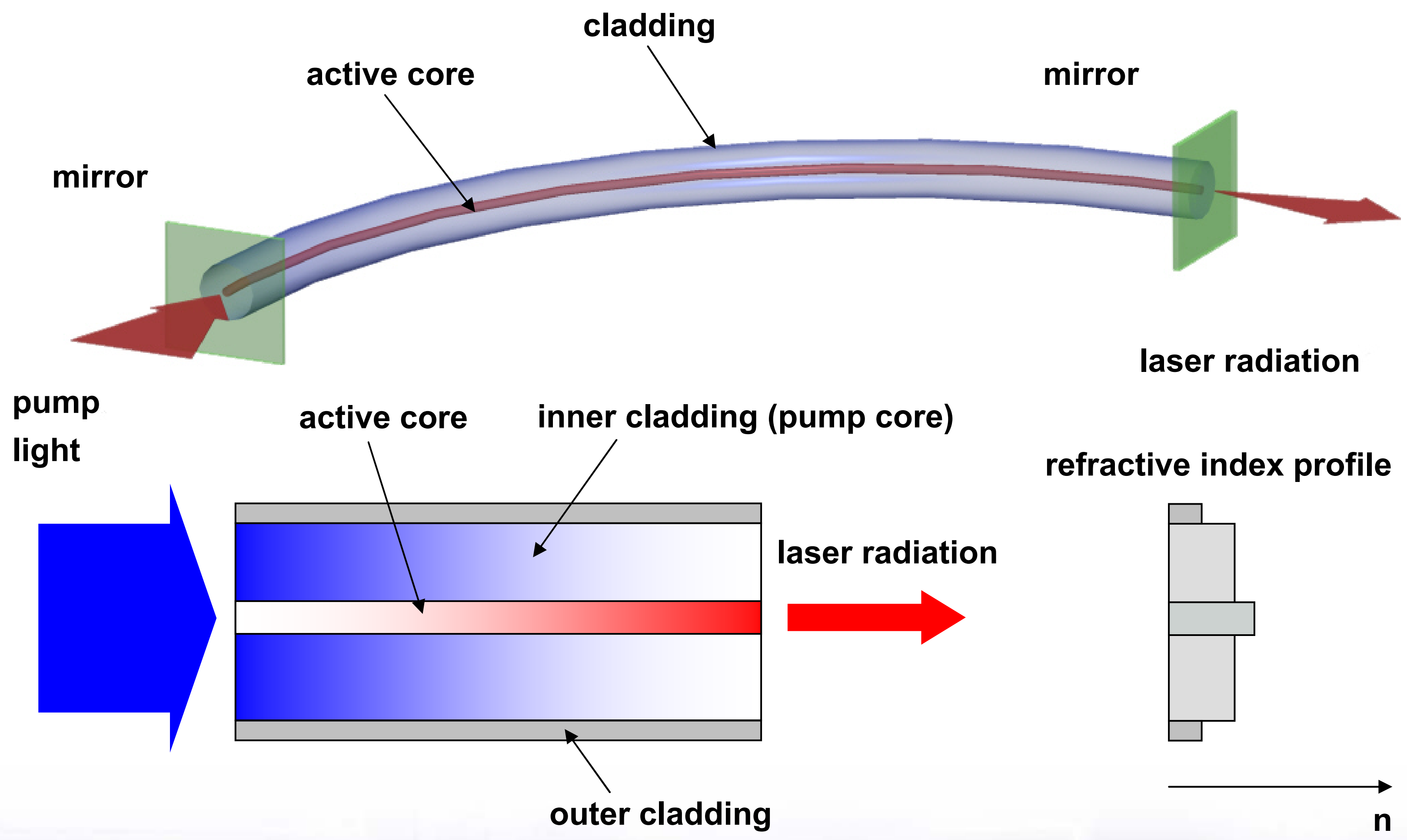
slab

fiber

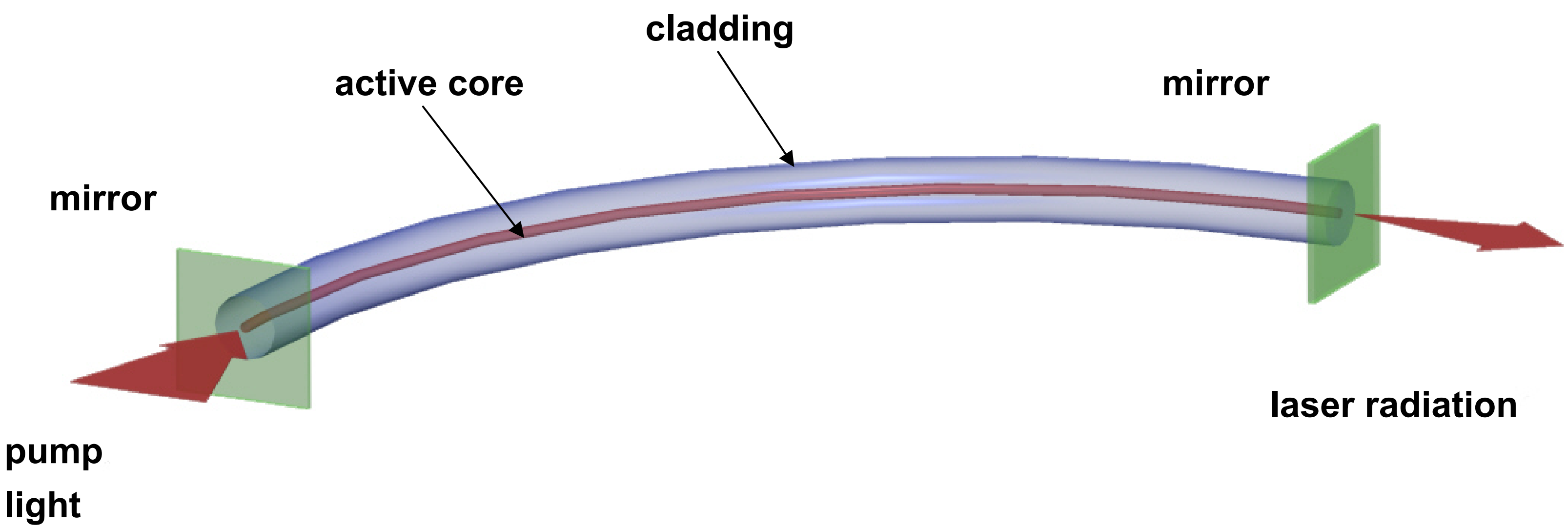
• • •

➔ **reduced thermo-optical distortions**

Double-clad fiber laser

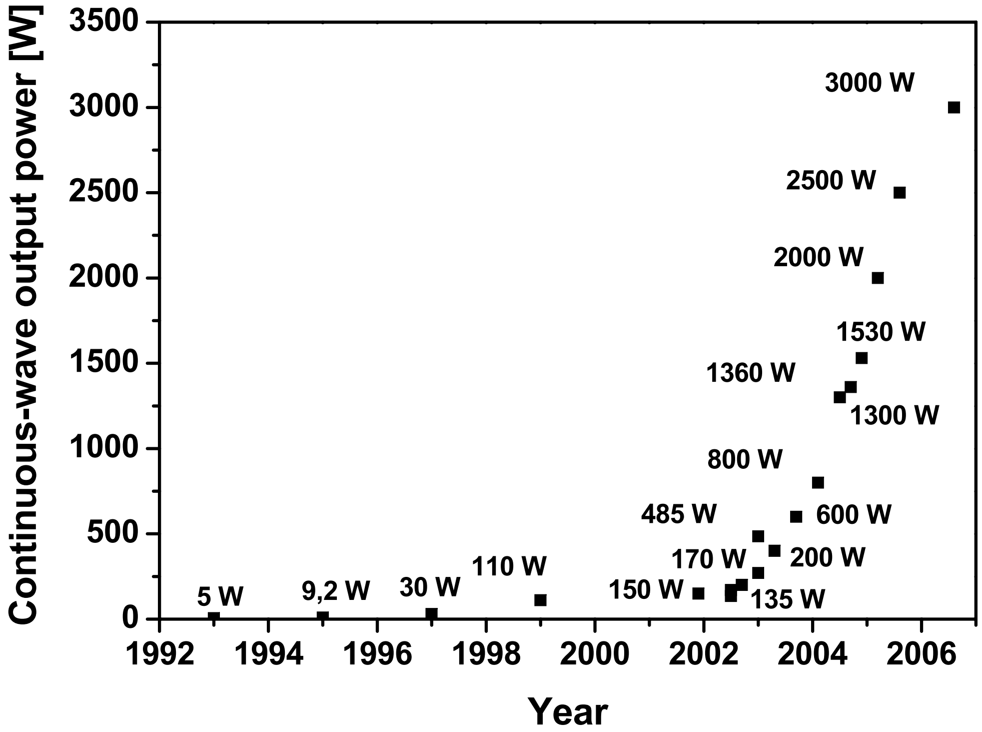


Properties of Rare-Earth-Doped Fibers



- no or reduced free space propagation
- immune against thermo-optical problems
- excellent beam quality
- high gain
- efficient, diode-pumped operation

Power evolution of single-mode fiber lasers

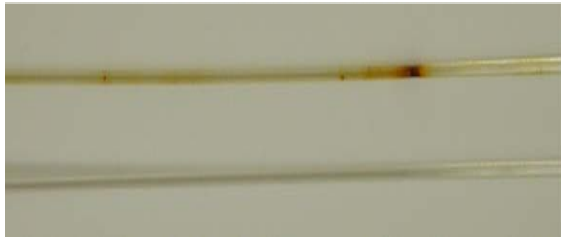


V. Fomin et al, "3 kW Yb fibre lasers with a single-mode output," International Symposium on High Power Fiber Lasers and their applications (2006)

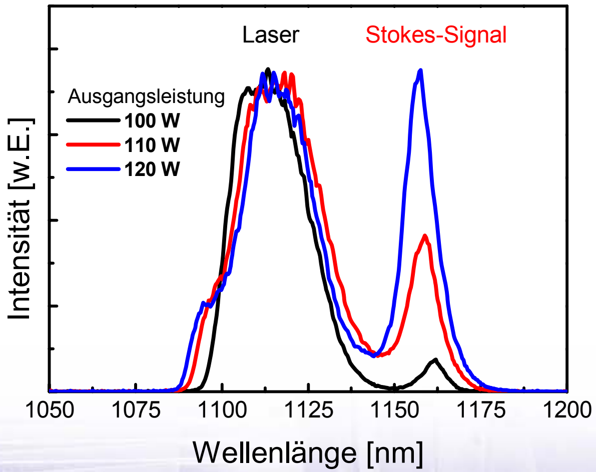
Performance-limiting effects

End-facet damage

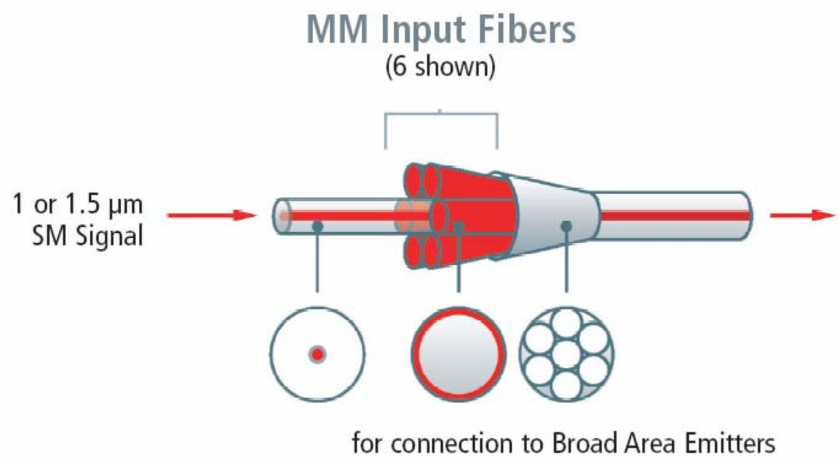
Thermal effects



Non-linear effects



Available pump power

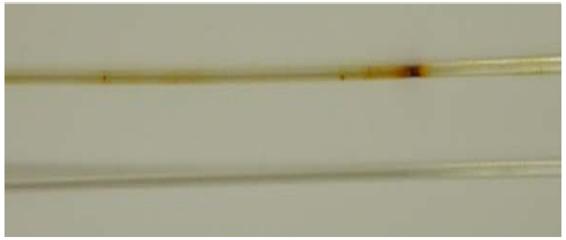


Source: www.specialtyphotonics.com

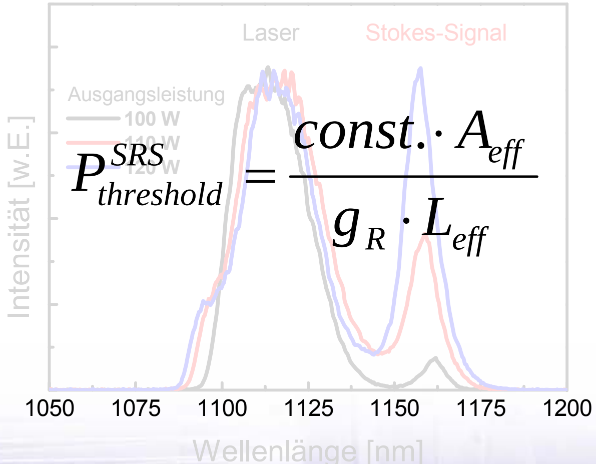
Performance-limiting effects

End-facet damage

Thermal effects

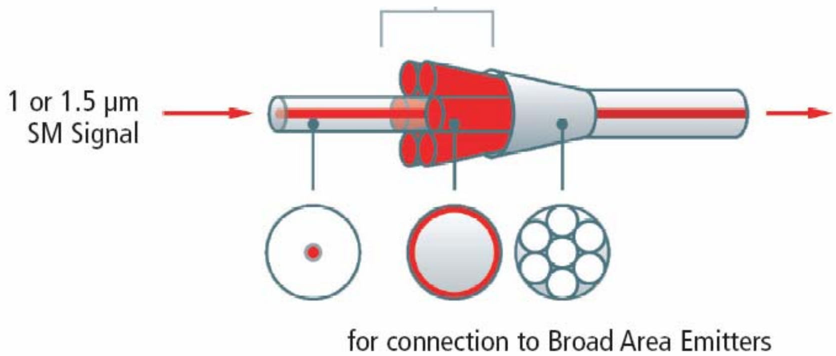


Non-linear effects



$$P_{threshold}^{SRS} = \frac{const. \cdot A_{eff}}{g_R \cdot L_{eff}}$$

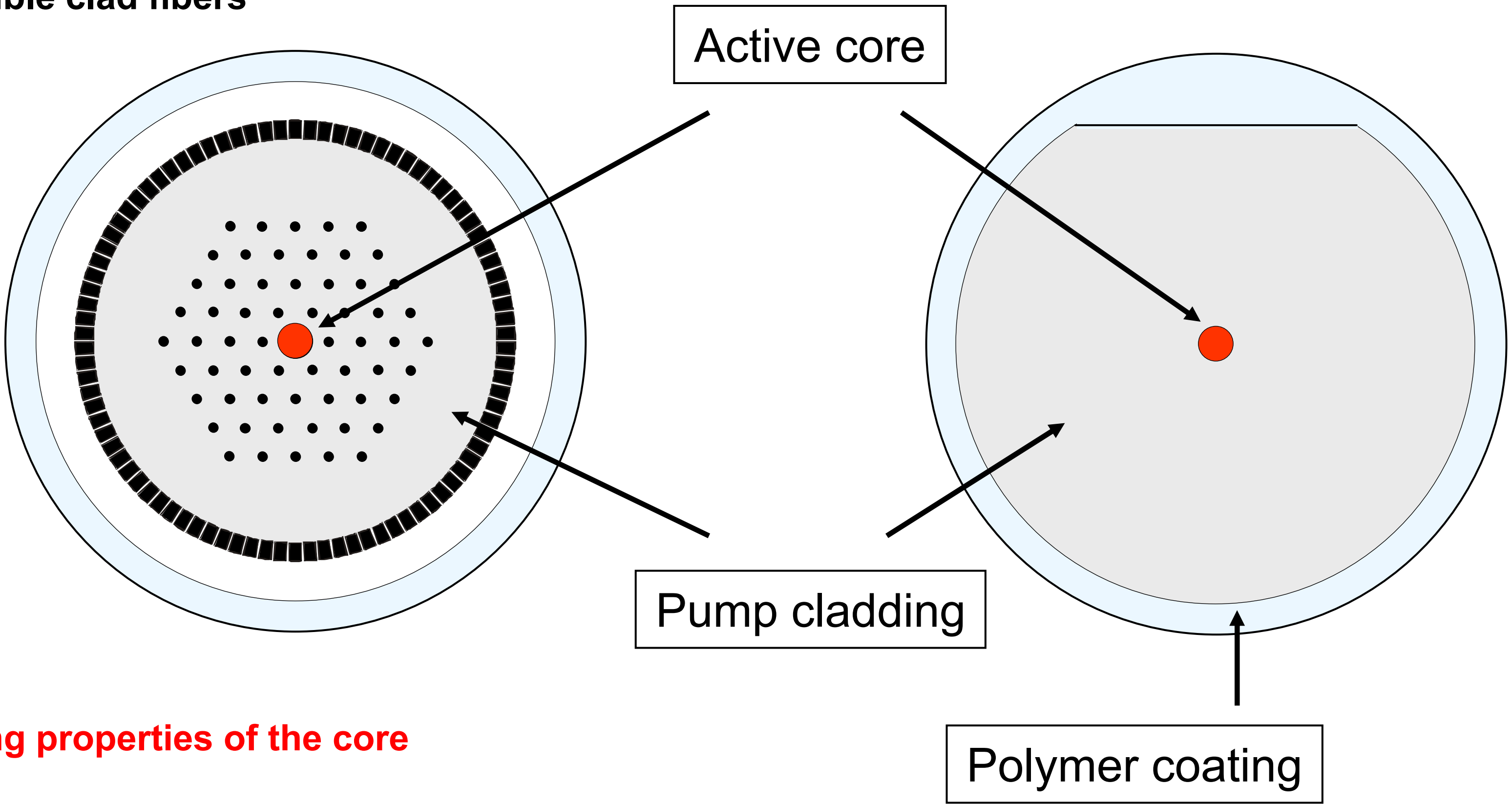
Available pump power



Source: www.specialtyphotonics.com

Photonic Crystal Fibers

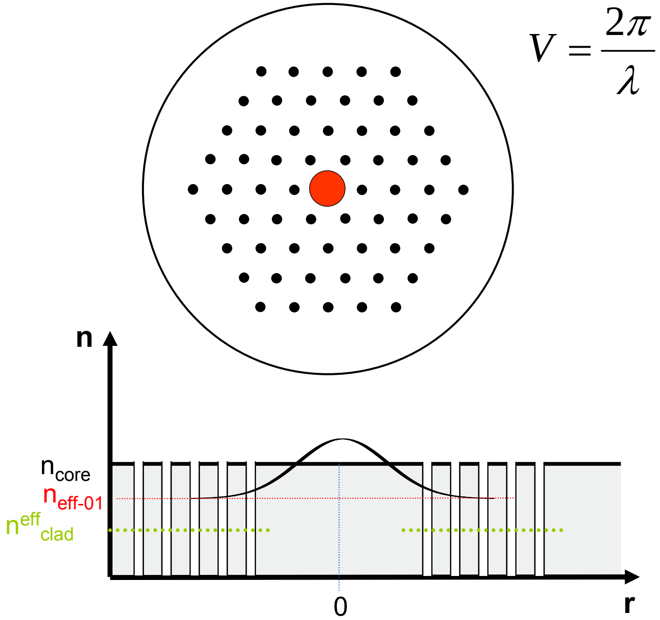
Double clad fibers



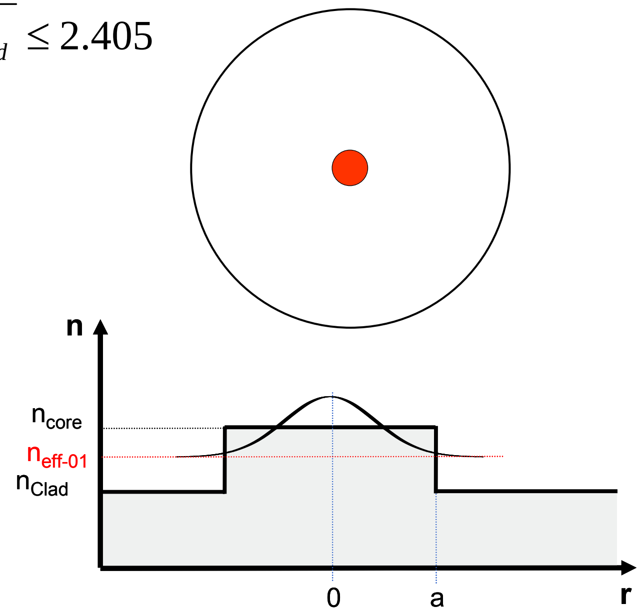
- **guiding properties of the core**
- **guiding of the pump light**

Index control of doped fiber cores

$$V = \frac{2\pi}{\lambda} a \cdot \sqrt{n_{core}^2 - n_{clad}^2} \leq 2.405$$



Microstructured Fiber



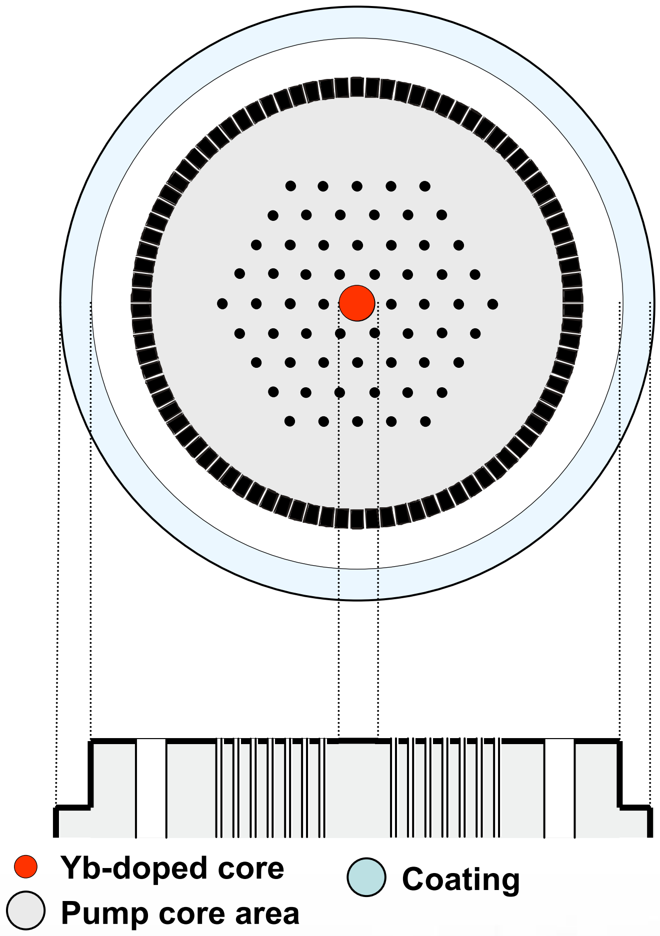
Step-index Fiber

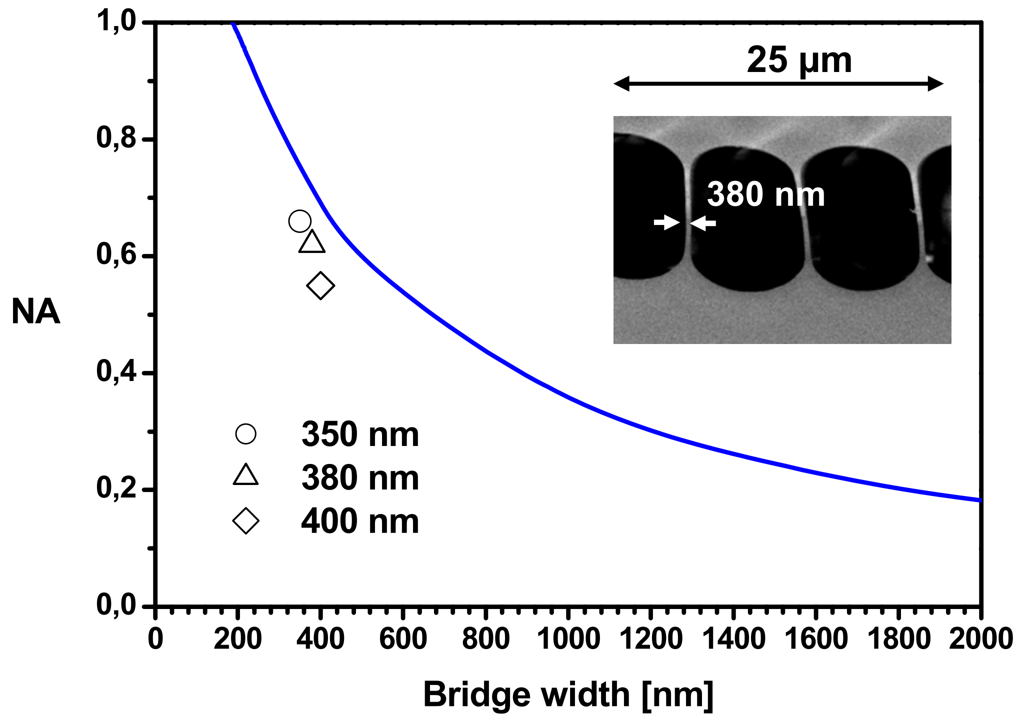
➡ **$\Delta n \sim 1 \cdot 10^{-4}$**
NA ~ 0.02

➡ **$\Delta n \sim 1 \cdot 10^{-3}$**
NA ~ 0.06

➡ **significantly larger single-mode core possible**

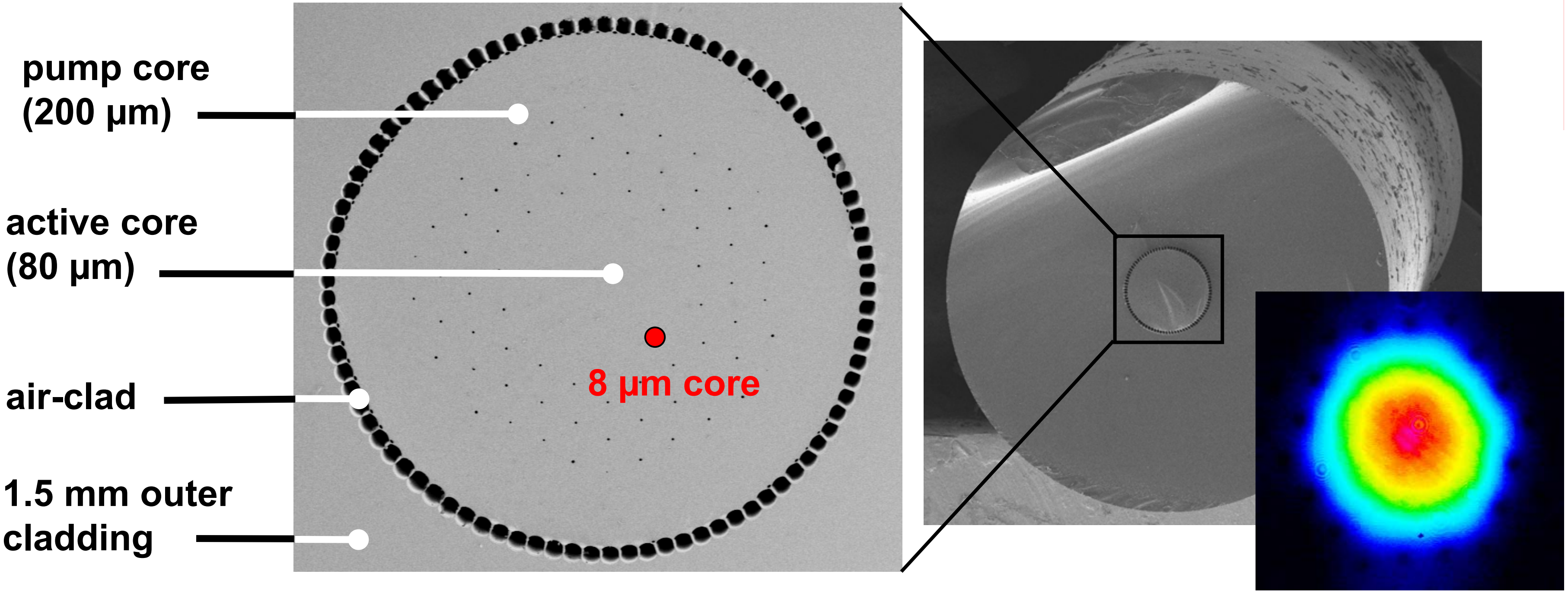
The air-cladding region





→ high numerical aperture inner cladding
no radiation has contact to coating material

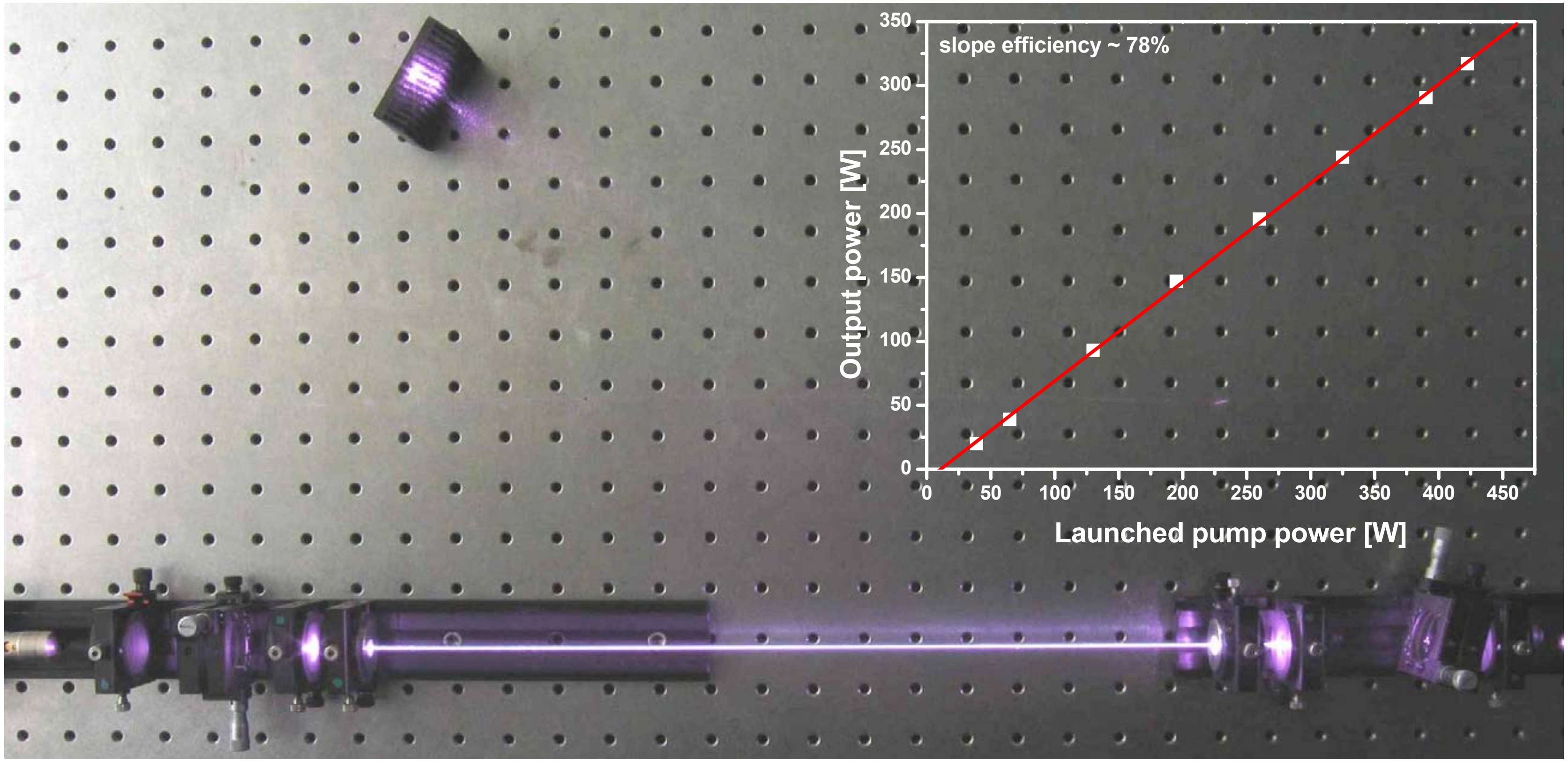
“rod-type” photonic crystal fiber



„rod-type“ fiber: 30 dB/m Pumplichtabsorption, 71 µm Modenfelddurchmesser, M^2 ~ 1.2

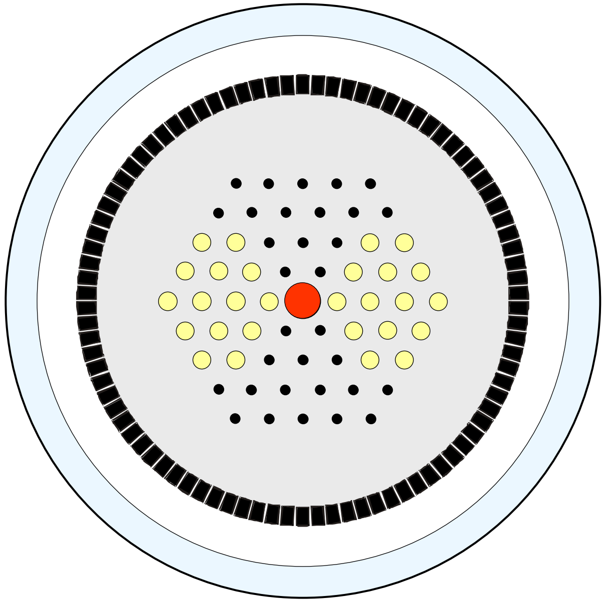
Limpert et. al., "High-power rod-type photonic crystal fiber laser," Opt. Express 13, 1055-1058 (2005)

Rod-type photonic crystal fiber laser



➡ 320 W continuous-wave, >10 mJ ns-pulses extracted

Rare-earth doped photonic crystal fibers

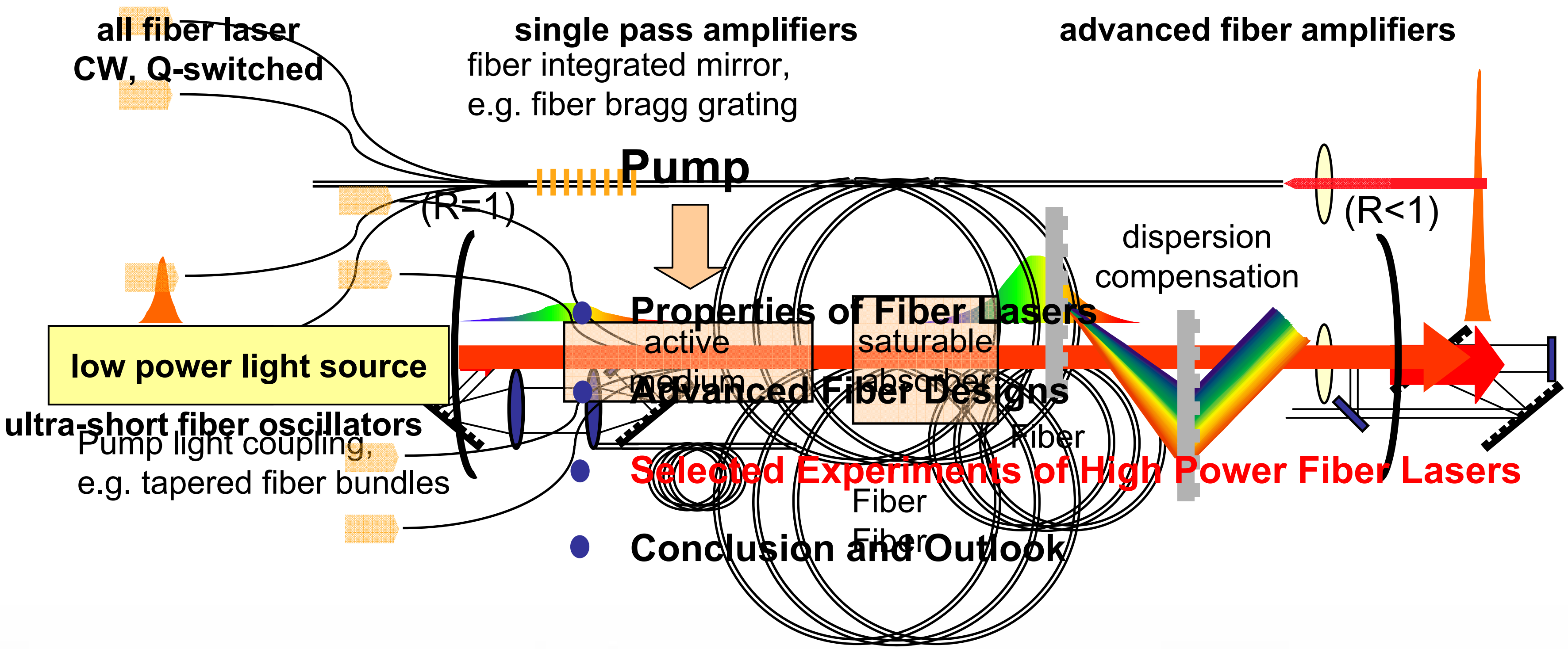


Design freedom to tailor optical, mechanical and thermo-optical properties

Advantages of PCF

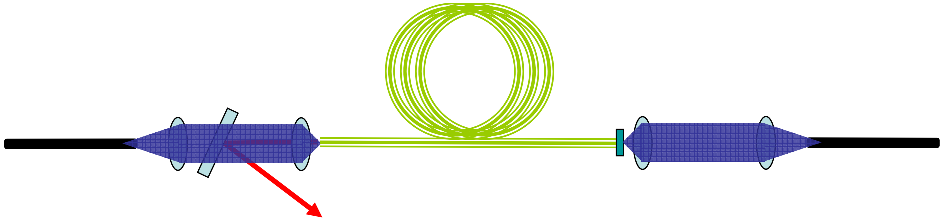
- **higher index control**
- **larger SM cores**
- **shorter fibers possible (0.5 m)**
- **comparable heat dissipation**
- **intrinsically polarizing without drawbacks**

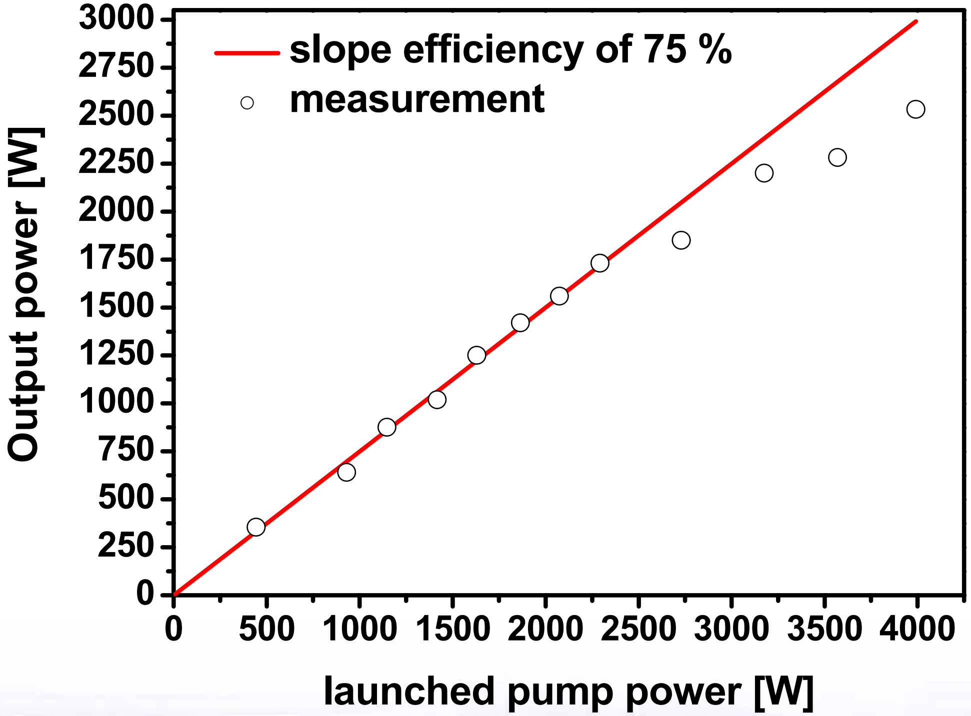
Fiber laser systems



- Properties of Fiber Lasers
- Advanced Fiber Designs
- Selected Experiments of High Power Fiber Lasers
- Conclusion and Outlook

High power continuous-wave fiber laser





•fiber length 15 m, forced air-cooling

•two side pump coupling of 2 kW

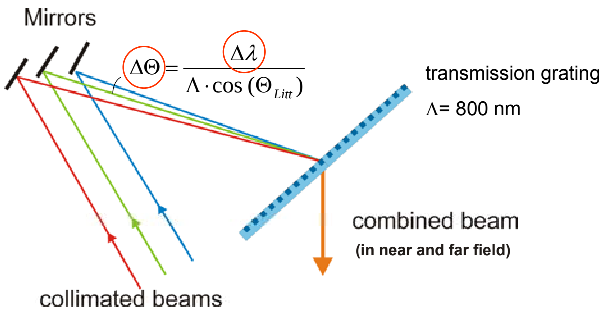
•fiber temperature max. 120°C

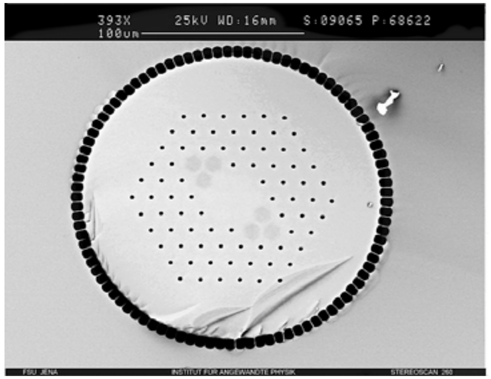
•beam quality $M^2 < 1.4$ at 2 kW

•max. 2.53 kW laser output

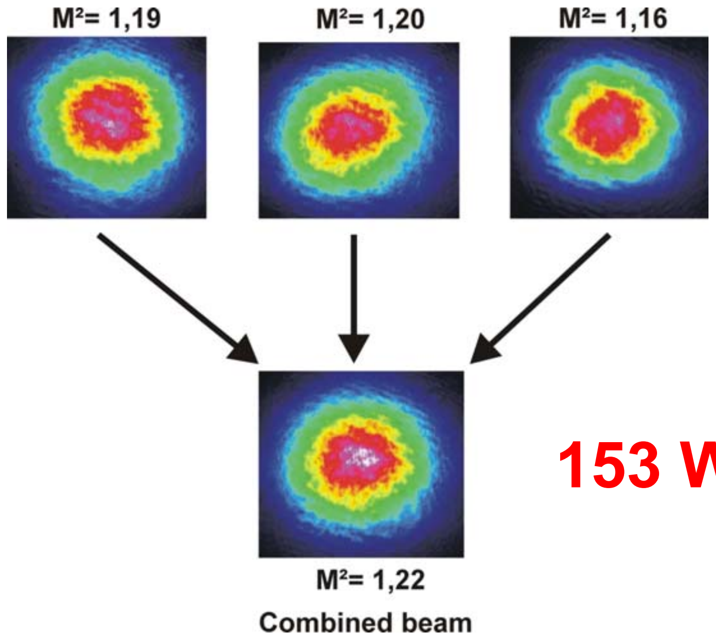
75% slope efficiency (below 1.5 kW, above wavelength drift of pump diode)

Scaling approach: Incoherent Combining





Polarizing PCF, 1.5 m,
40 µm core



153 W

Combining-efficiency 95 %
Degree of Polarization 98%

➡ **Scalable while maintaining beam quality**

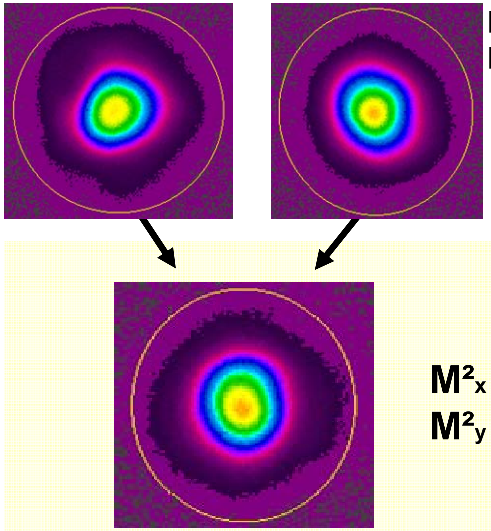
S. Klingebiel,F. Röser,B. Ortac, J. Limpert, A. Tünnermann, "Spectral beam combining of Yb-doped fiber lasers with high efficiency," JOURNAL OF THE OPTICAL SOCIETY OF AMERICA B-OPTICAL PHYSICS **24** (8): 1716-1720 (2007)

Combining of pulsed fiber lasers

two beams (ΔT ~ 10ns):

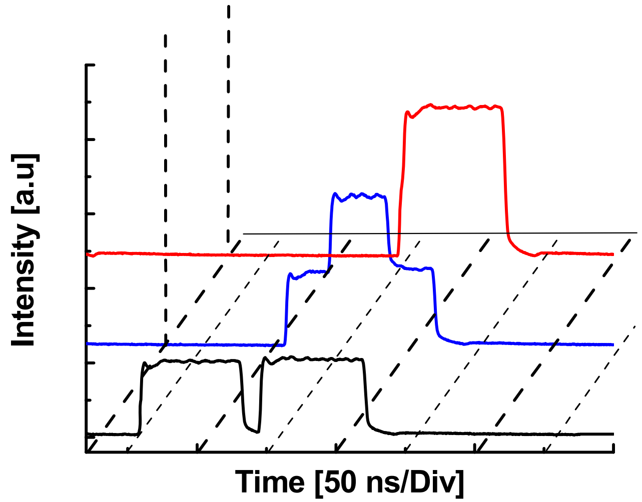
M^2x =1.17
M^2y =1.10

M^2x =1.22
M^2y =1.13



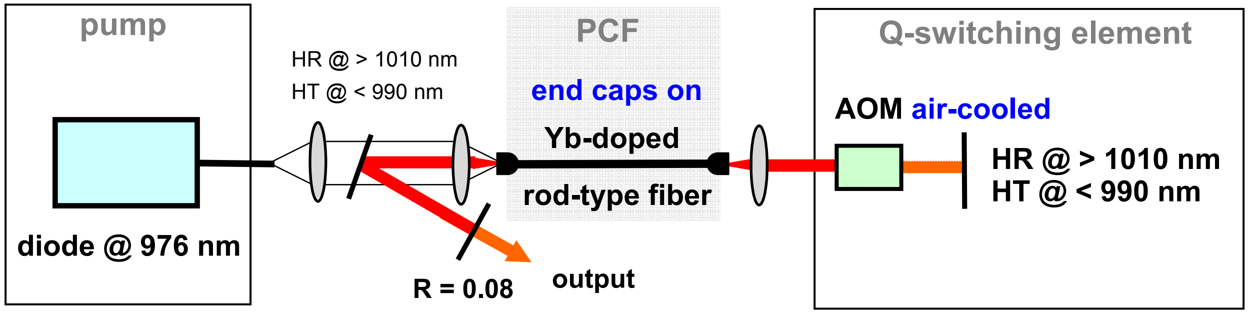
M^2_x =1.17
M^2_y =1.18

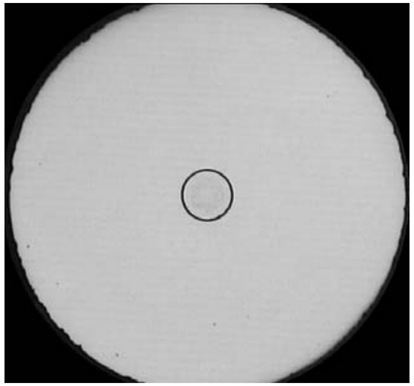
SPIRICON™ M^2 measurement

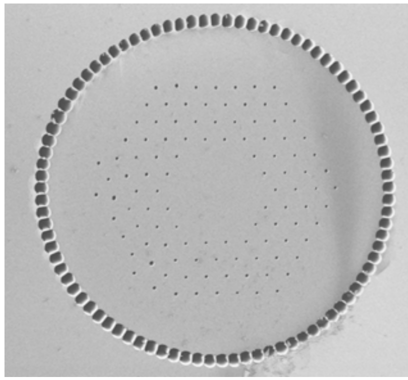


➡ **scaling of MW peak power pulsed fiber sources beyond self-focusing limit of 4 MW**

Q-switching of fiber lasers





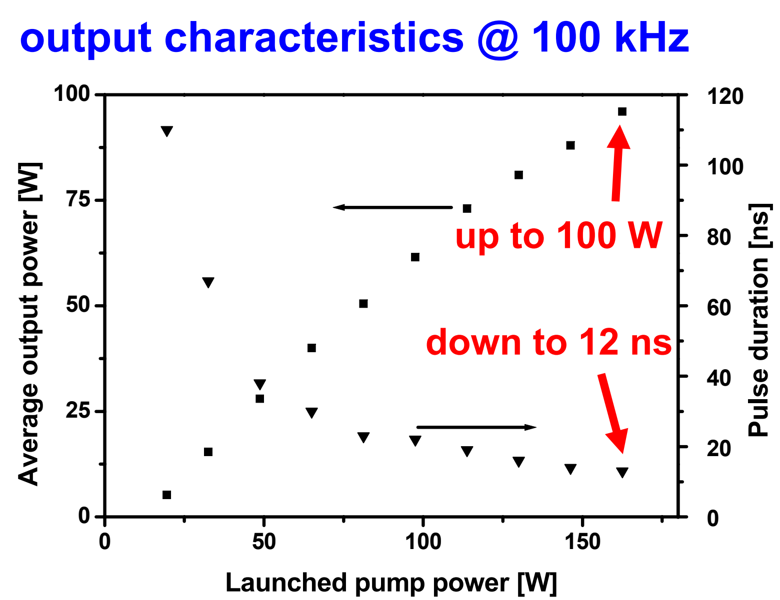


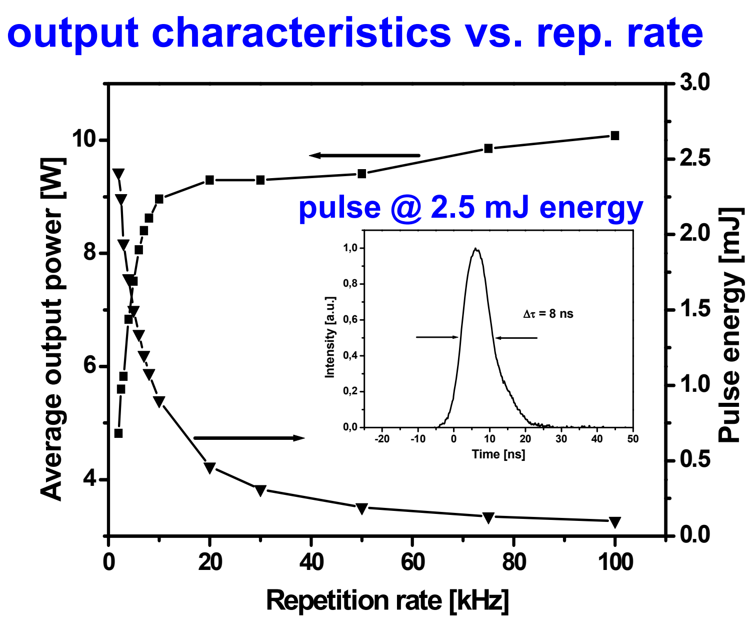
Microscope image of the rod-type photonic crystal fiber and close-up to the inner cladding and core region.

Fiber parameter:

outer diameter: up to 2 mm
60 µm Yb-doped core, A_{eff} ~ 2000 µm^2,
180 µm (NA ~ 0.6) inner cladding
30 dB/m pump absorption @ 976 nm,
(0.5 m absorption length)

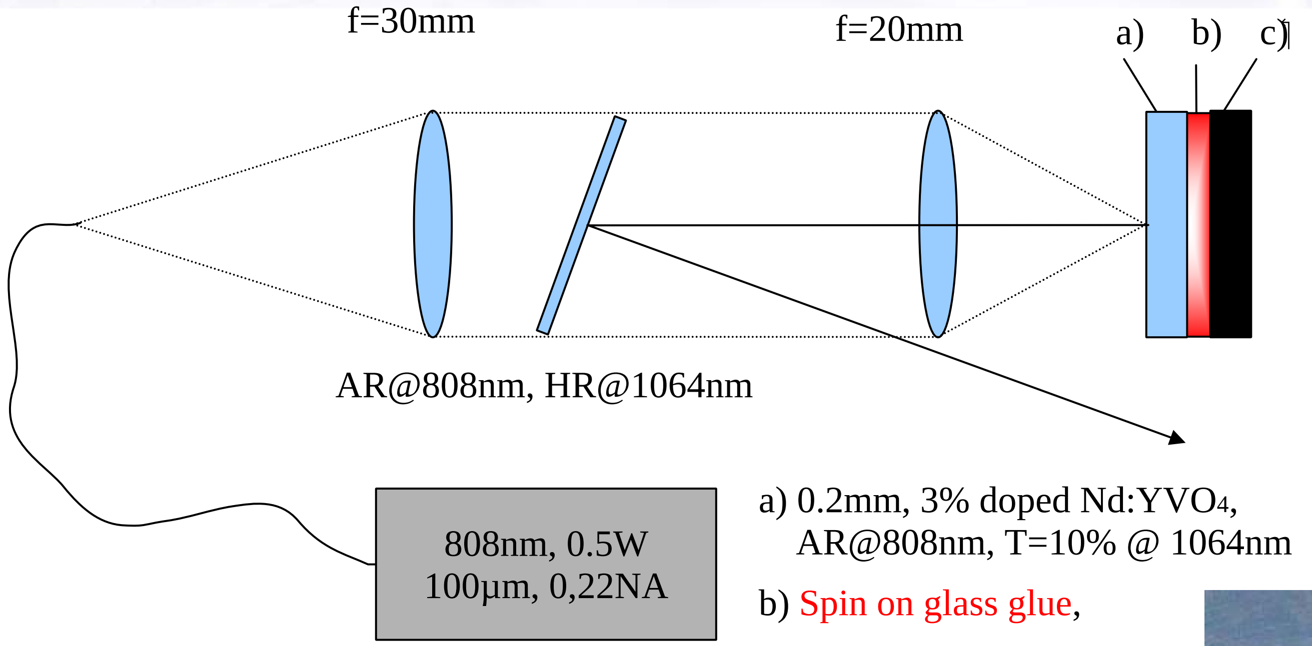
Q-switching of fiber lasers





O. Schmidt, J. Rothhardt, F. Röser, S. Linke, T. Schreiber, K. Rademaker, J. Limpert, S. Ermeneux, P. Yvernault, F. Salin, A. Tünnermann, "Millijoule pulse energy *Q*-switched short-length fiber laser," Optics letters Vol.32, No.11, 1551-1553, 2007

Quasi-monolithic, passively Q-switched microchip laser



- -Unmatched simplicity
- -No moving parts in the resonator
- -Simple gluing technique
- -Spin on glass glue
  - *high dielectric strength
  - *high transparency

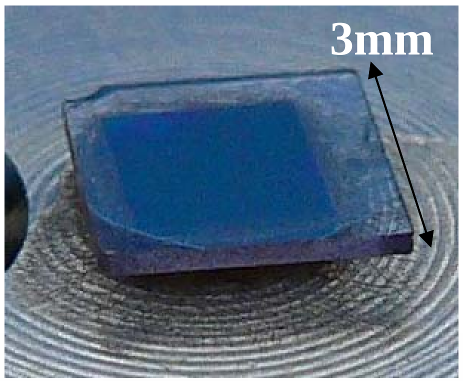
a) 0.2mm, 3% doped Nd:YVO_4, AR@808nm, T=10% @ 1064nm

b) Spin on glass glue,

c) SESAM, ΔR=20%, T_R= 320ps,

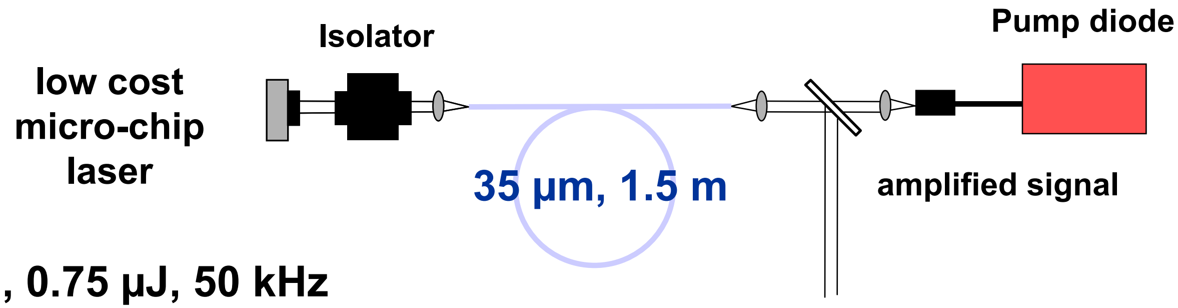
- **•1µJ, 50ps, 40kHz**
- **•0.5µJ, 110ps, 170kHz**

D. Nodop, J. Limpert, R. Hohmuth, W. Richter, M. Guina, and A. Tünnermann, "High-pulse-energy passively Q-switched quasi-monolithic microchip lasers operating in the sub-100-ps pulse regime," Opt. Lett. **32**, 2115-2117 (2007)

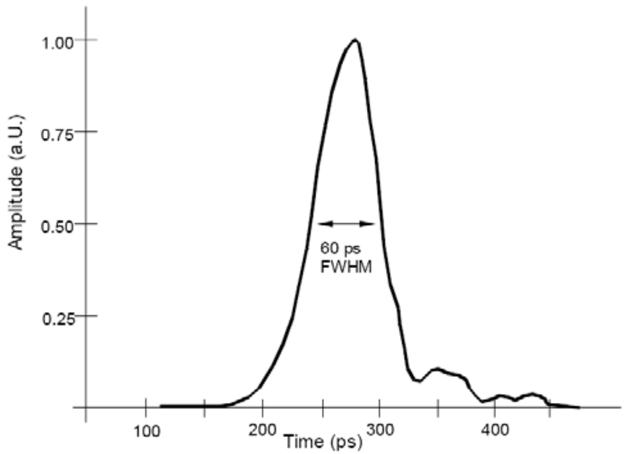


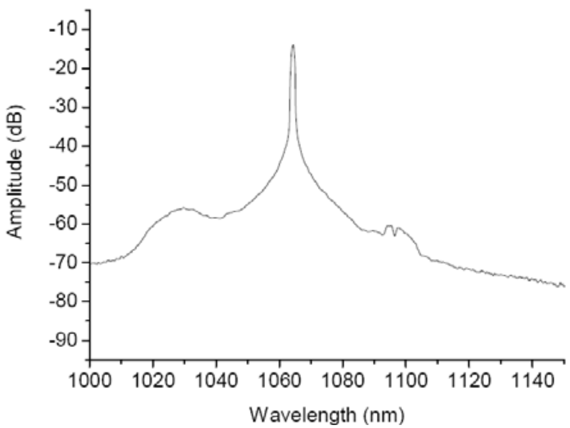
Current production costs:~300€

Fiber based amplification of ps-µchip lasers



60 ps, 0.75 µJ, 50 kHz



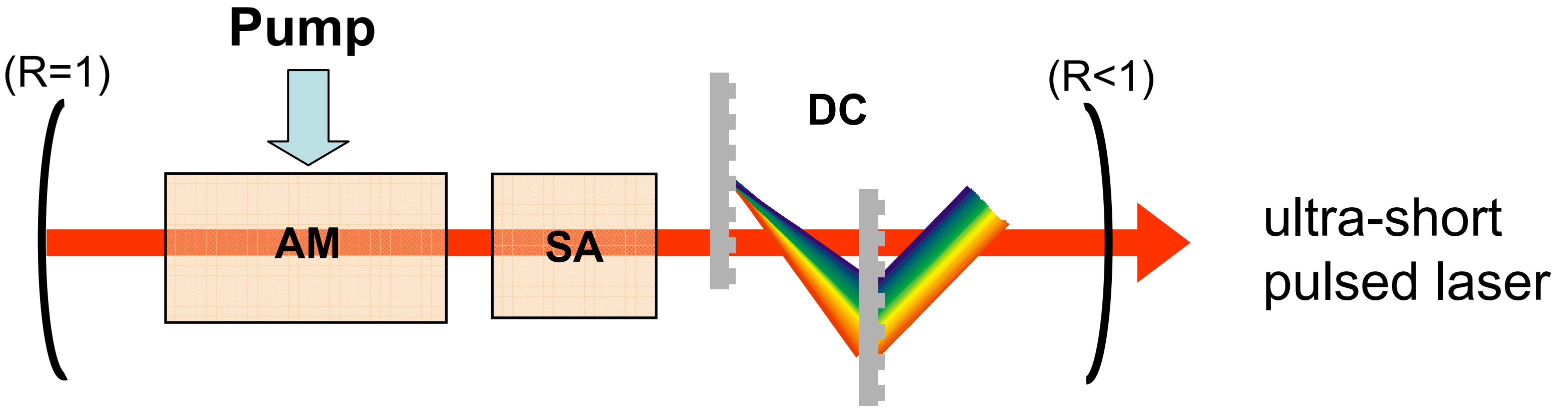


60 ps, 80 µJ, 50 kHz
peak power: 1.33 MW

↓

micromachining

Ultra-short pulse generation

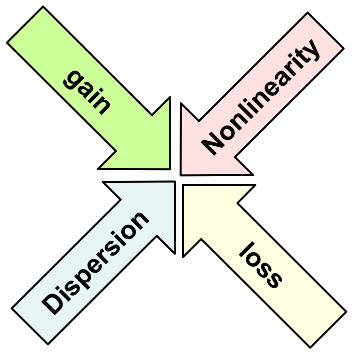


•*active medium (AM)*
-e.g. Yb-doped fiber

•*saturable absorber (SA)*
-favours pulse against noise background
-initiates mode-locking

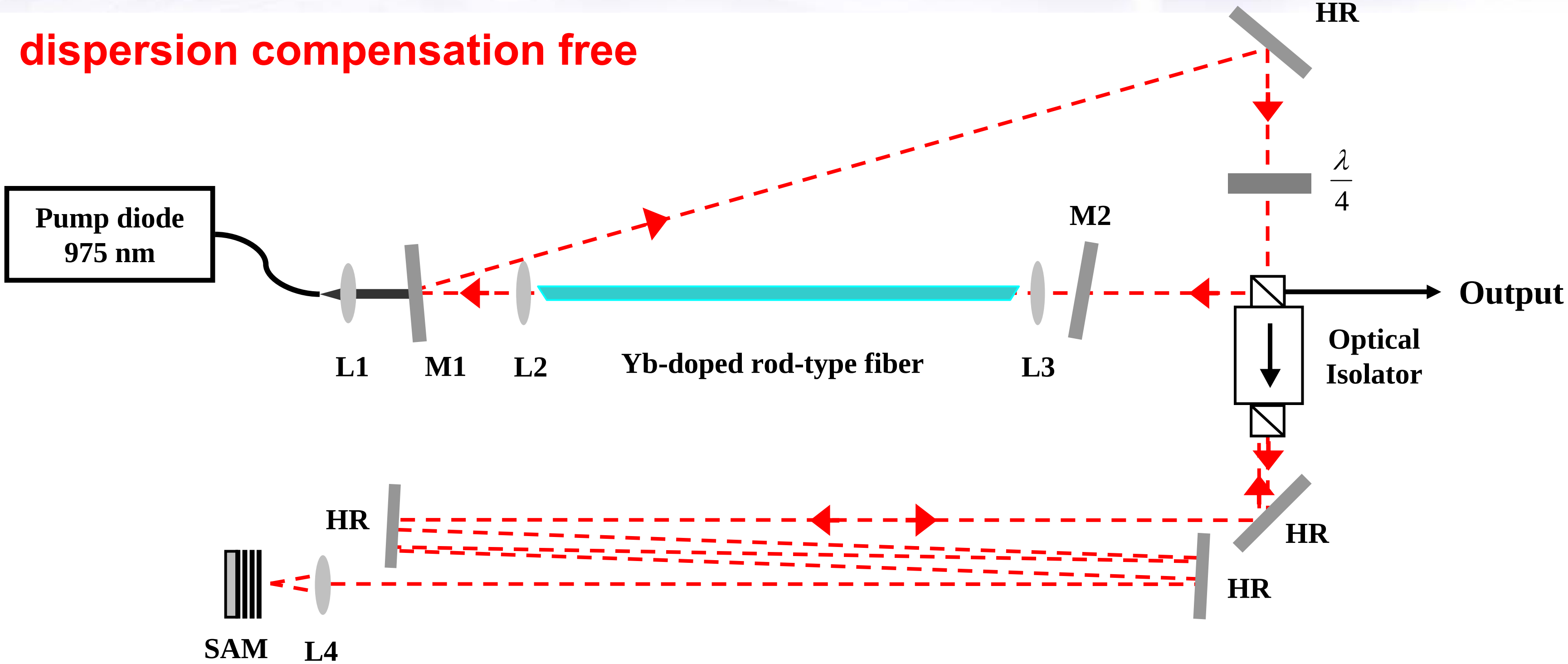
•*dispersion compensation (DC)*
- keeps the pulse short during roundtrip

Theory:
dissipative, nonlinear system:



High-energy femtosecond fiber laser

dispersion compensation free



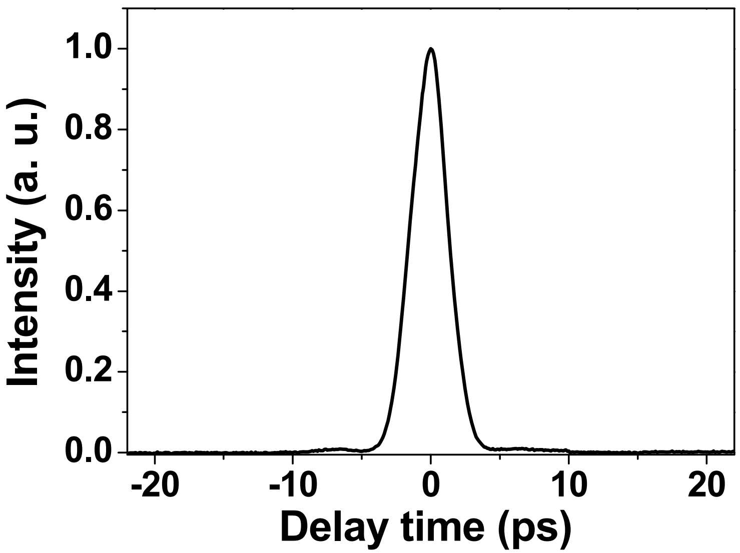
Modulation depth 30%
Fast relaxation time 200 fs
Slow relaxation time 500 fs

Total cavity dispersion : + 0.012 ps²
Repetition rate : 10.18 MHz

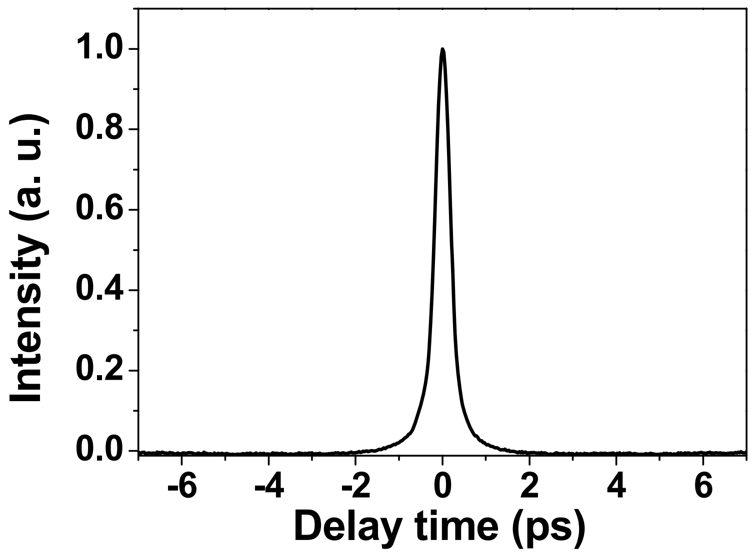
B. Ortaç, O. Schmidt, T. Schreiber, J. Limpert, A. Tünnermann, A. Hideur,
"High-energy femtosecond Yb-doped dispersion compensation free fiber laser," Optics Express, vol. 15, pp. 10725– 10732, 2007.

High-energy femtosecond fiber laser - Results

Autocorrelation trace



Extra-cavity compression



- Output pulse duration = 4 ps
- Compressed pulse duration = 400 fs

Single pulse characterization:

Average output power: 2.7 W

Energy per pulse: 265 nJ

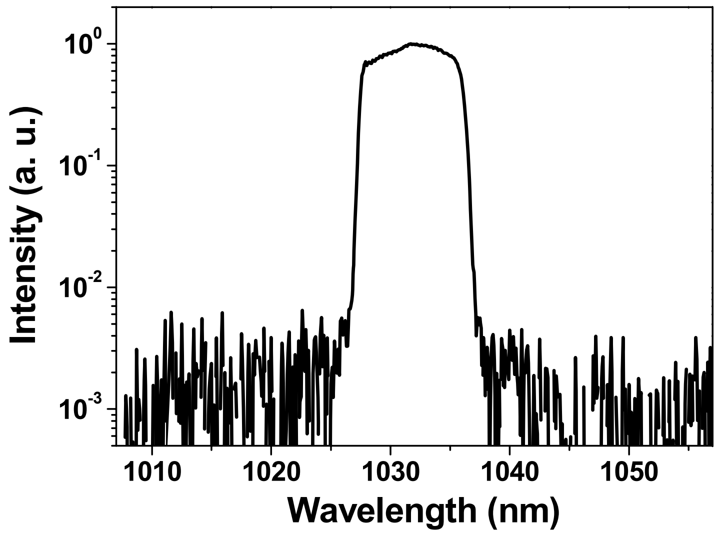
Compression efficiency: 75 %

Energy per pulse: 200 nJ

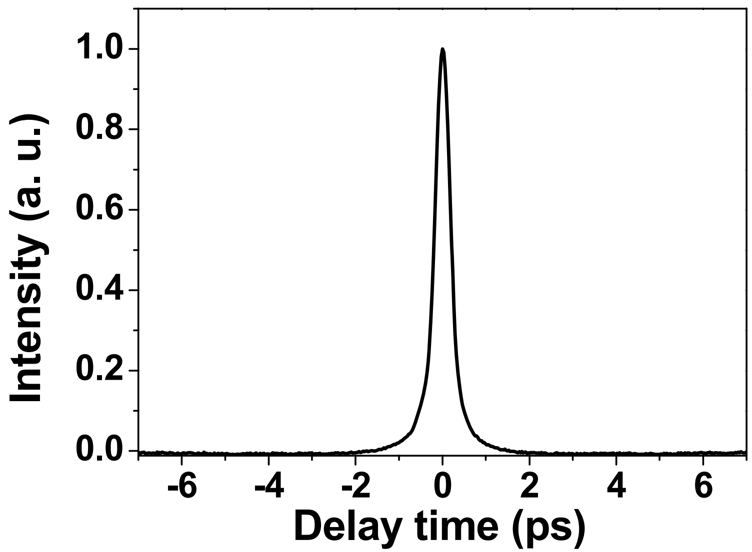
Peak power: 500 kW

High-energy femtosecond fiber laser - Results

Optical Spectrum



Extra-cavity compression



- **Spectral bandwidth = 8.4 nm**
- **Compressed pulse duration = 400 fs**

Single pulse characterization:

Average output power: 2.7 W

Energy per pulse: 265 nJ

Compression efficiency: 75 %

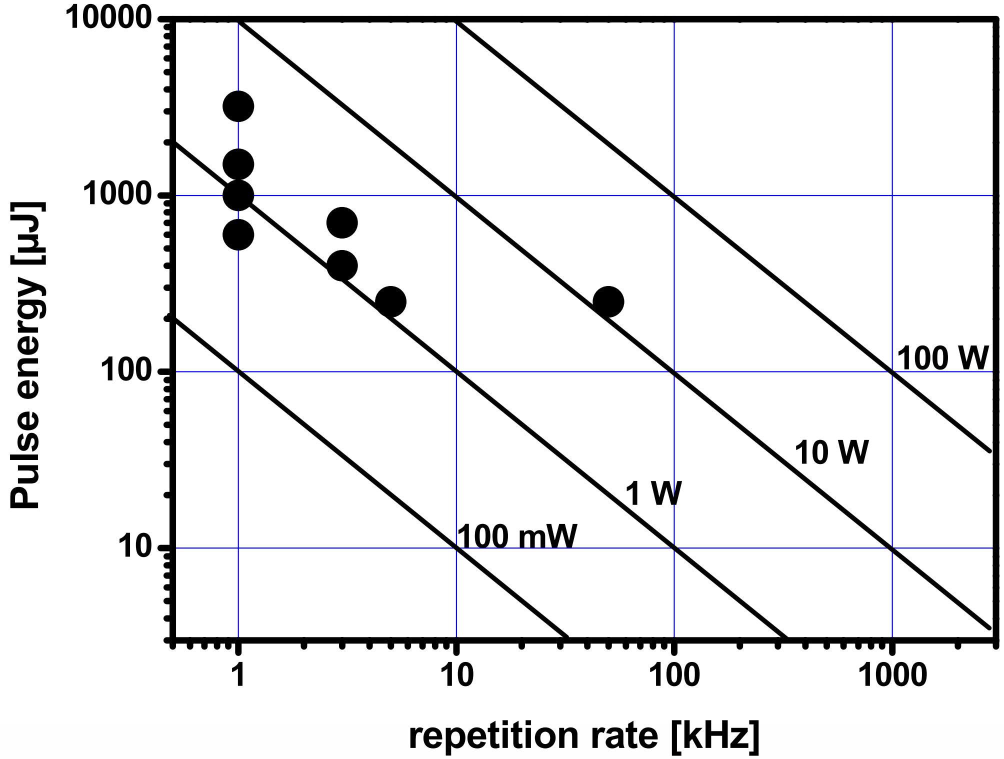
Energy per pulse: 200 nJ

Peak power: 500 kW

Ultra-short pulse fiber amplification systems

Higher average power

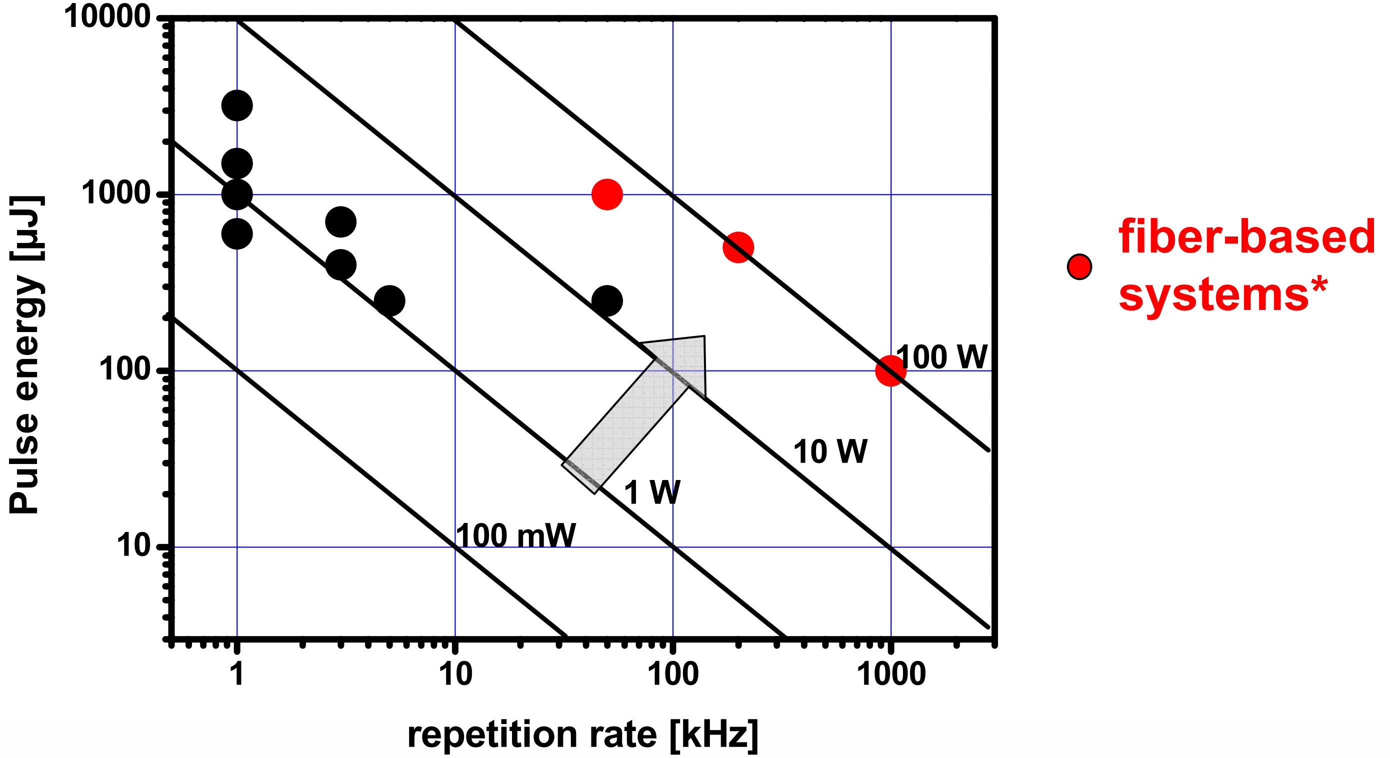
Higher pulse energy ← → **Higher repetition rate**



Ultra-short pulse fiber amplification systems

Higher average power

Higher pulse energy ← → **Higher repetition rate**



* Röser et. al., „Millijoule pulse energy high repetition rate femtosecond fiber chirped-pulse amplification system," Opt. Lett. 32, 3495 (2007)
* Röser et. al., „90 W average power 100 µJ energy femtosecond fiber chirped-pulse amplification system," Opt. Lett. 32, 2230 (2007)

Influence of self-phase modulation (SPM)

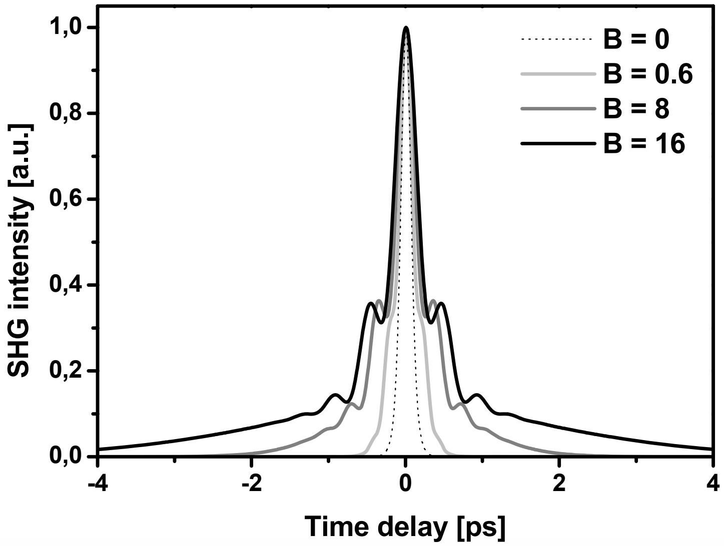
Nonlinear phase:

$$\phi_{NL}^{SPM}(z,T)=\gamma\left|A(z,T)\right|^{2} z$$

Accumulated nonlinear phase (B-integral):

$$B=\frac{2\cdot\pi}{\lambda}\int_{0}^{L} n_2\cdot I(z)\,dz$$

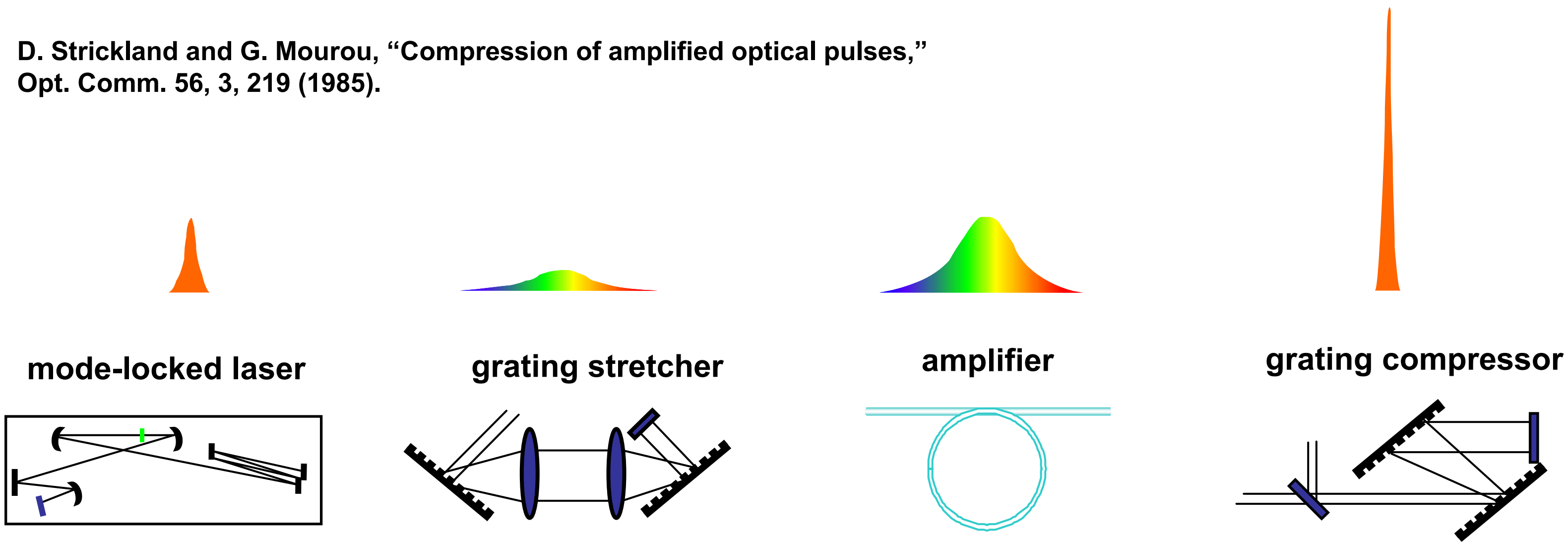
Simulated autocorrelation traces



➡ **Reduction of pulse quality**

Chirped Pulse Amplification (CPA)

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

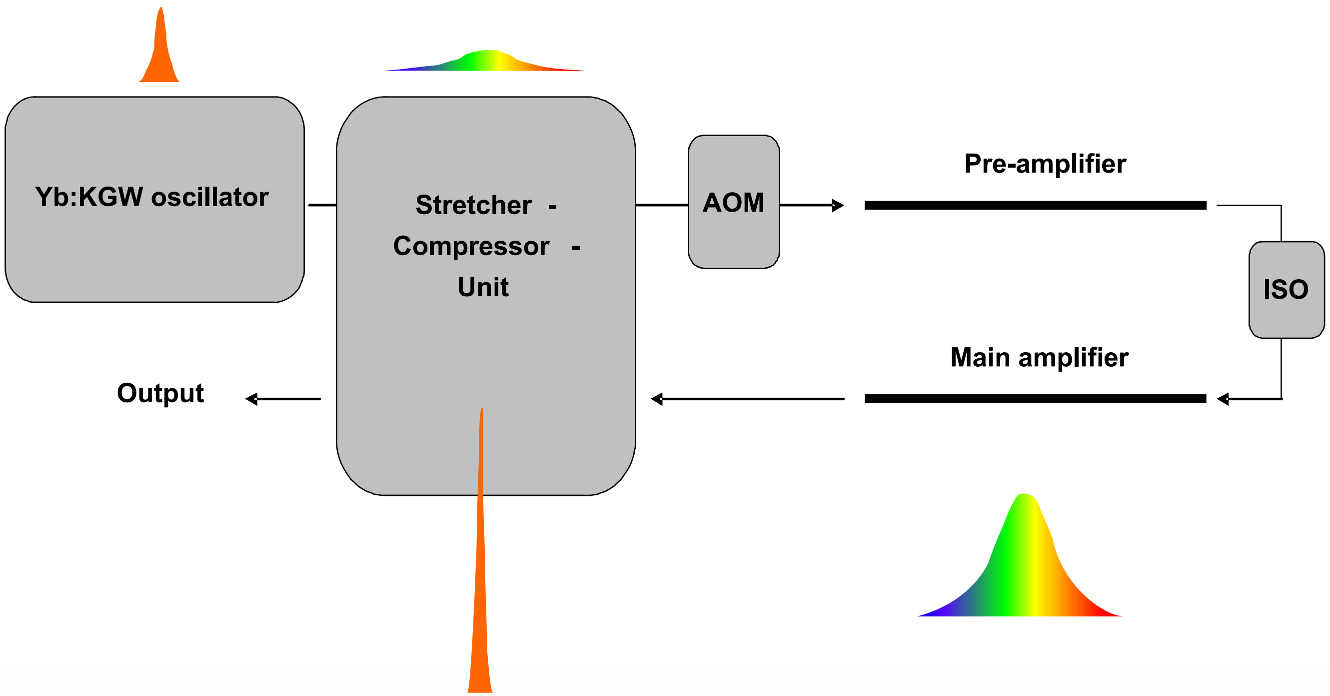


➡ **reduced pulse peak power during amplification**

➡ **reduced nonlinearity**
enhanced damage threshold

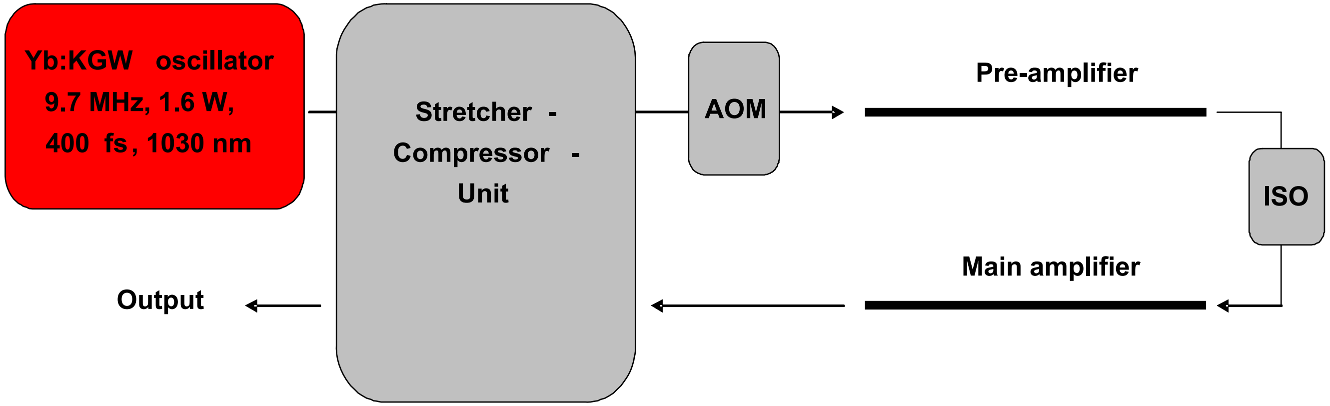
State of the art FCPA System

Schematic Setup



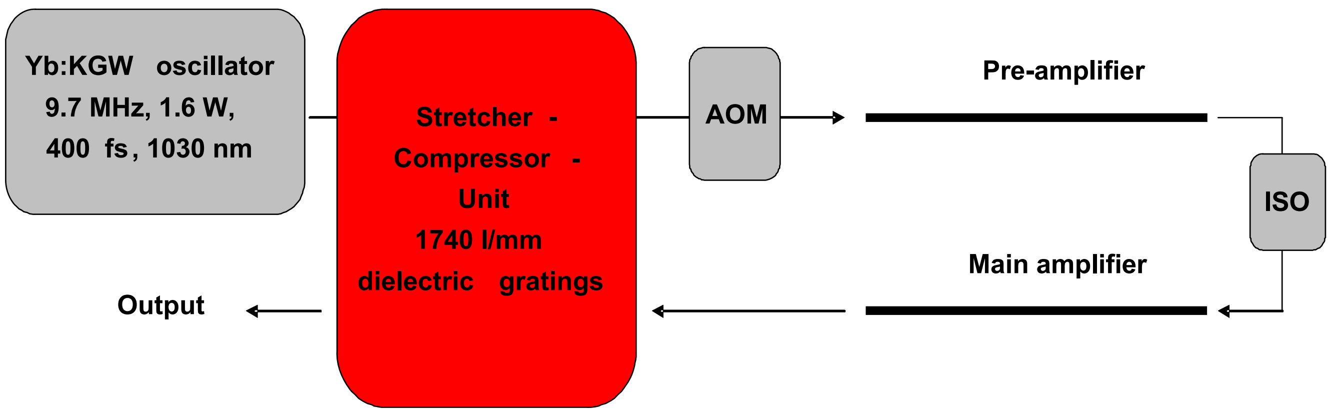
State of the art FCPA System

Schematic Setup



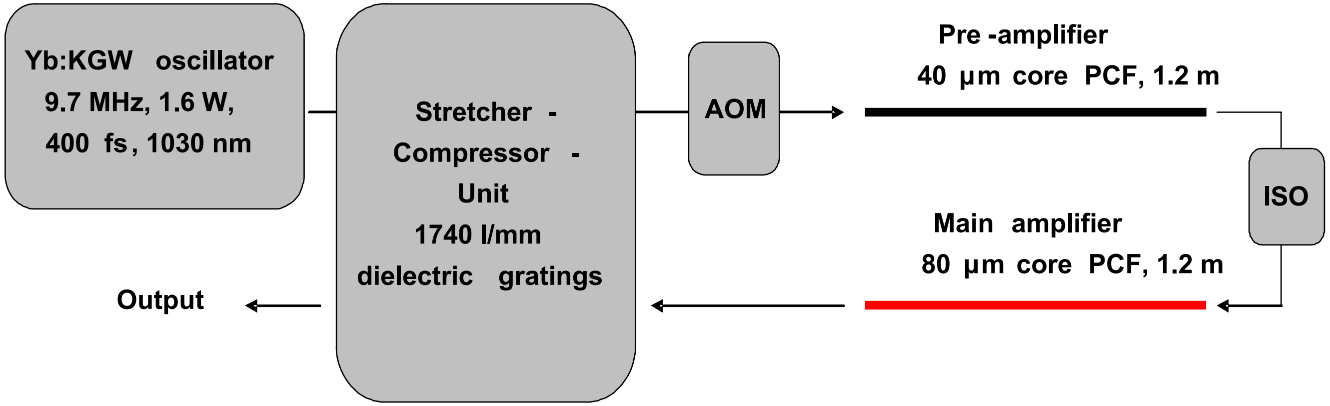
State of the art FCPA System

Schematic Setup



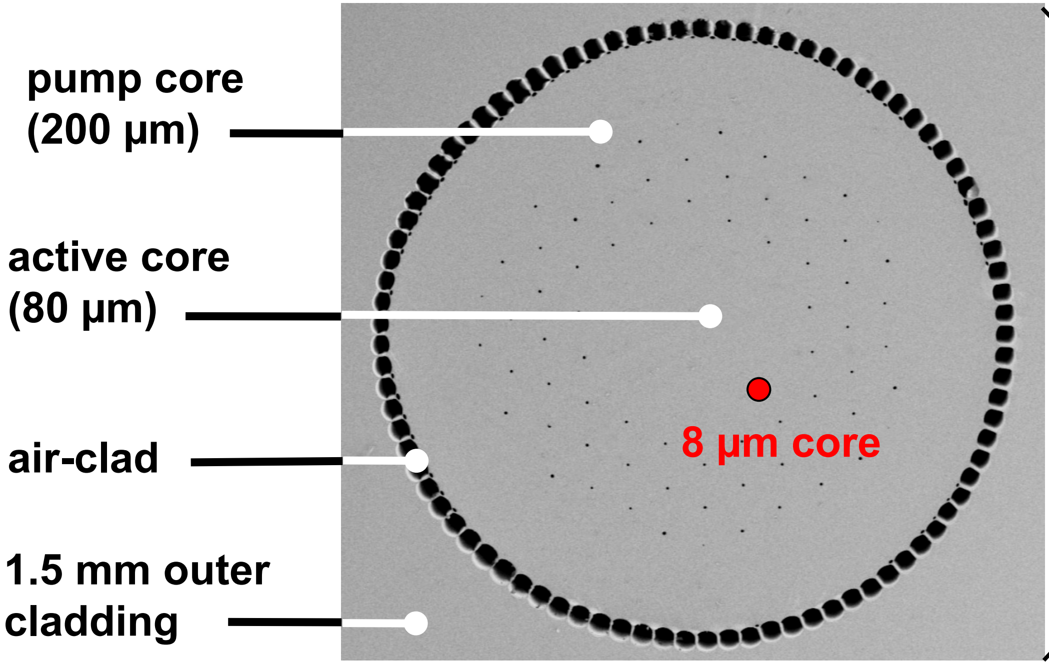
State of the art FCPA System

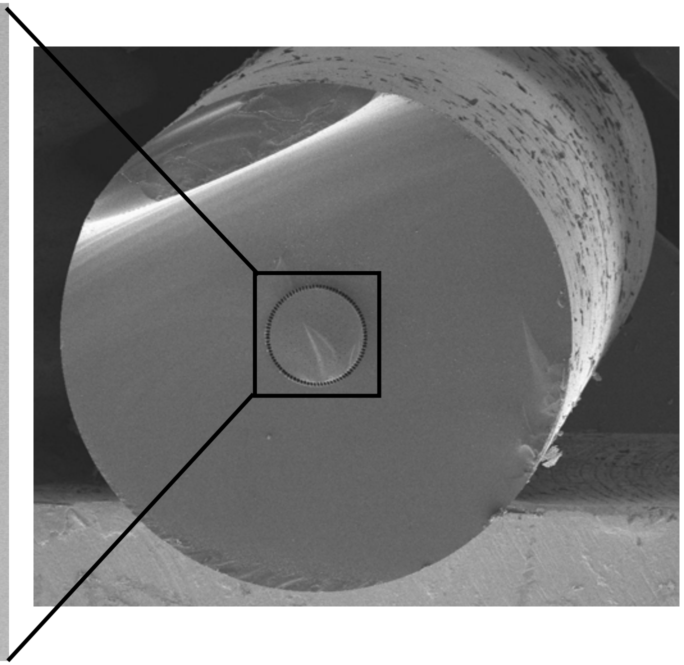
Schematic Setup



State of the art FCPA System

Rod-type photonic crystal fiber





High pump light absorption (30dB/m) -> short fiber length
+ large mode area (>100x of standard fiber) -> ultralow Nonlinearity

Limpert et. al., "High-power rod-type photonic crystal fiber laser," Opt. Express 13, 1055-1058 (2005)

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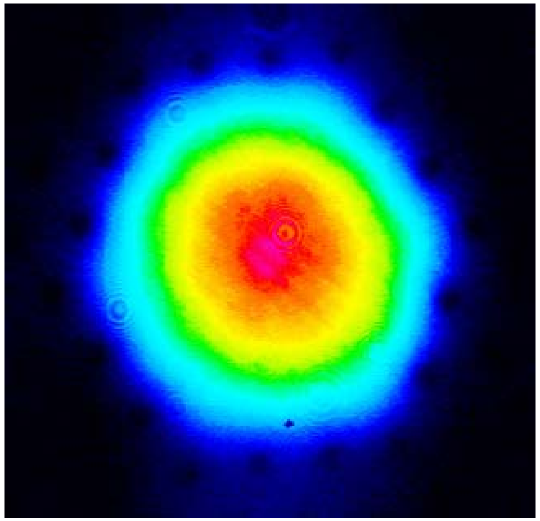
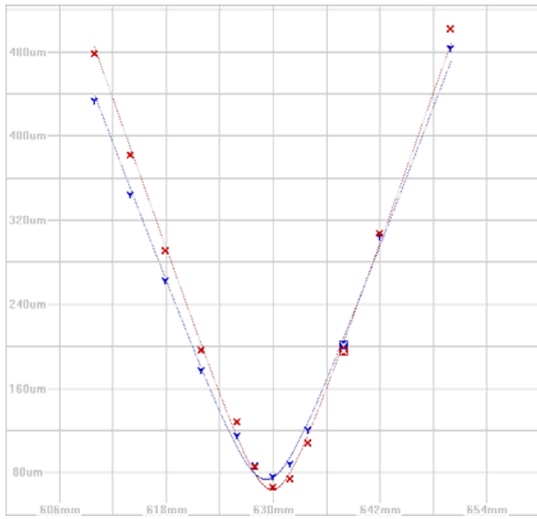
200/80 Rod-type PCF, 1.2m length

Near field image



MFD = 71 µm
-> MFA ~ 4000 µm²

Beam quality-measurement



M^2_x = 1.17 , M^2_y = 1.26
(Spiricon™, 4σ method)

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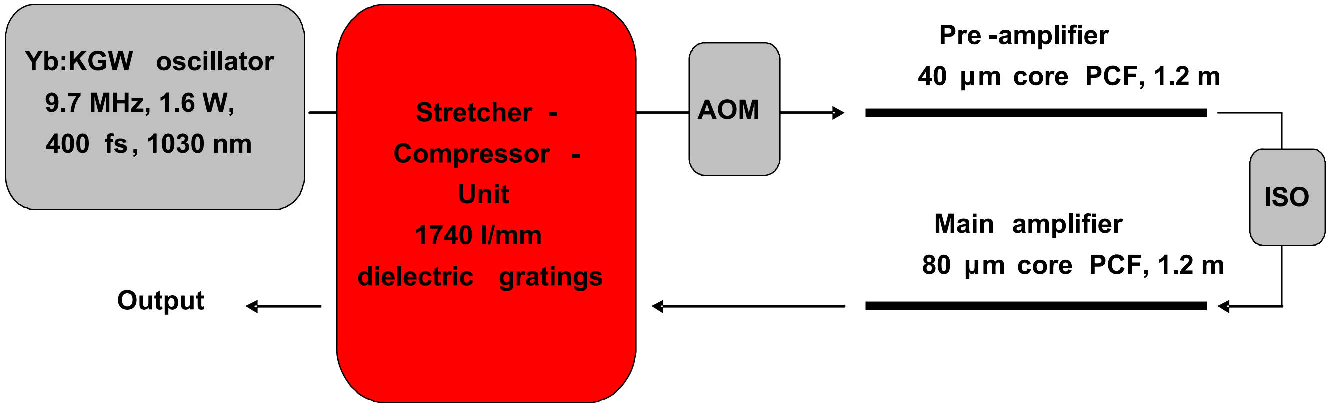
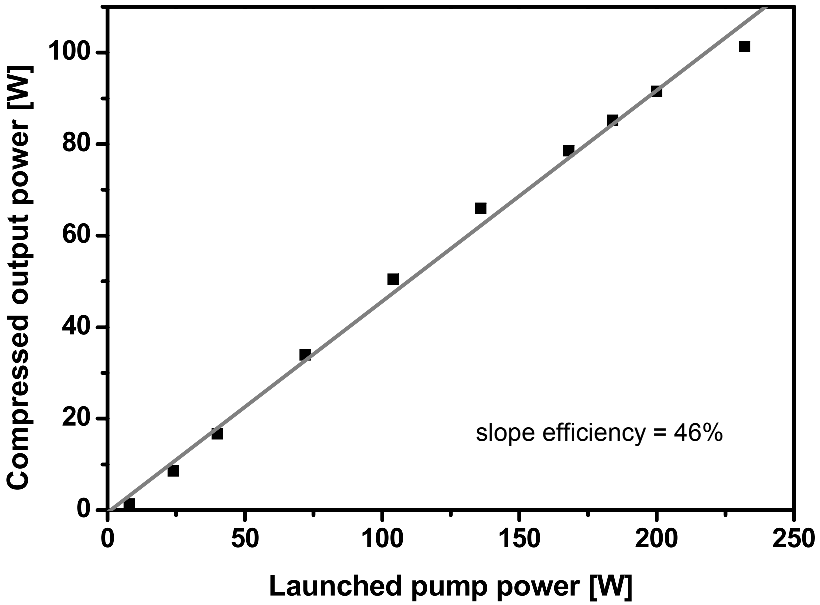
Schematic Setup



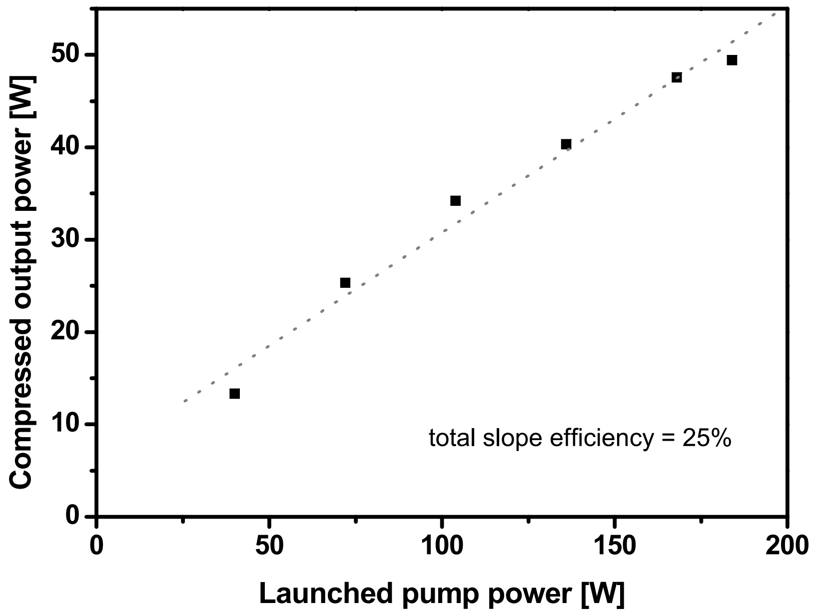
- multilayer dielectric reflection gratings – average power scalable
- 70% compressor throughput efficiency

State of the art FCPA System

Output characteristics



100 W compressed @ 200 kHz
-> 0.5 mJ pulse energy



50 W compressed @ 50 kHz
-> 1 mJ pulse energy

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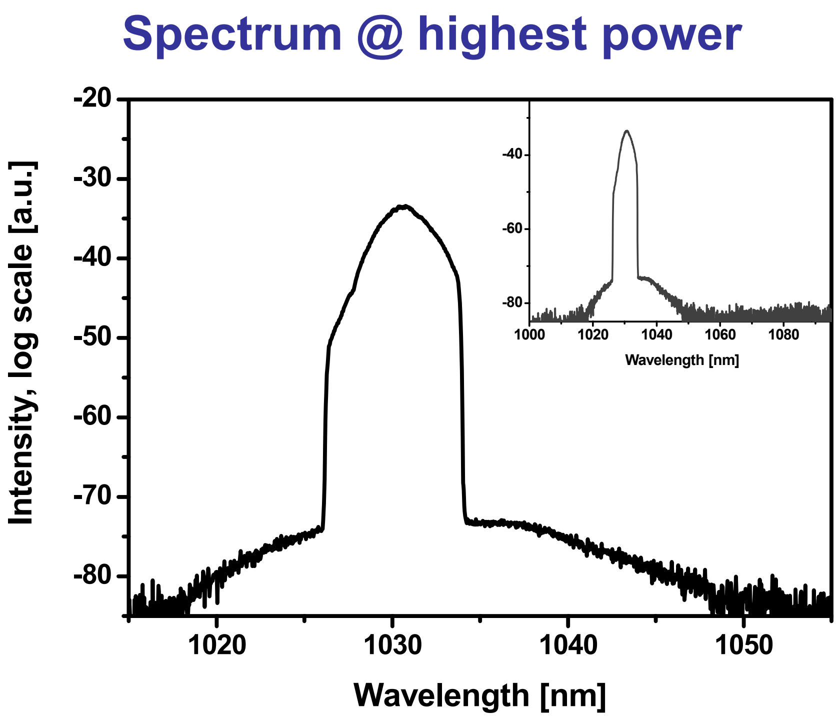
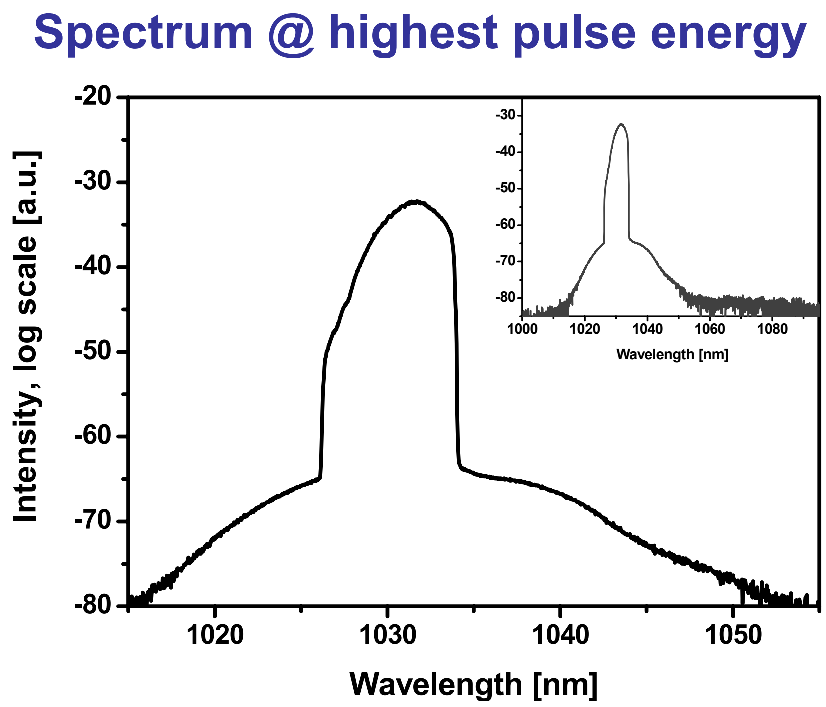
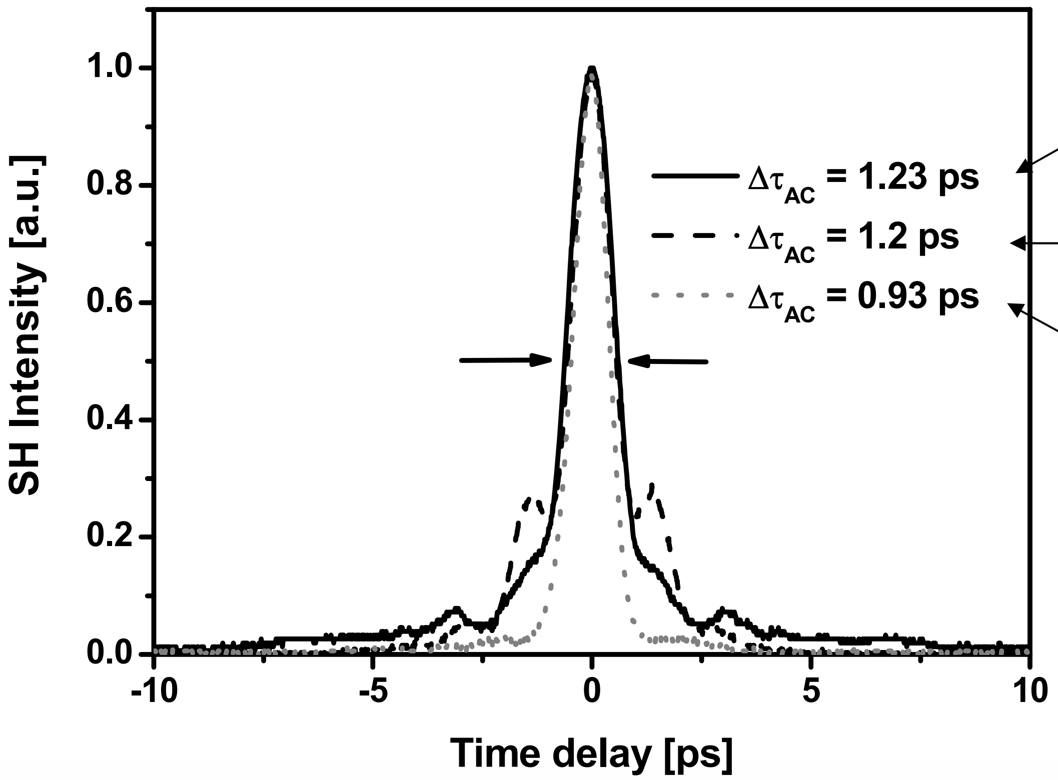




ASE supression better than 30 dB
Extended measurement shows no sign of Stimulated Raman Scattering
(1st stokes expected at 1080nm)

State of the art FCPA System

Autocorrelation



50 kHz / 1 mJ
(B-Integral 7)

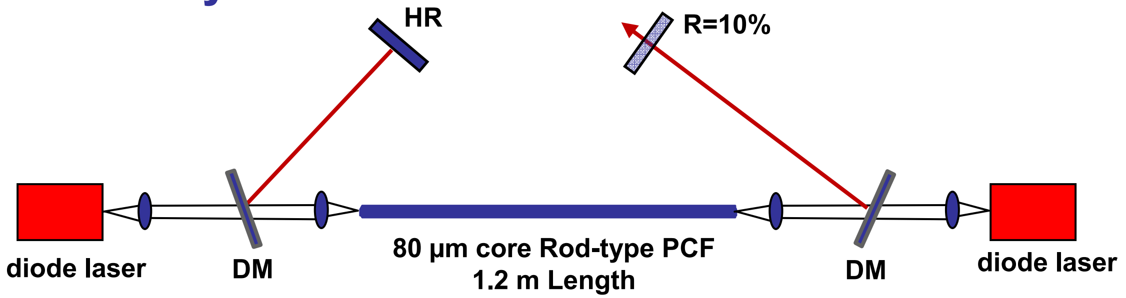
200 kHz / 500 µJ
(B-Integral 4.7)

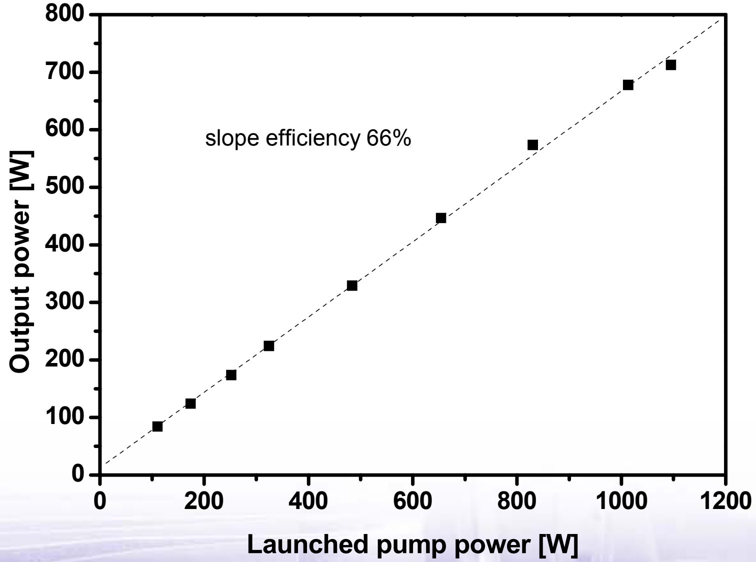
At low pulse energy

1mJ, 800 fs => pulse peak power ~ 1 GW!

Average power scalability of main amplifier

Schematic Setup cw cavity



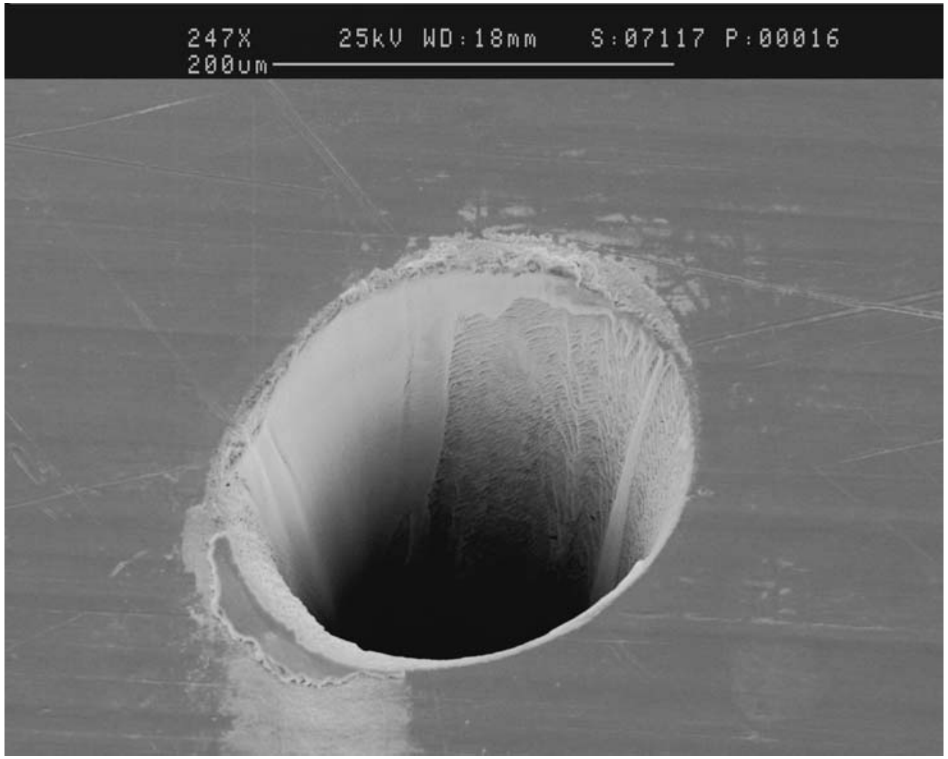


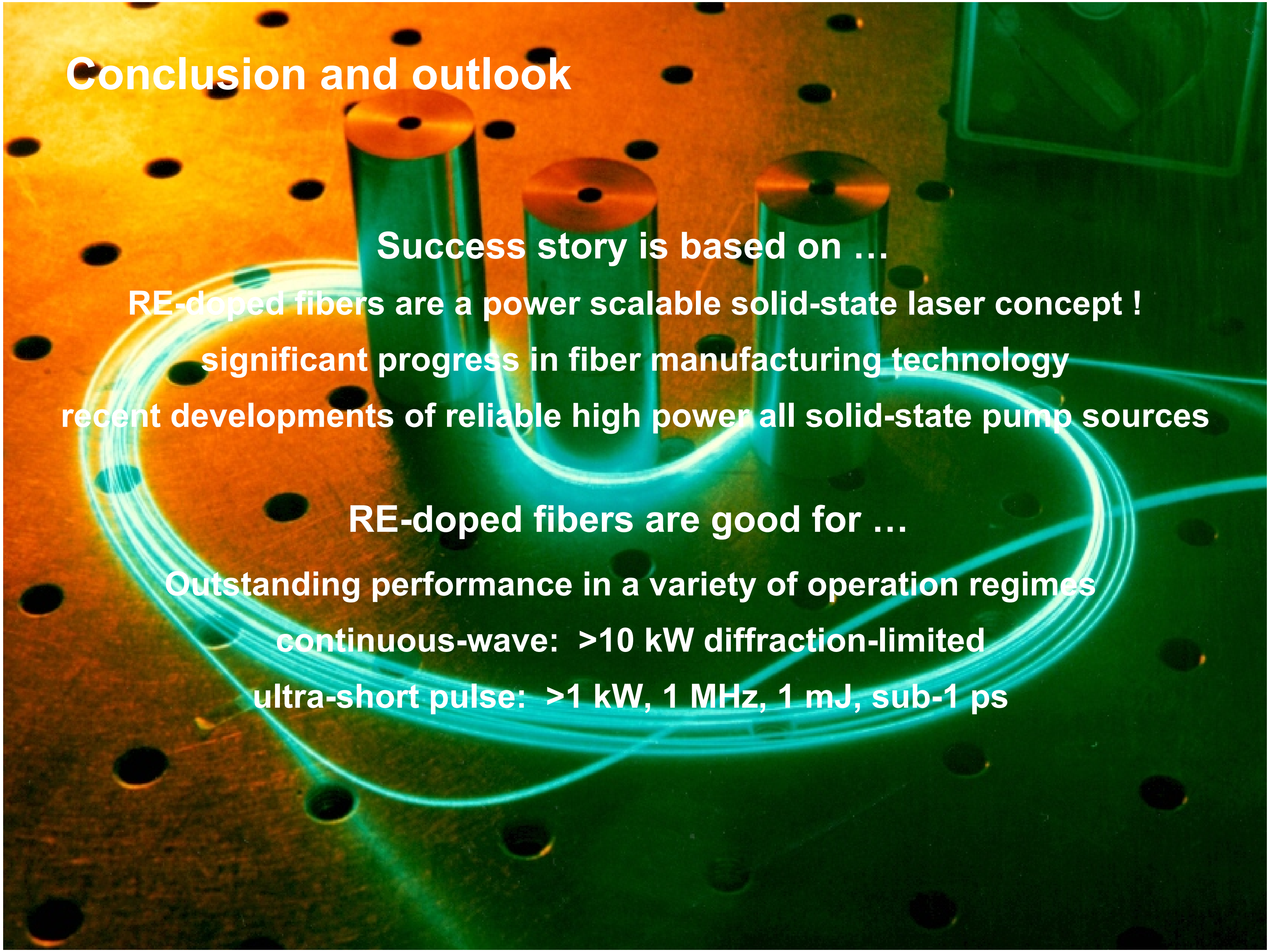
710 W max. output (pump power limited)

570 W/m with no thermal degradation (passively cooled)

1 kW, 1 MHz, 1 mJ, sub-1 ps !

Laser trepanning with high average power on copper

Copper (Cu 99.9%) Thickness: **0.5 mm** Rep.rate.: **975 kHz** Pulse Energy : **70 µJ** Focal length: 80mm Fluence: ~ 2.32 J/cm^2 Number of rounds: 50	
trepanning radius	75 µm
rotating speed	106 rounds/s
breakthrough time	**75 ms**


Conclusion and outlook
Success story is based on …
RE-doped fibers are a power scalable solid-state laser concept !
significant progress in fiber manufacturing technology
recent developments of reliable high power all solid-state pump sources
RE-doped fibers are good for …
Outstanding performance in a variety of operation regimes
continuous-wave: >10 kW diffraction-limited
ultra-short pulse: >1 kW, 1 MHz, 1 mJ, sub-1 ps