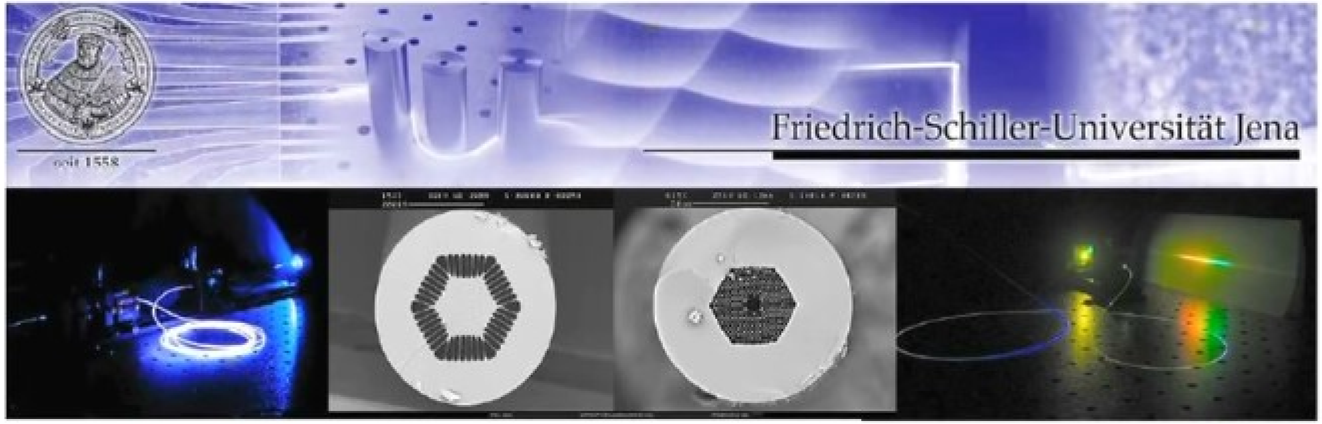



# *High power fiber lasers and amplifiers*

**Jens Limpert**

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

**Jens Limpert**
Jens.Limpert@uni-jena.de

+49 (0) 36 41. 947 811
+49 (0) 36 41. 947 802

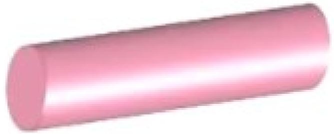
Institute of Applied Physics

# Outline of the talk

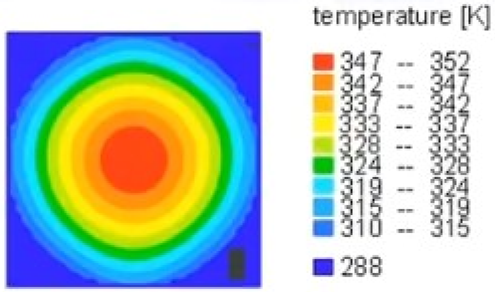
*High power fiber lasers and amplifiers*

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

# Solid-State Laser Concepts

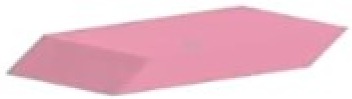


rod

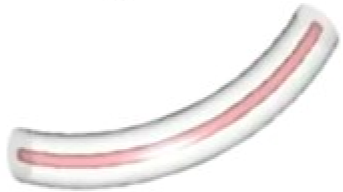



→ power dependent thermal lensing and thermal stress-induced birefringence

disk



slab

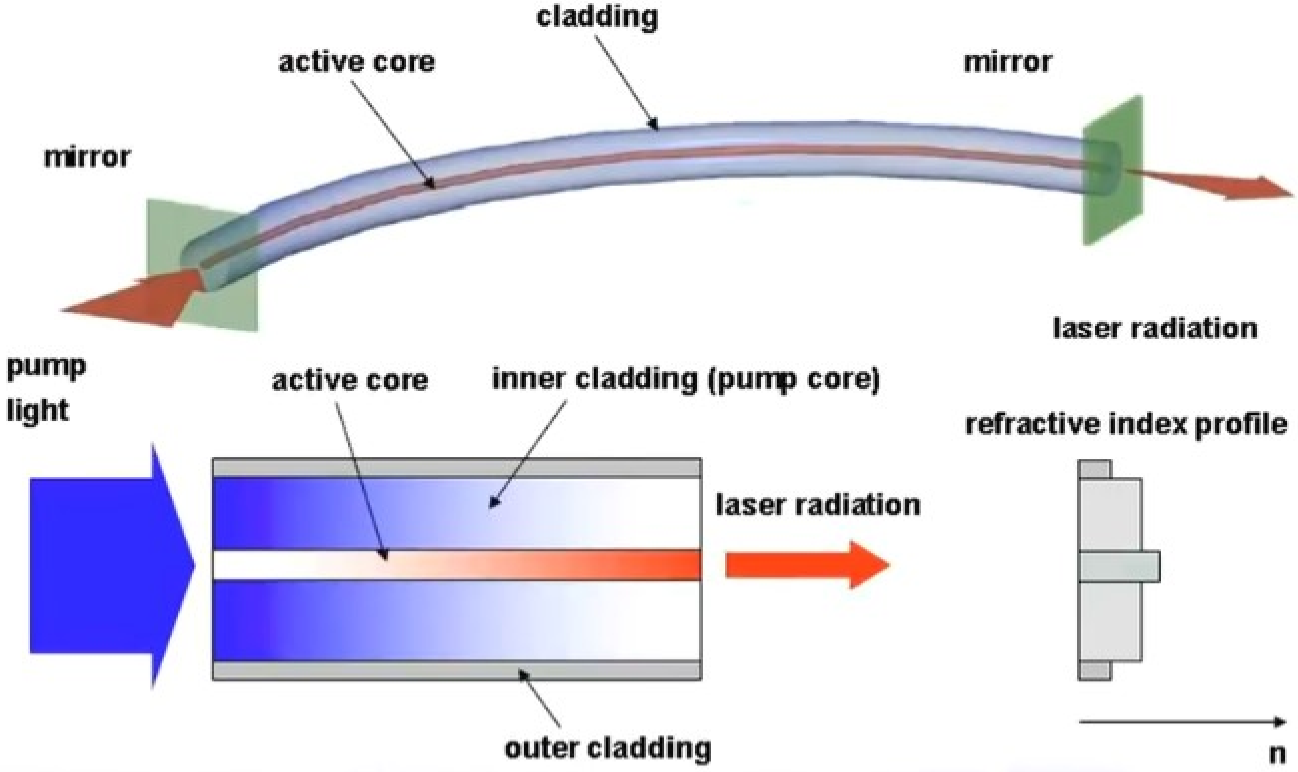


fiber

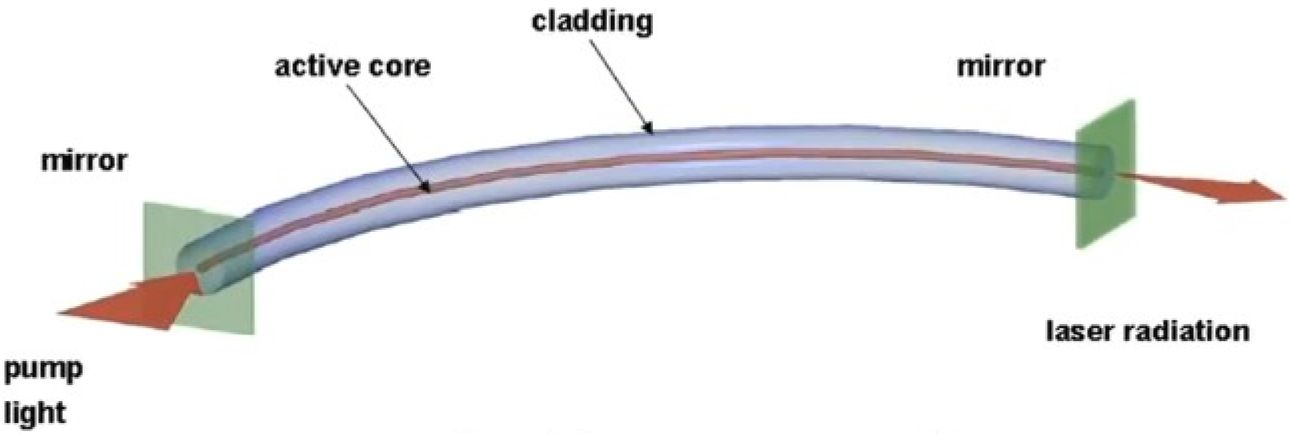
• • •

→ reduced thermo-optical distortions

# Double-clad fiber laser

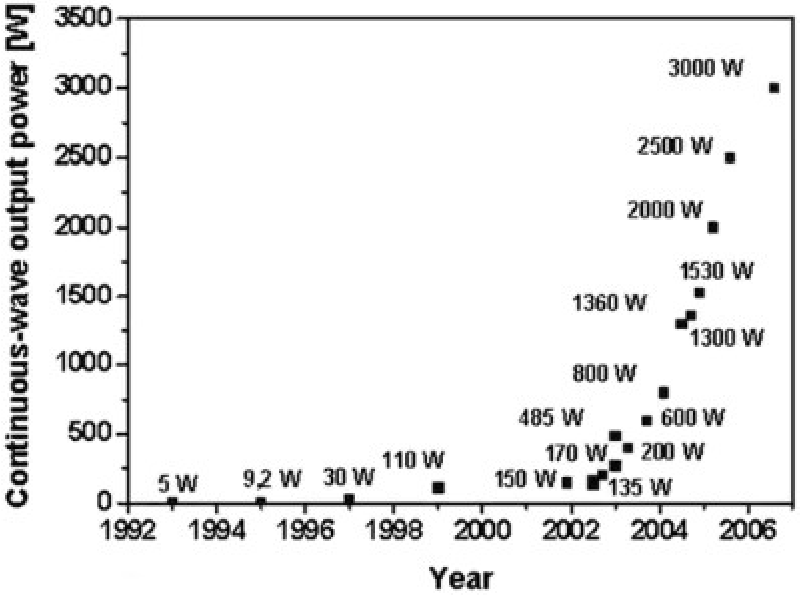


# Properties of Rare-Earth-Doped Fibers




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

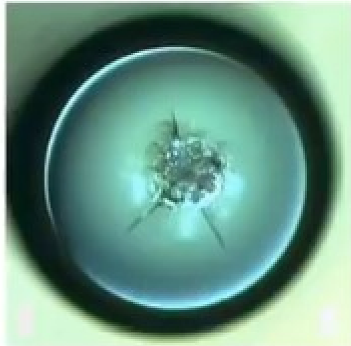
# Power evolution of single-mode fiber lasers




**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)

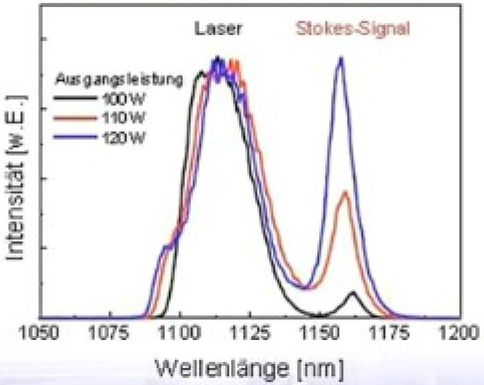
# Performance-limiting effects

## End-facet damage

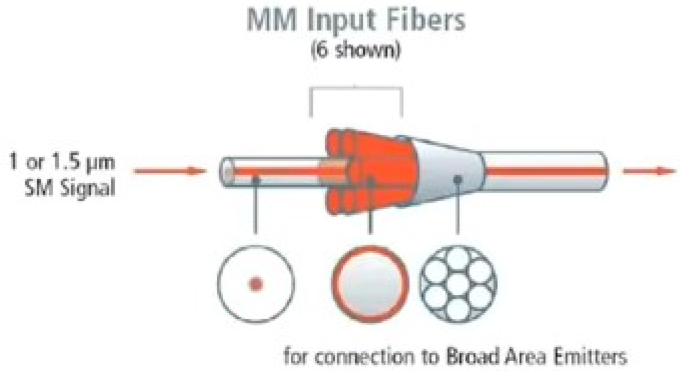


## Thermal effects

## Non-linear effects



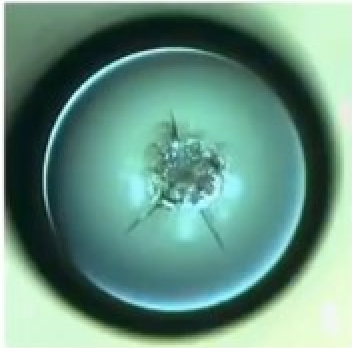

## Available pump power




Source: www.specialtyphotonics.com

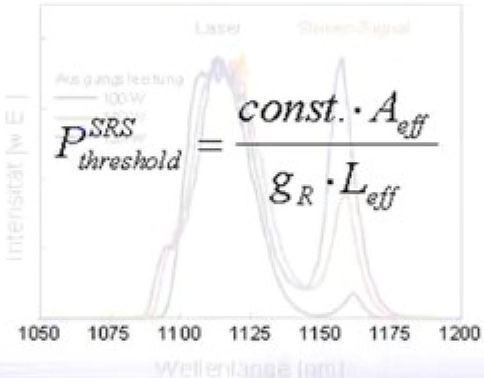
# Performance-limiting effects

## End-facet damage



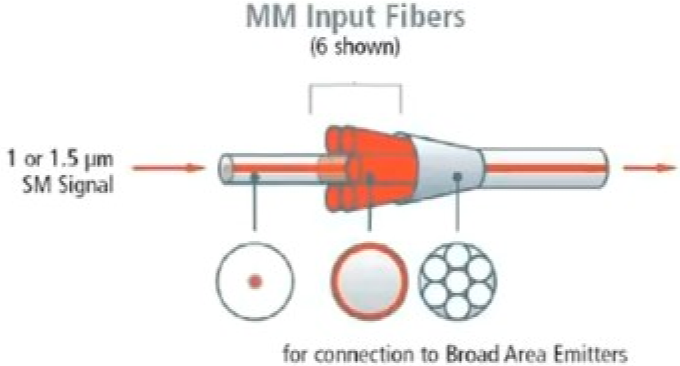
## Thermal effects

## Non-linear effects




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

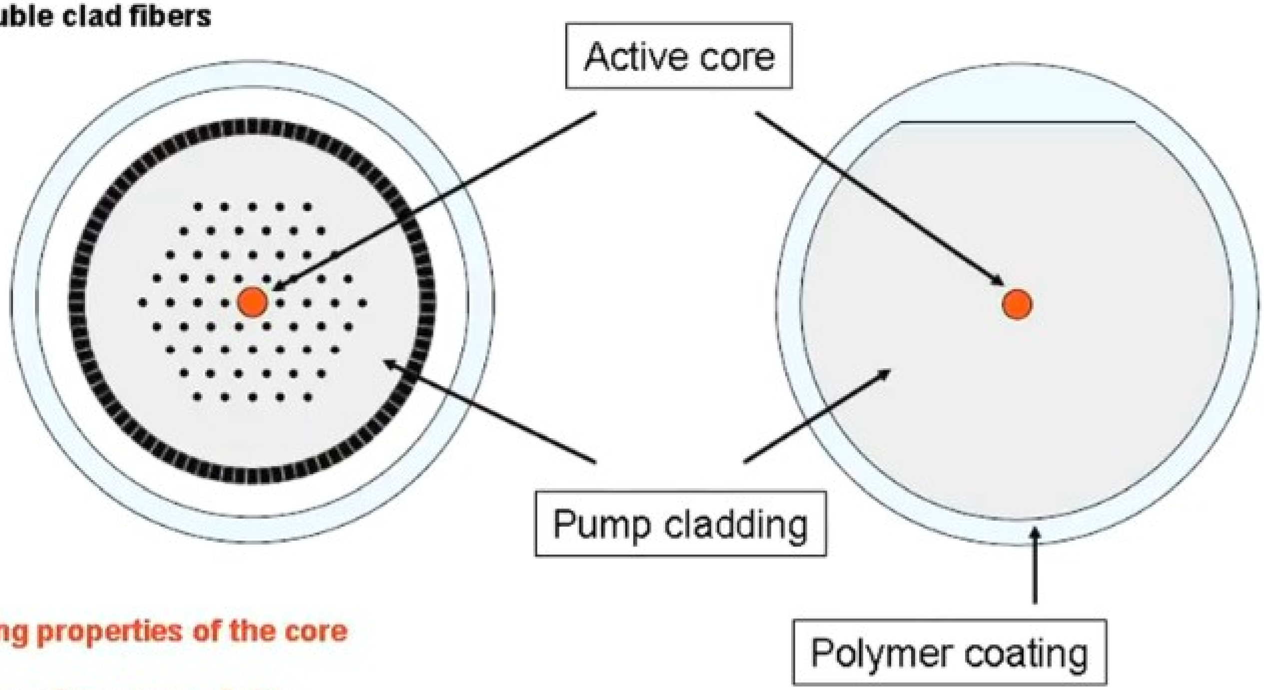
## Available pump power




Source: www.specialtyphotonics.com

# Photonic Crystal Fibers

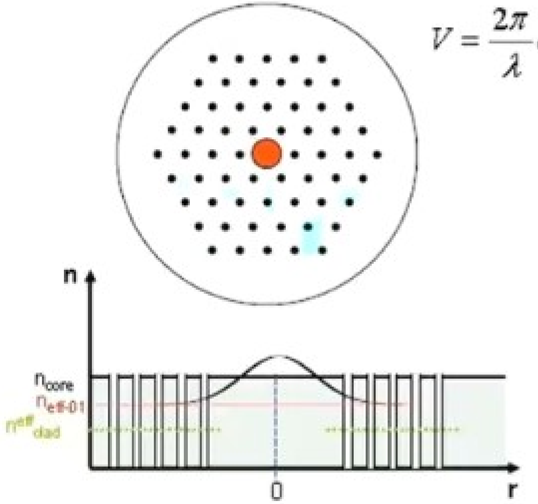
**Double clad fibers**



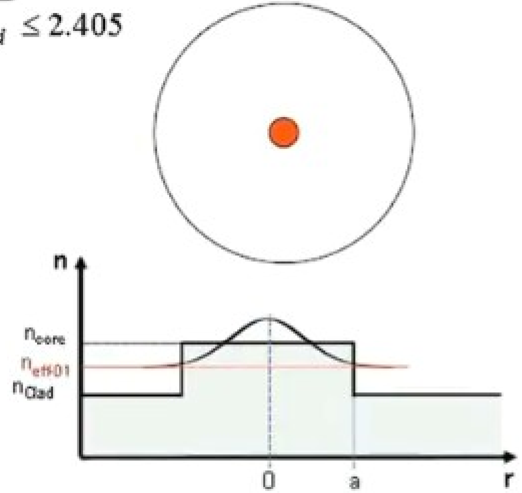

- guiding properties of the core
- guiding of the pump light

# 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**



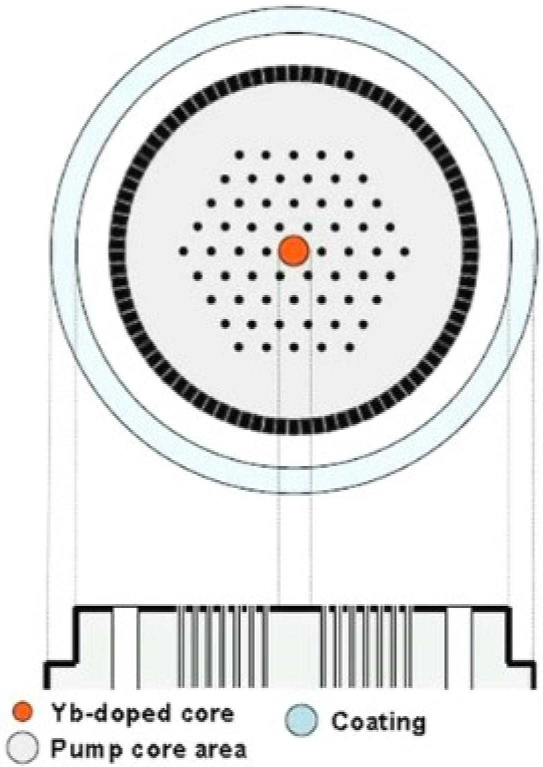

**Step-index Fiber**

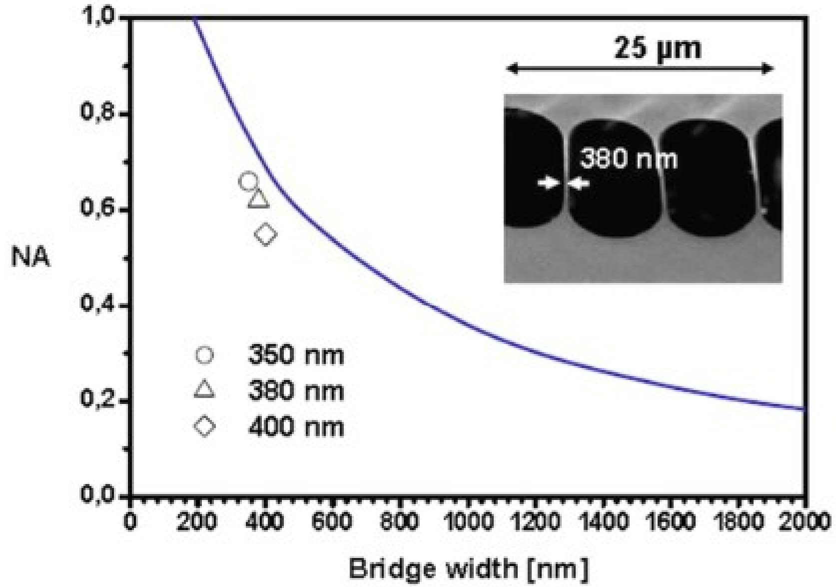
➜ **$\Delta n \sim 1 \cdot 10^{-4}$**
**NA ~ 0.02**

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

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

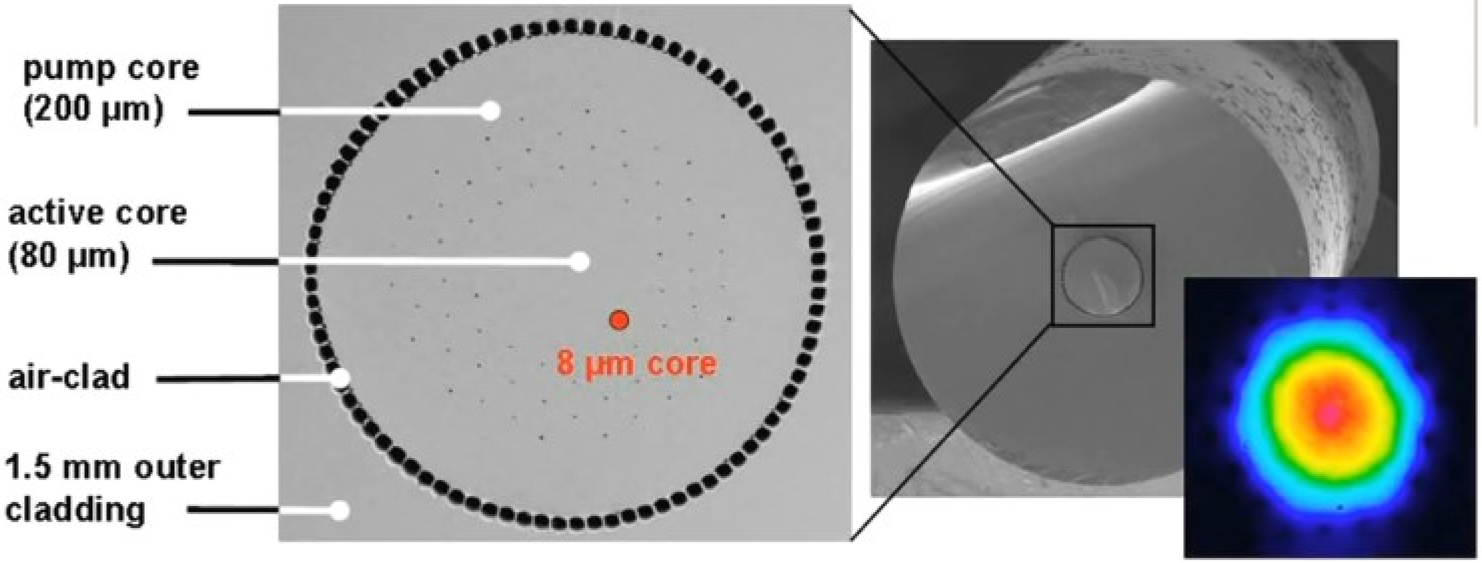
# The air-cladding region




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

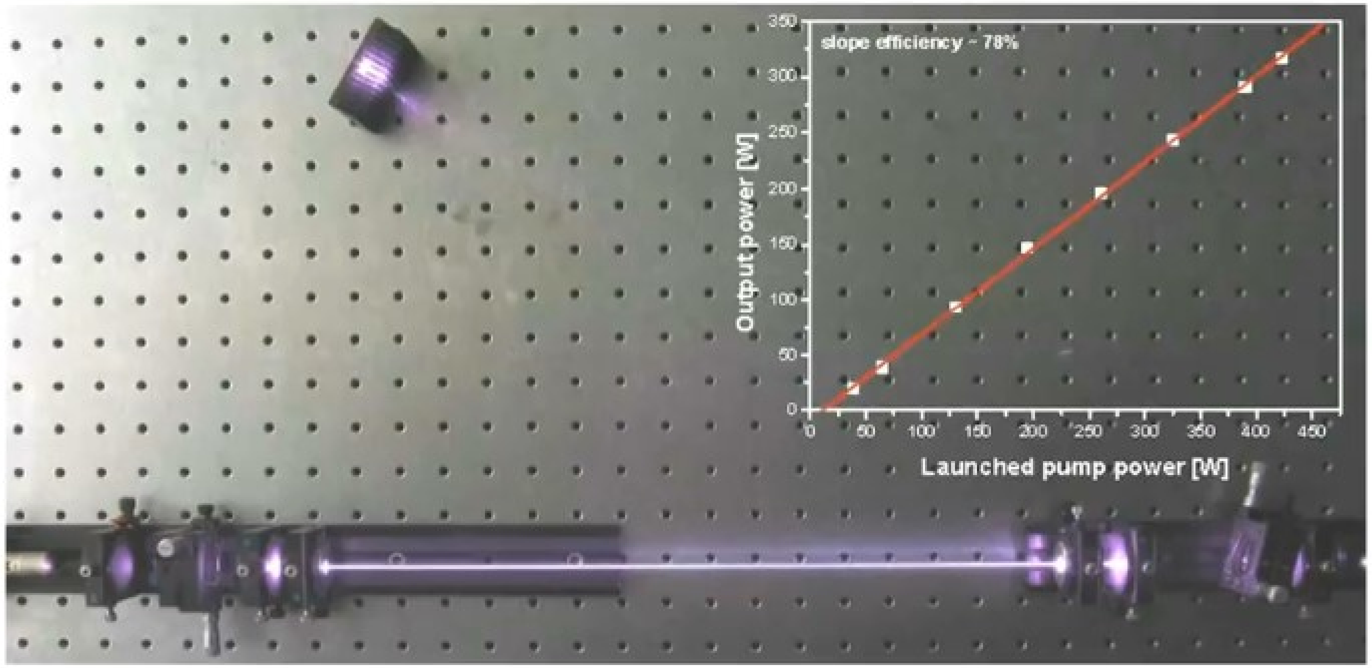
# "rod-type" photonic crystal fiber




„rod-type" fiber: **30 dB/m** Pumplichtabsorption, **71 µm** Modenfelddurchmesser, $M^2 \sim 1.2$

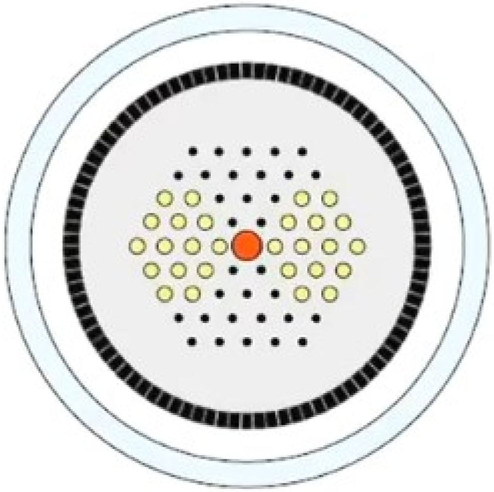
Limpert et. al., "High-power rod-type photonic crystal fiber laser," Opt. Express 13, 1055-1058 (2005)

# Rod-type photonic crystal fiber laser




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

# Rare-earth doped photonic crystal fibers

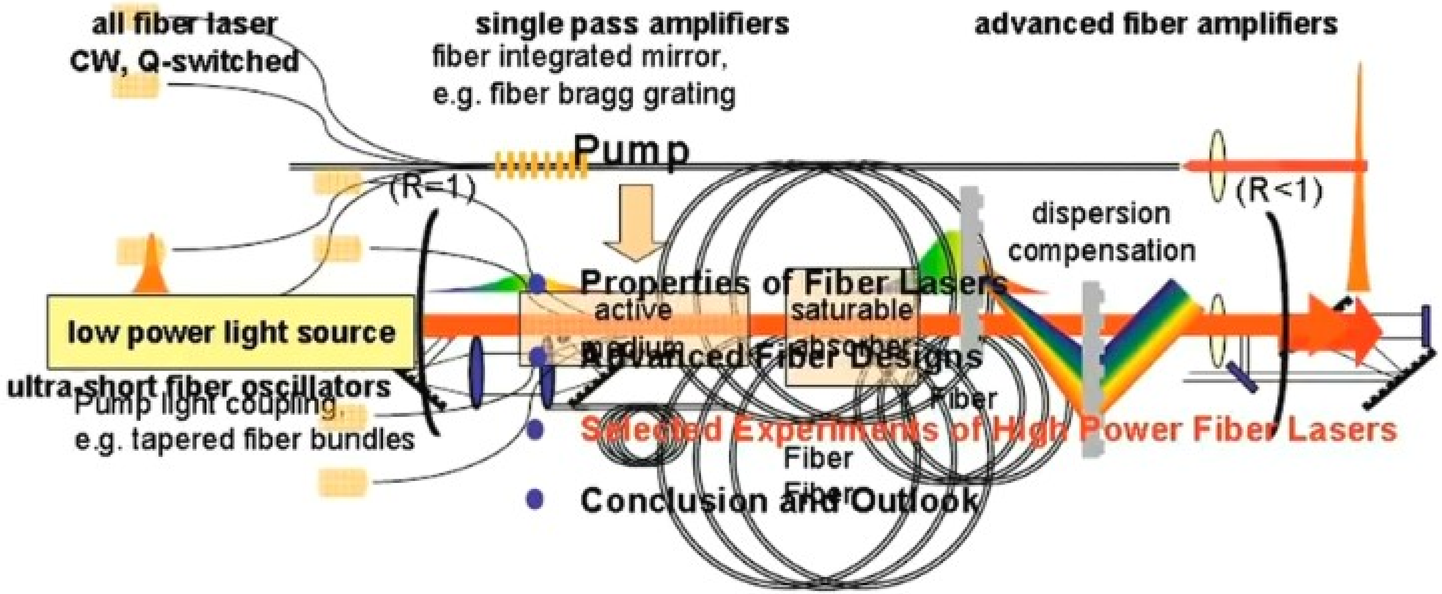


**Design freedom to tailor optical, mechanical and thermo-optical properties**

**Advantages of PCF**

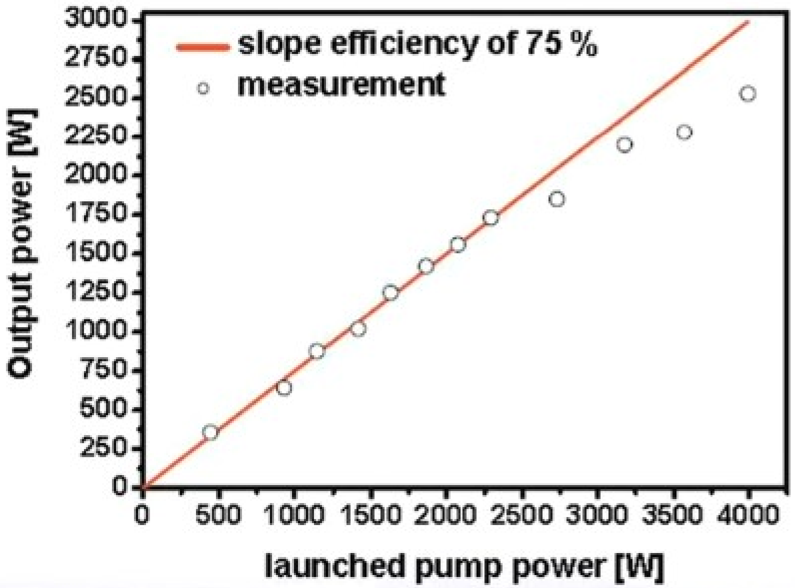
- higher index control
- larger SM cores
- shorter fibers possible (0.5 m)
- comparable heat dissipation
- intrinsically polarizing without drawbacks

# Fiber laser systems




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

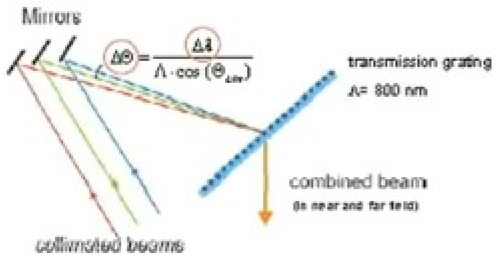
# High power continuous-wave fiber laser



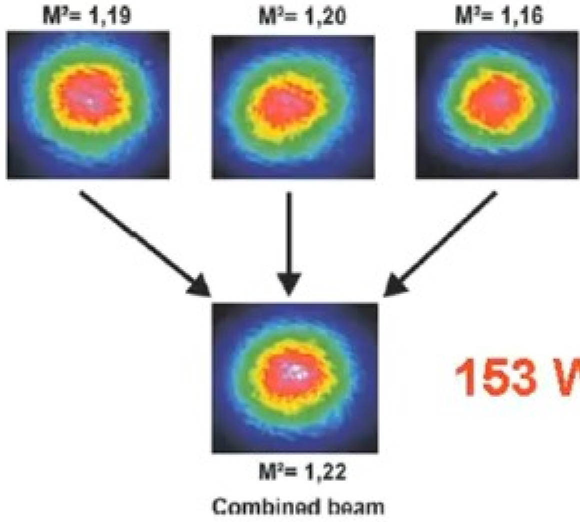

- fiber length 15 m, forced air-cooling
- two side pump coupling of 2 kW
- fiber temperature max. 120°C
- beam quality $M^2 < 1.4$ at 2 kW
- max. 2.53 kW laser output

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**

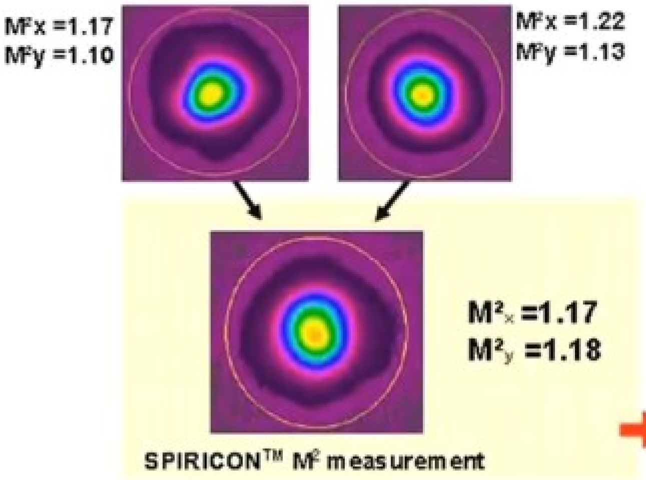
**Combining-efficiency 95 %**
**Degree of Polarization 98%**

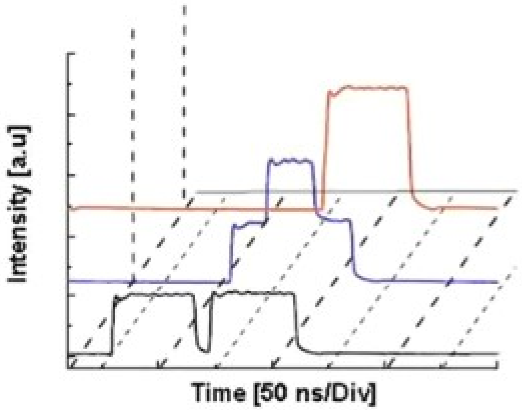
➔ **Scalable while maintaining beam quality**

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

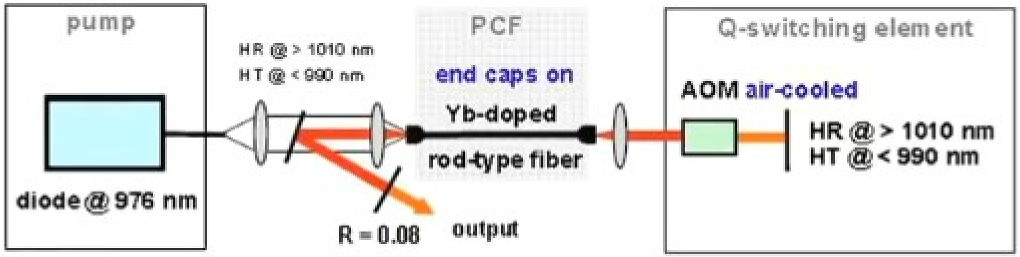
two beams ($\Delta T \sim 10ns$):

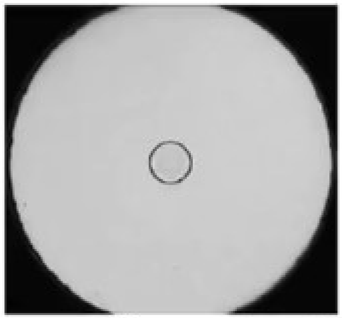


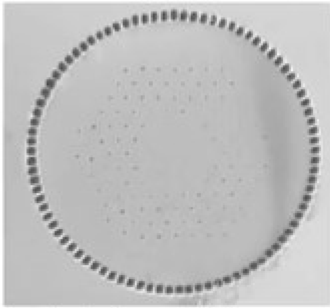




→ scaling of MW peak power pulsed fiber sources beyond self-focusing limit of 4 MW

# Q-switching of fiber lasers





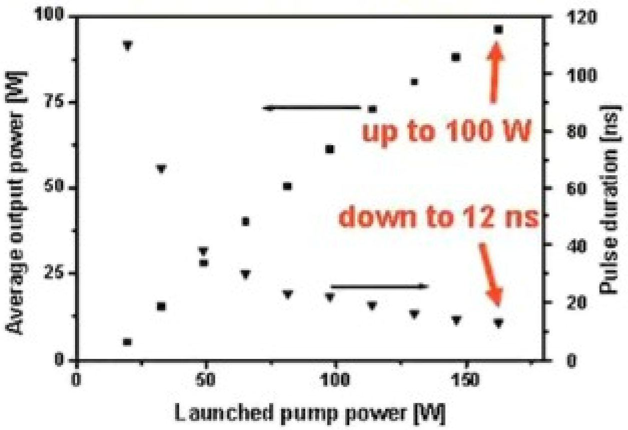
*Microscope image of the rod-type photonic crystal fiber and close-up to the inner cladding and core region.*

**Fiber parameter:**

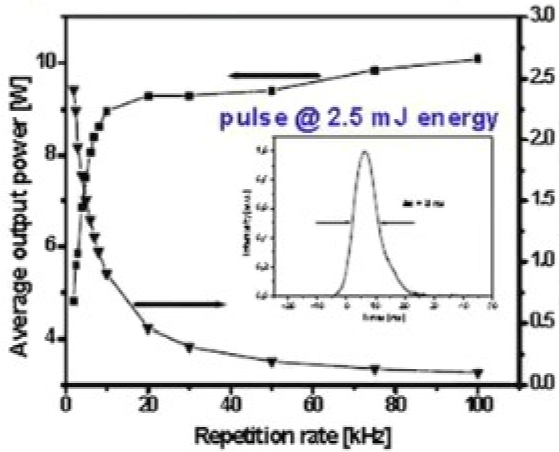
outer diameter: up to 2 mm
60 µm Yb-doped core, $A_{eff}$ ~ 2000 µm$^2$,
180 µm (NA ~ 0.6) inner cladding
30 dB/m pump absorption @ 976 nm,
(0.5 m absorption length)

# Q-switching of fiber lasers

### output characteristics @ 100 kHz



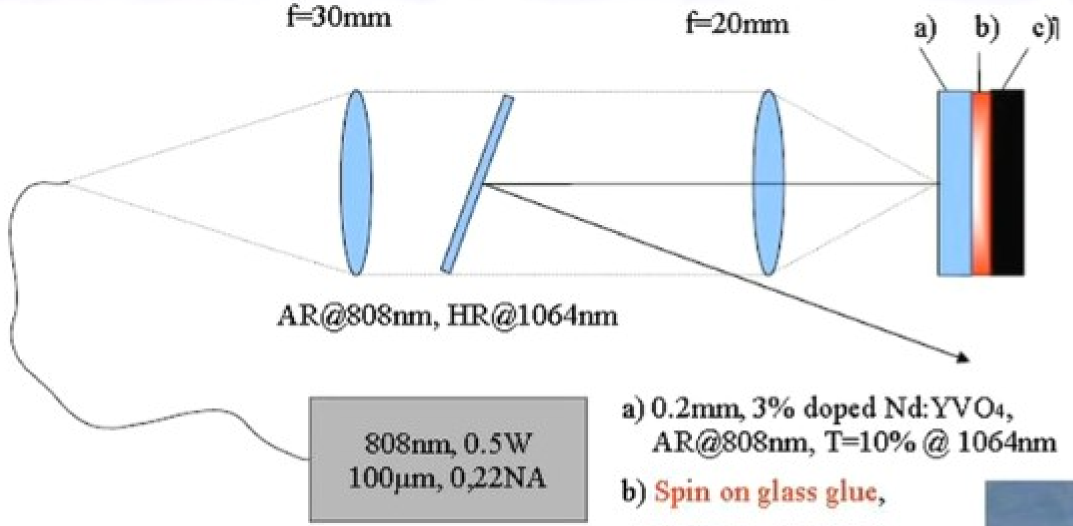

### output characteristics vs. rep. rate





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

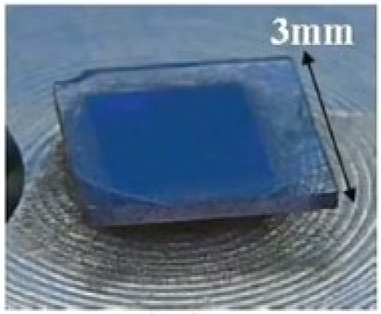
-Spin on glass glue
 *high dielectric strength
 *high transparency

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,

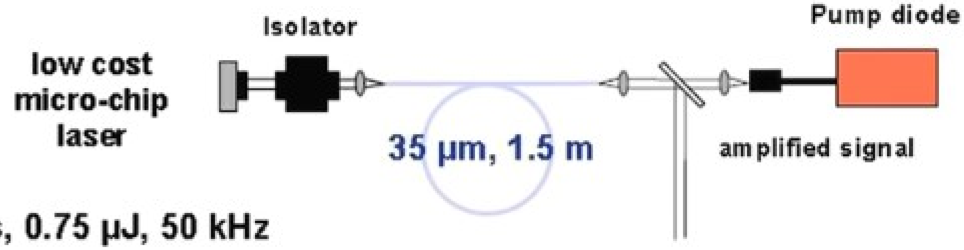
- **1µJ, 50ps, 40kHz**
- **0.5µJ, 110ps, 170kHz**



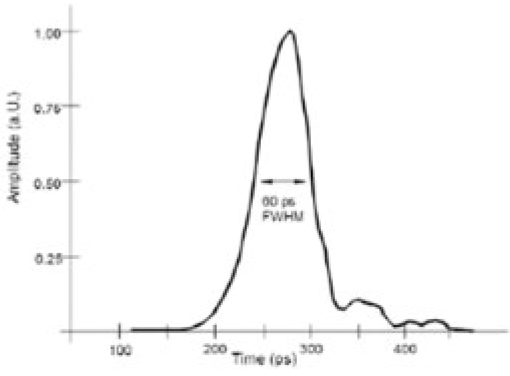

Current production costs:~300€

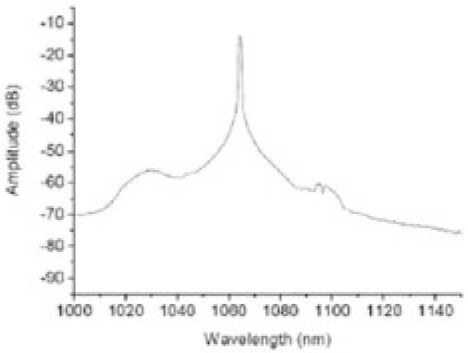
D. Nodop, J. Limpert, R. Hohmuth, W. Richter, M. Guina, and A. Tünnermann, "High-pulse-energy passively Q-switched quasi-monolithic microchip lasers operating in the sub-100-ps pulse regime," Opt. Lett. **32**, 2115-2117 (2007)

# Fiber based amplification of ps-µchip lasers




60 ps, 0.75 µJ, 50 kHz

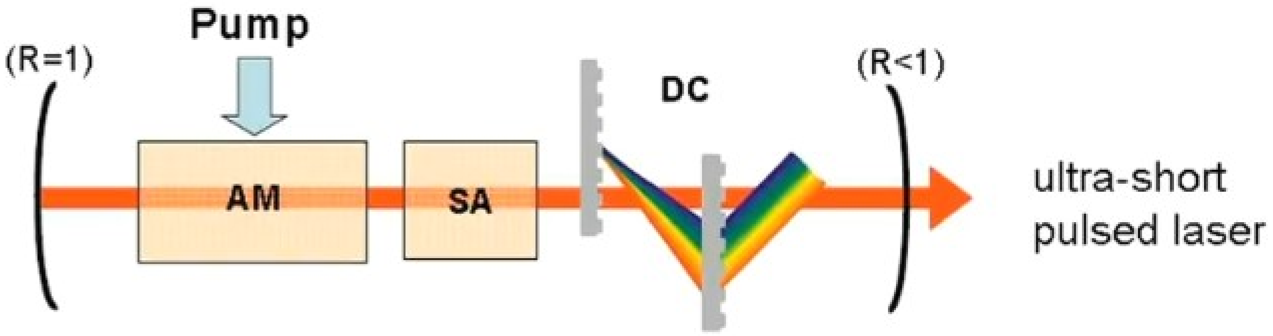


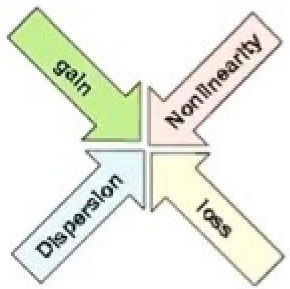

60 ps, 80 µJ, 50 kHz
peak power: 1.33 MW

micromachining

# Ultra-short pulse generation



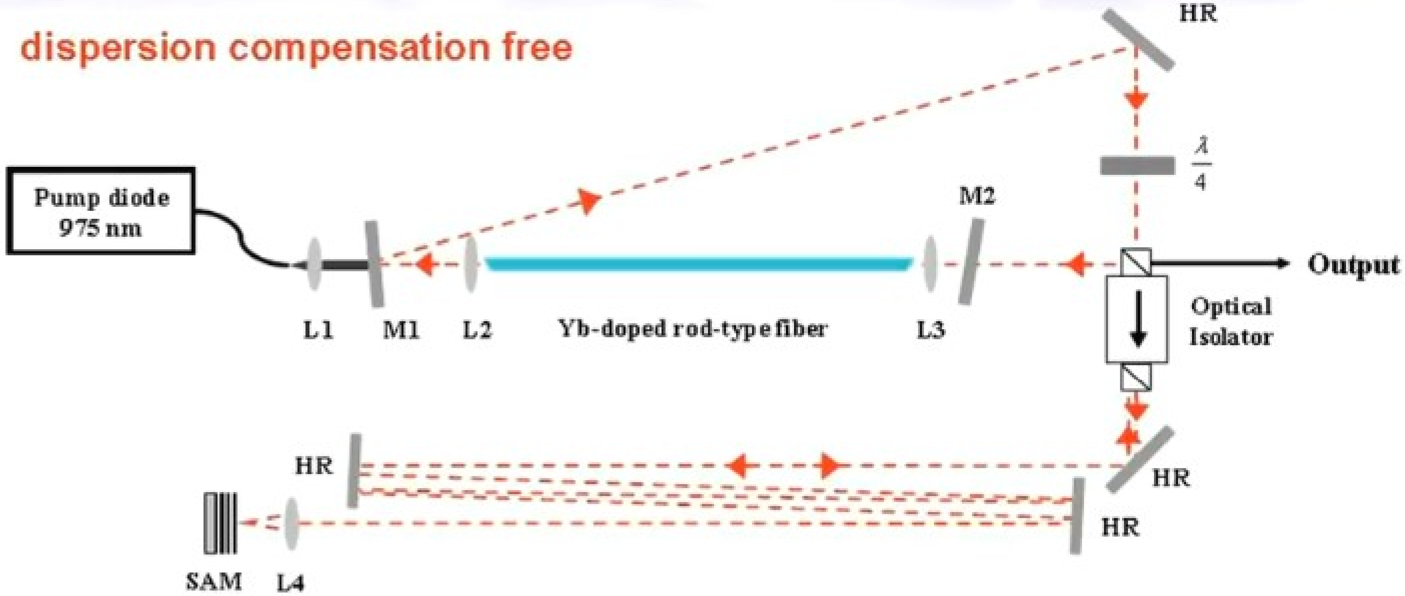

Theory:
dissipative, nonlinear system:




- *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*

# High-energy femtosecond fiber laser

dispersion compensation free



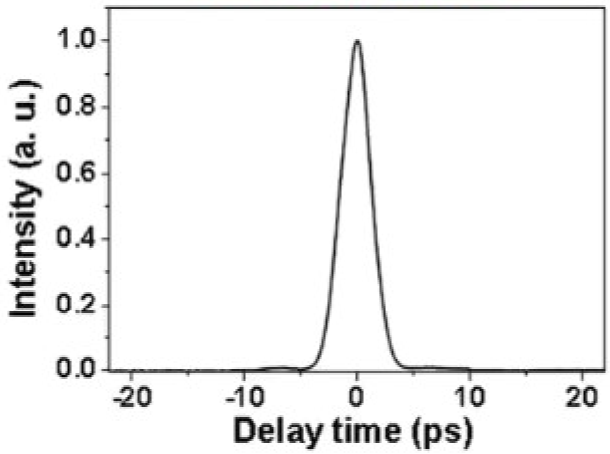

**Modulation depth 30%**
**Fast relaxation time 200 fs**
**Slow relaxation time 500 fs**

Total cavity dispersion : + 0.012 $ps^2$
Repetition rate : 10.18 MHz

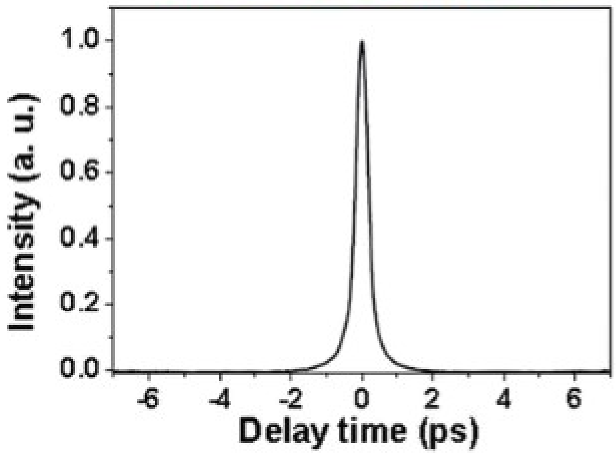
B. Ortaç, O. Schmidt, T. Schreiber, J. Limpert, A. Tünnermann, A. Hideur,
"High-energy femtosecond Yb-doped dispersion compensation free fiber laser," Optics Express, vol. 15, pp. 10725–10732, 2007.

# 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

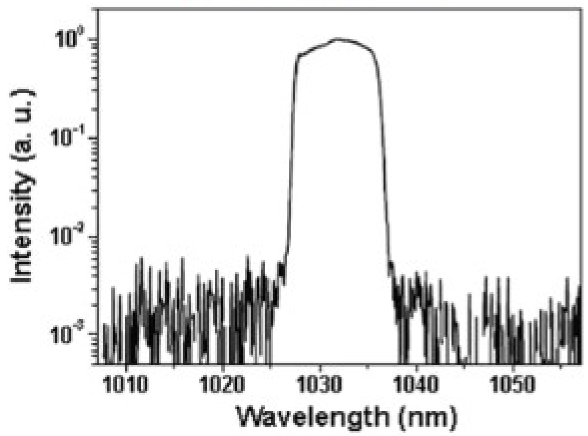
Compression efficiency: 75 %

Energy per pulse: 200 nJ

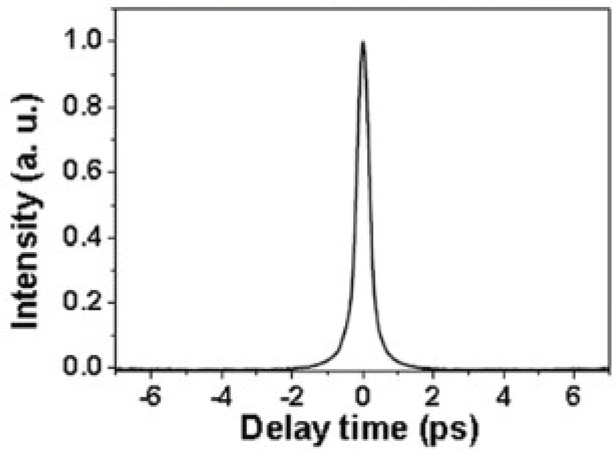
Peak power: 500 kW

# 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 %

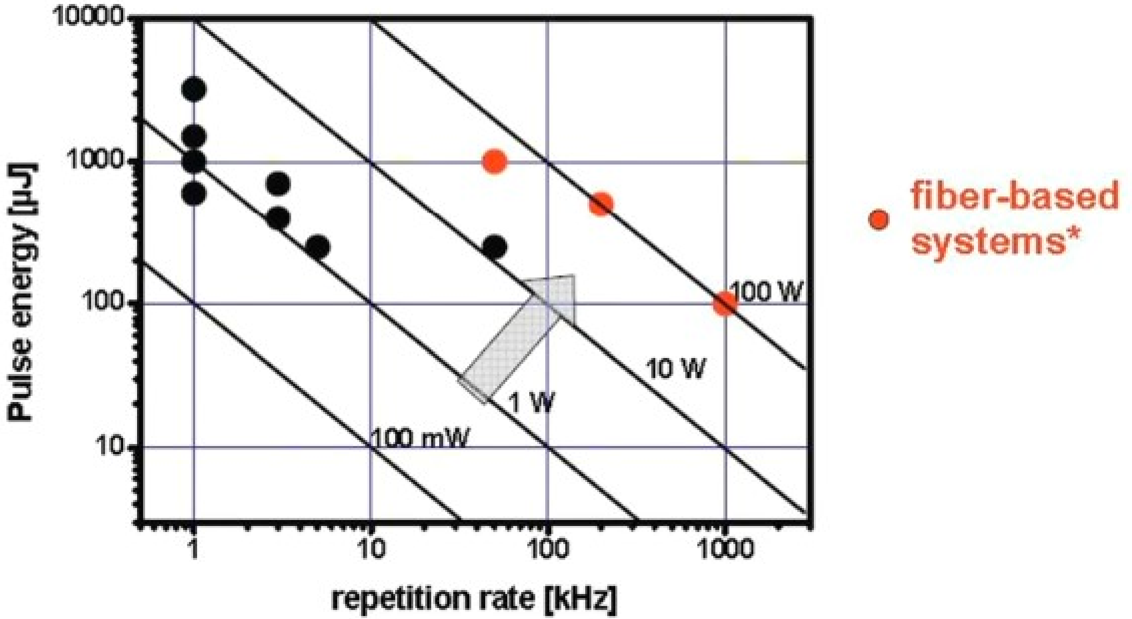
Energy per pulse: 200 nJ

Peak power: 500 kW

# Ultra-short pulse fiber amplification systems

Higher average power

Higher pulse energy — Higher repetition rate




* 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)

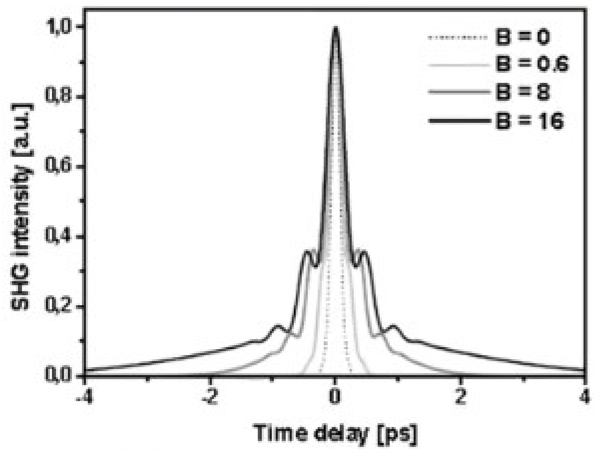
**Nonlinear phase:**

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

**Accumulated nonlinear phase (B-integral):**

$$B = \frac{2\cdot\pi}{\lambda}\int_0^L n_2 \cdot I(z)\,dz$$

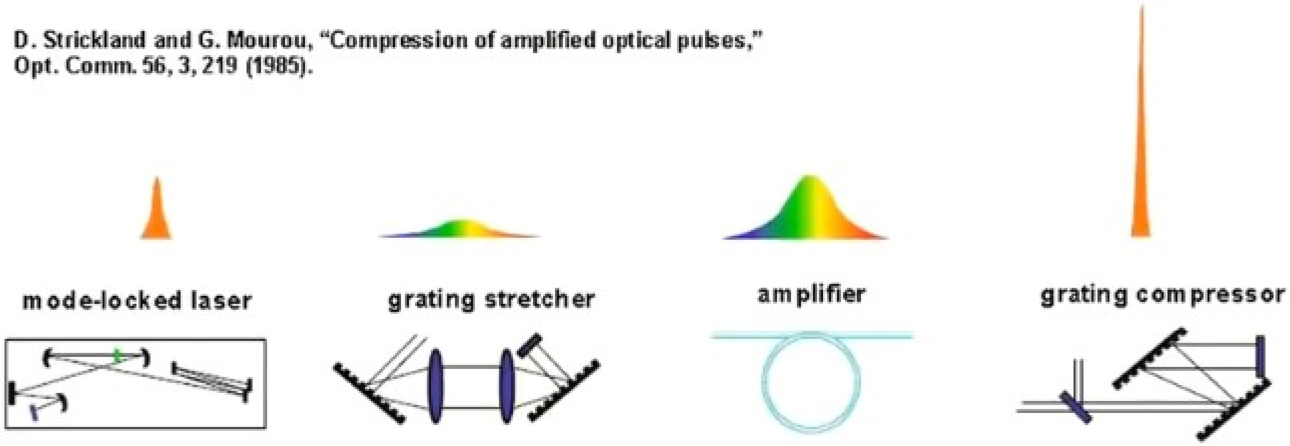
**Simulated autocorrelation traces**




→ Reduction of pulse quality

# Chirped Pulse Amplification (CPA)

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

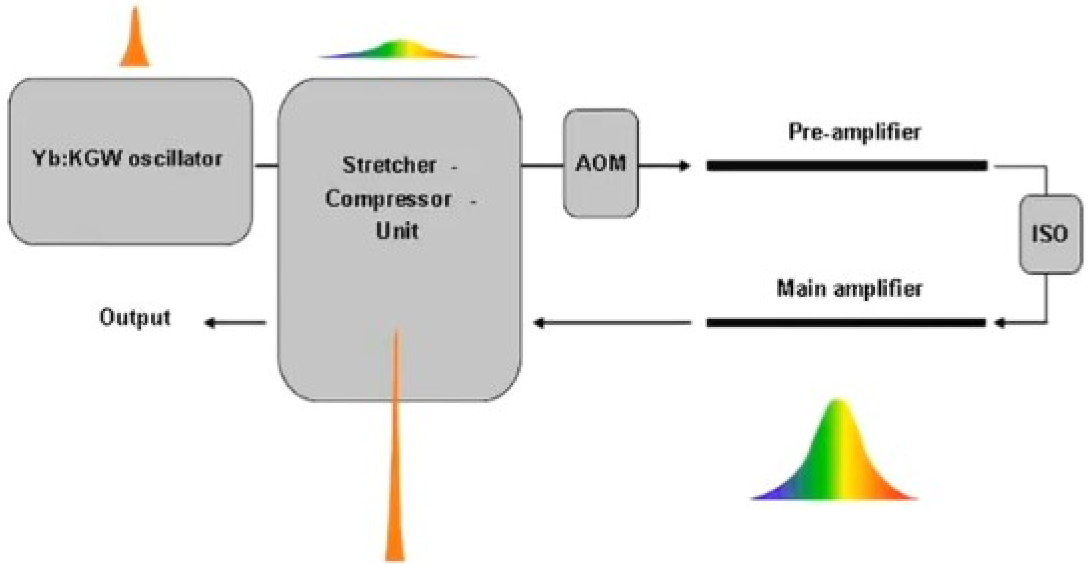



→ reduced pulse peak power during amplification

→ reduced nonlinearity
enhanced damage threshold

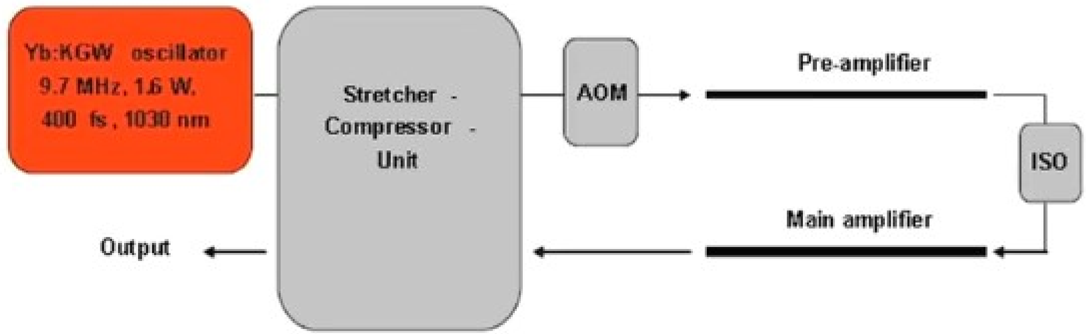
# State of the art FCPA System

## Schematic Setup



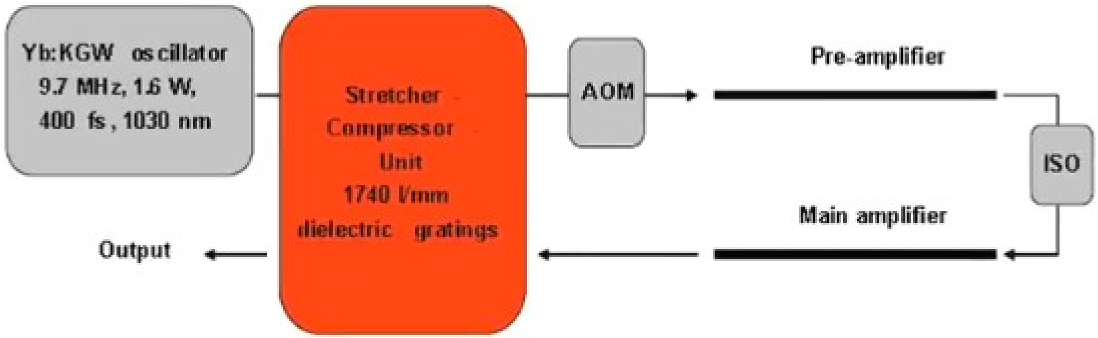
# State of the art FCPA System

## Schematic Setup



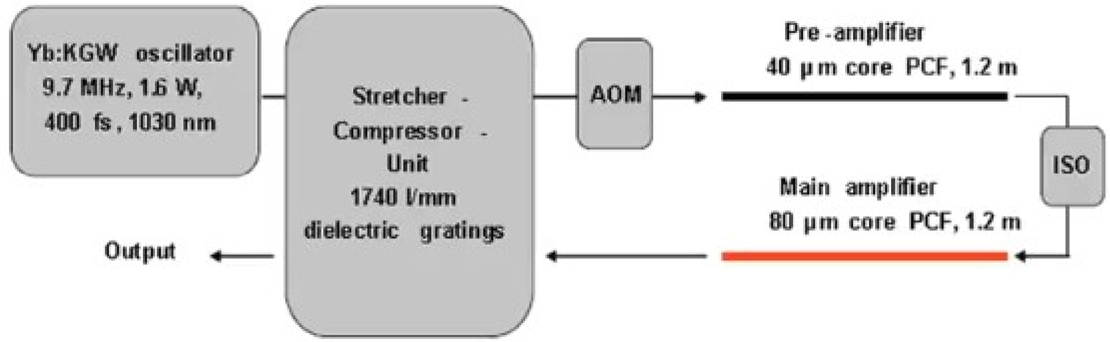
# State of the art FCPA System

## Schematic Setup



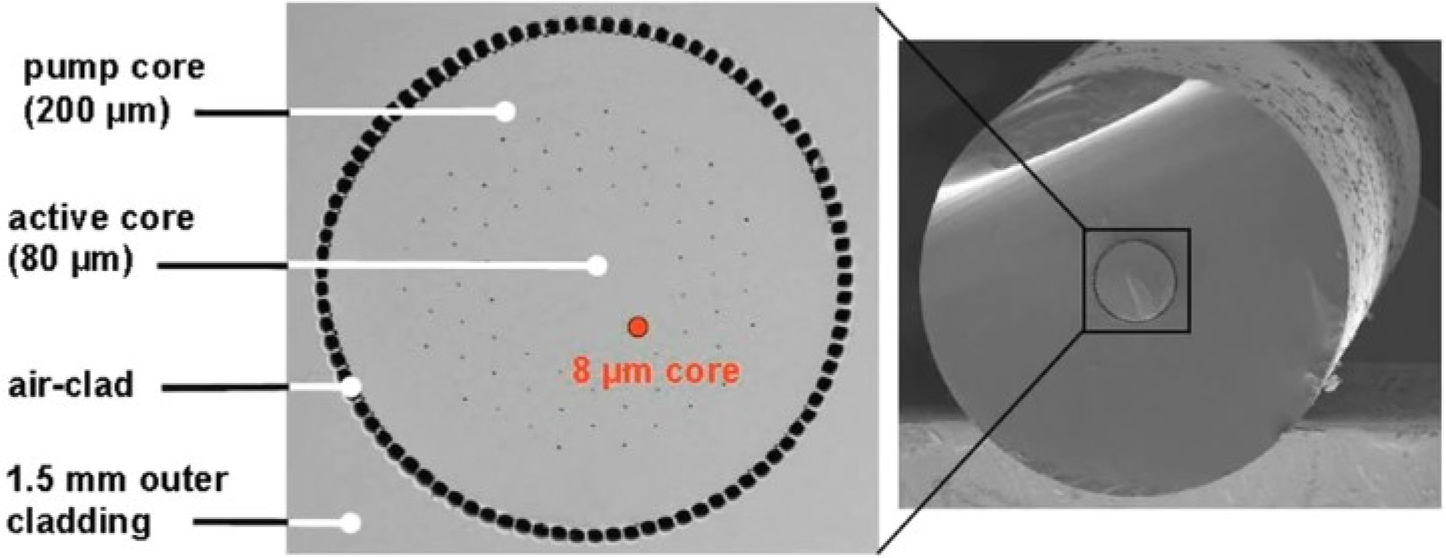
# State of the art FCPA System

## Schematic Setup



# State of the art FCPA System

## Rod-type photonic crystal fiber



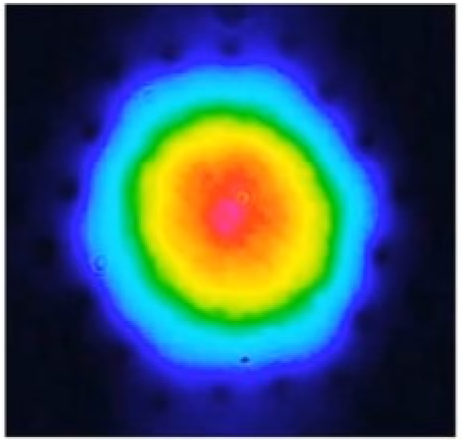

High pump light absorption (30dB/m) -> short fiber length
+ large mode area ( >100x of standard fiber) -> ultralow Nonlinearity

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

## State of the art FCPA System

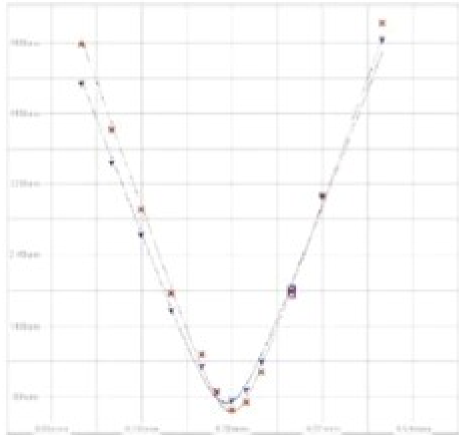
200/80 Rod-type PCF, 1.2m length

Near field image



$MFD = 71\ \mu m$
$\rightarrow MFA \sim 4000\ \mu m^2$

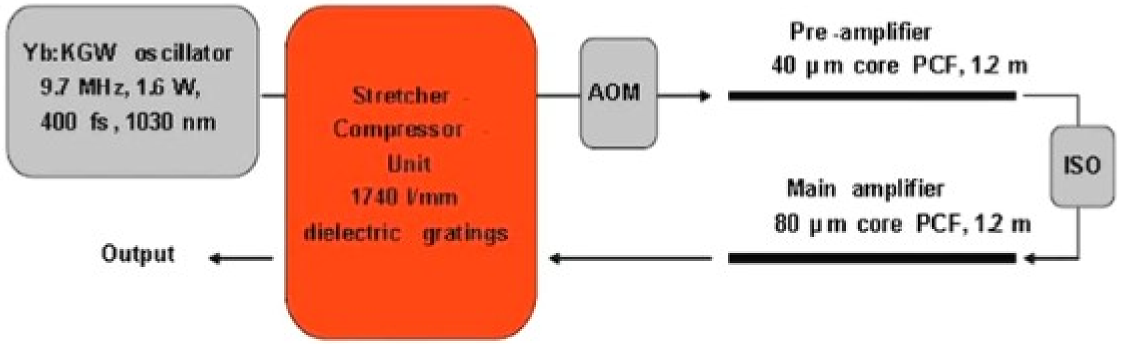
Beam quality-measurement



$M^2_x = 1.17$ , $M^2_y = 1.26$
(Spiricon™, $4\sigma$ method)

# State of the art FCPA System

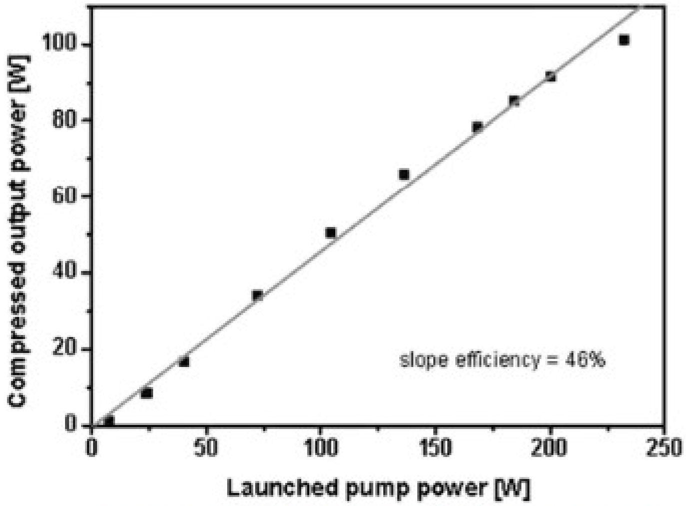
## Schematic Setup

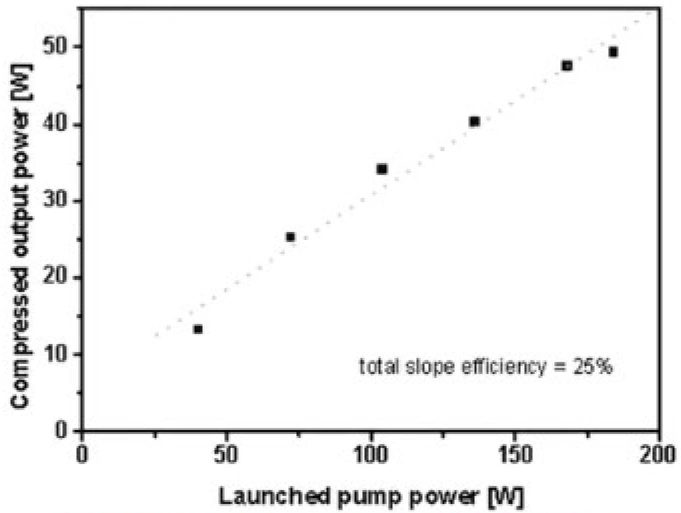



- multilayer dielectric reflection gratings – average power scalable
- 70% compressor throughput efficiency

# State of the art FCPA System

## Output characteristics



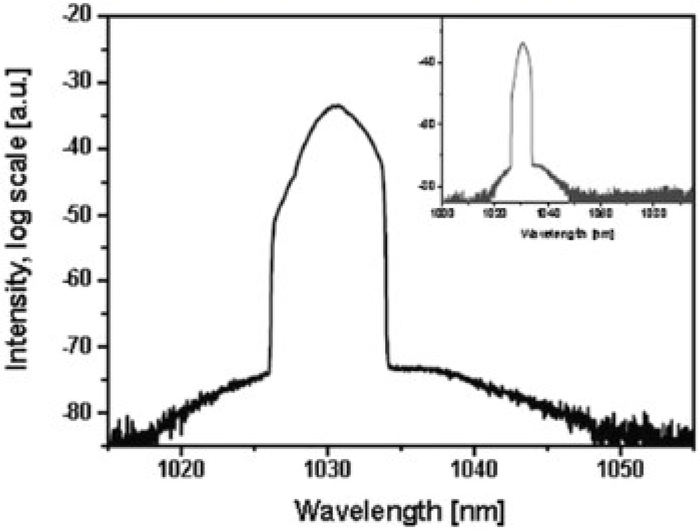




100 W compressed @ 200 kHz
-> 0.5 mJ pulse energy

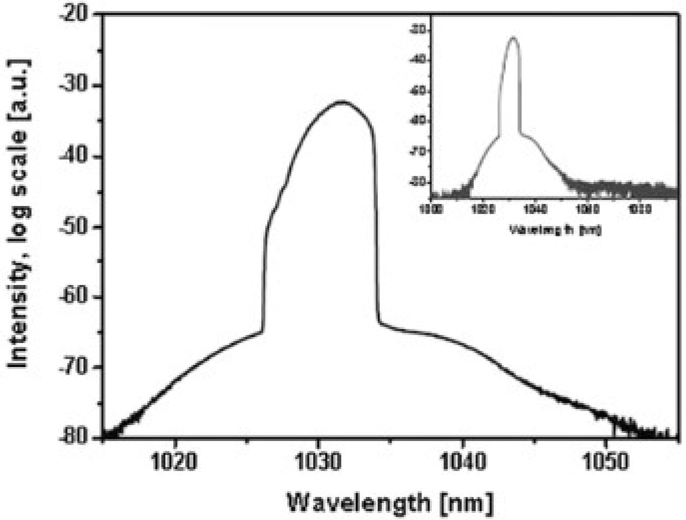
50 W compressed @ 50 kHz
-> 1 mJ pulse energy

# State of the art FCPA System

Spectrum @ highest power

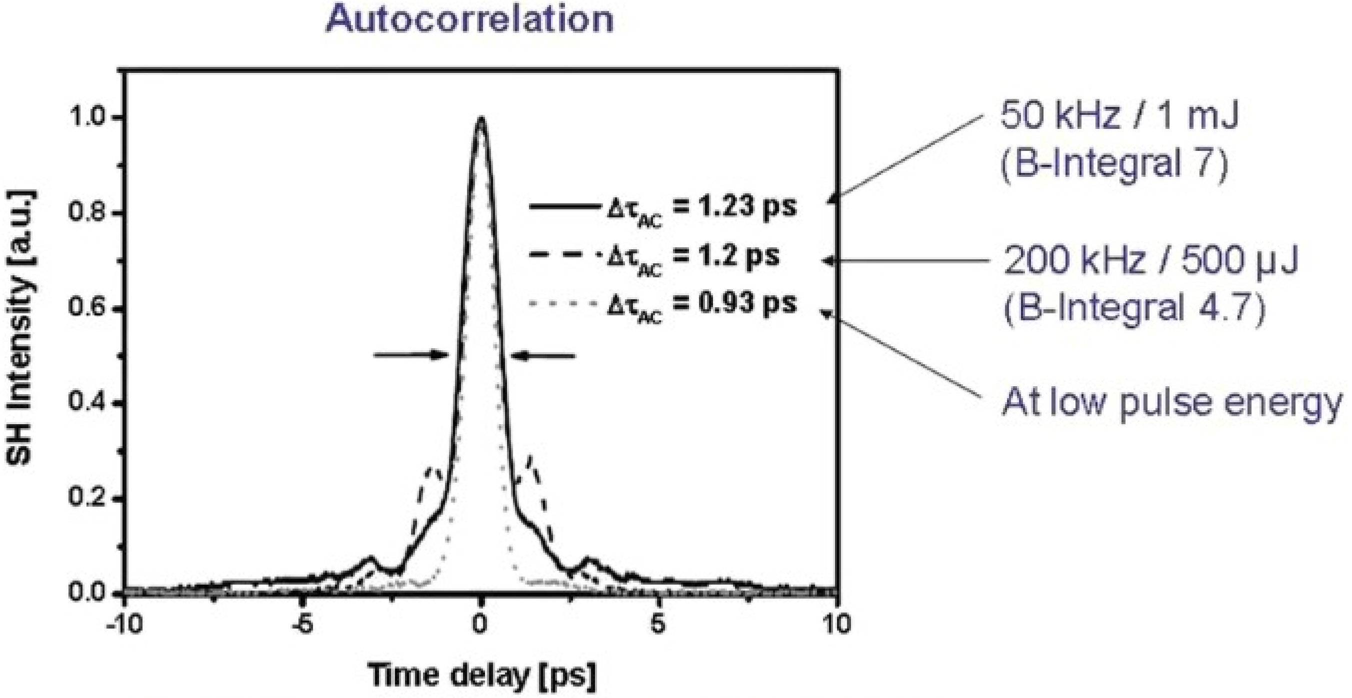



Spectrum @ highest pulse energy




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

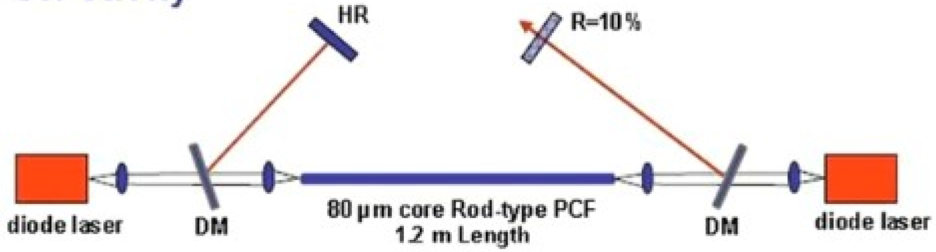
# State of the art FCPA System

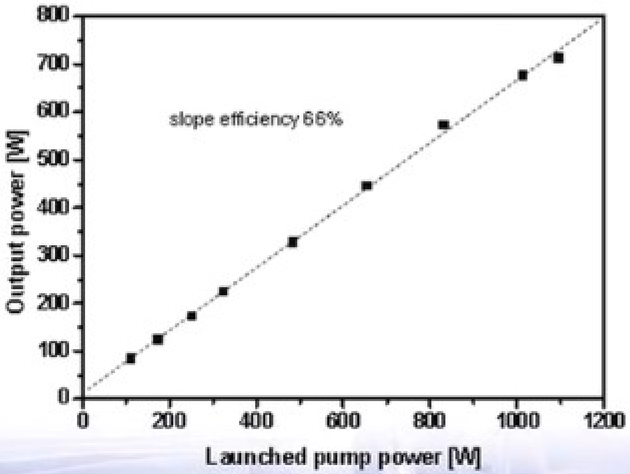



1mJ, 800 fs => pulse peak power ~ 1 GW!

# Average power scalability of main amplifier

Schematic Setup cw cavity



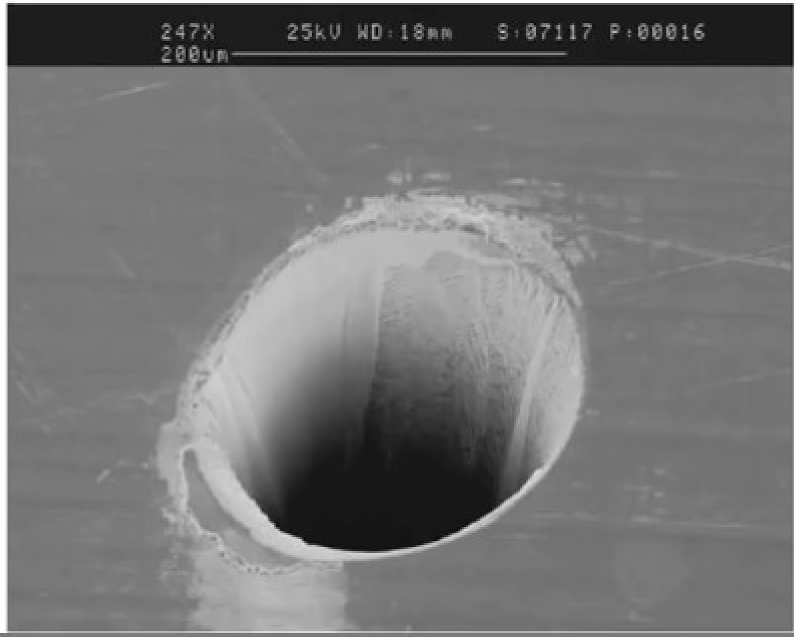




710 W max. output (pump power limited)

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