

28-29 September 2010

**SET-171 Mid-IR Fiber Laser Workshop**

## **Scaling of fiber laser systems based on novel components and high power capable packaging and joining technologies**

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# Outline



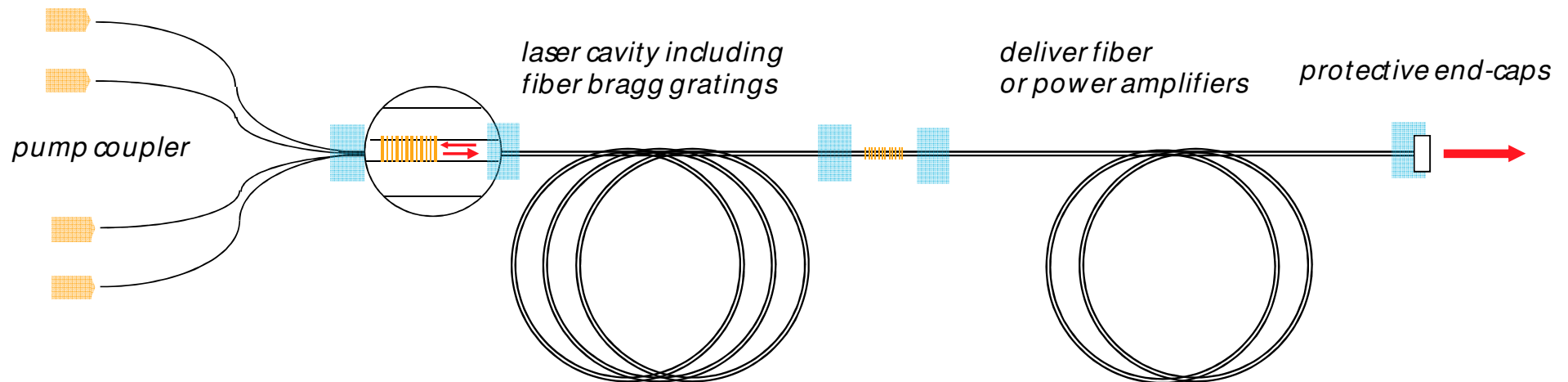
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- introduction
- packaging and joining technologies
  - Application to microchip lasers
- novel components
  - Applications to fiber laser system scaling
- example of MID-IR source
- possible further directions

# Fiber Laser Introduction

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- fiber lasers and amplifiers
  - high gain, excellent and power independent beam quality

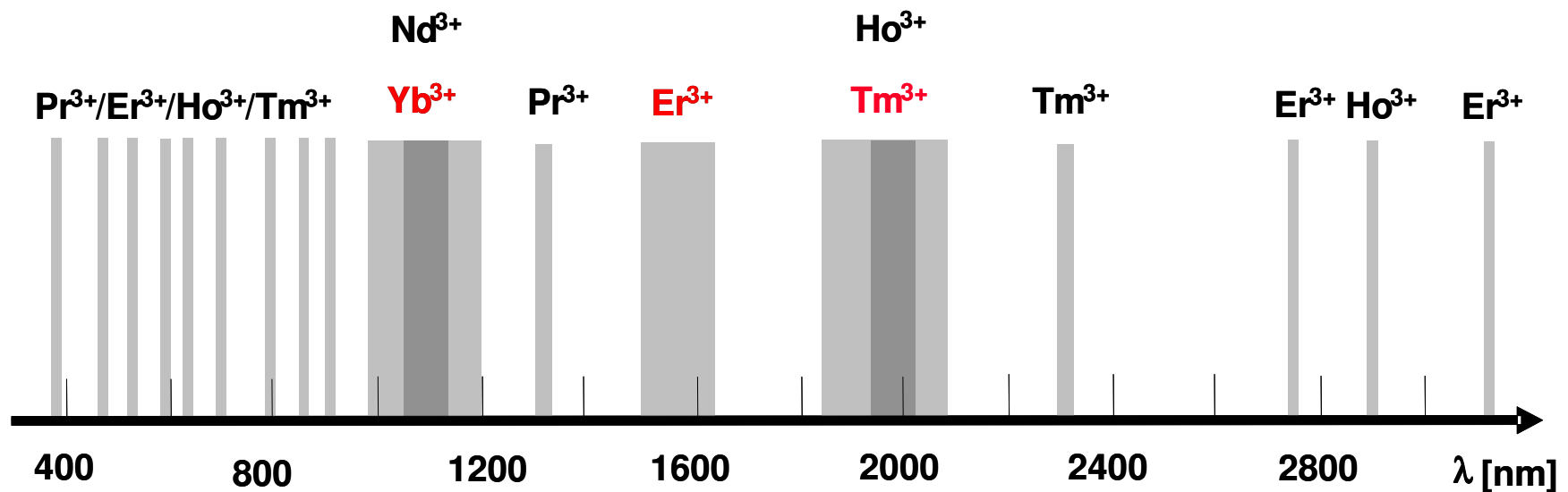


- all fiber setup for stability

# Fiber Laser Introduction

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- rare-earth doped fibers, kW average power levels available



- long wavelength by heavy metal cation fibers (e.g zirconium, ZBLAN fibers), which are not as „stable“ as fused silica)

# Outline



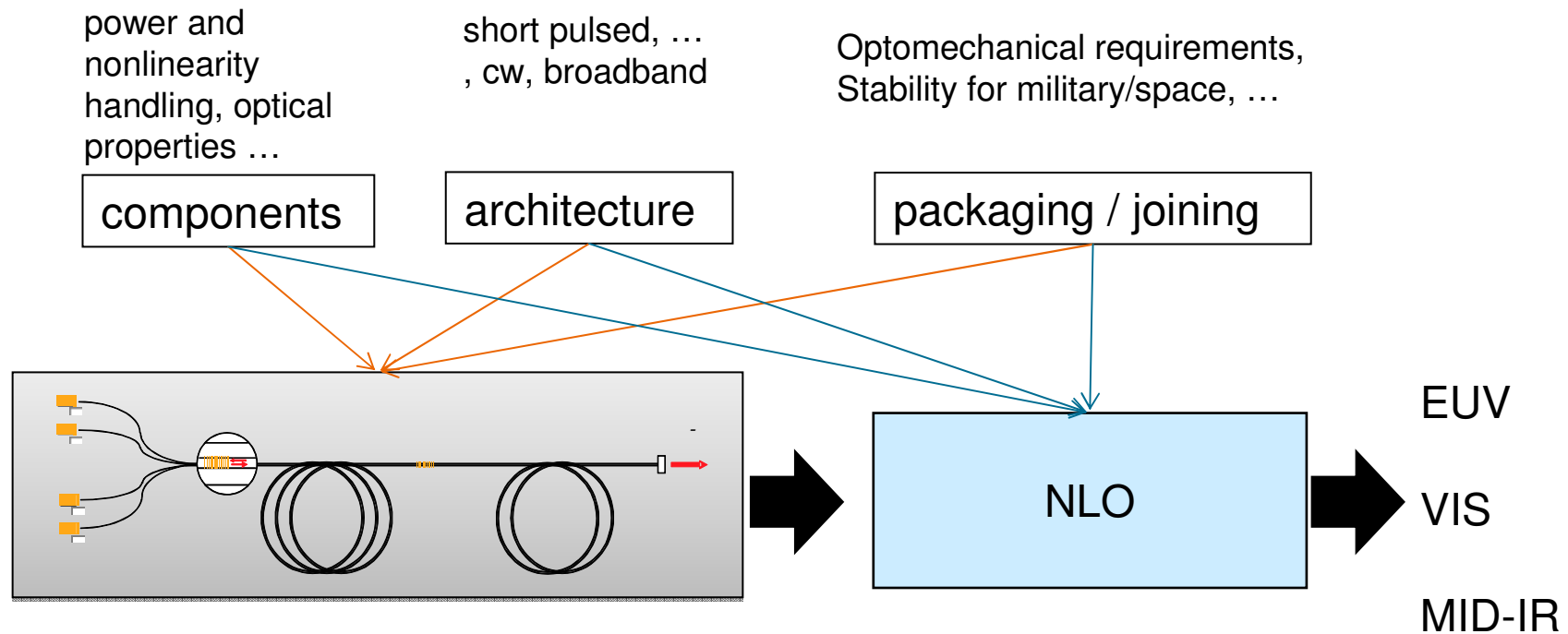
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  - Application to microchip lasers
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# Fiber Laser Introduction

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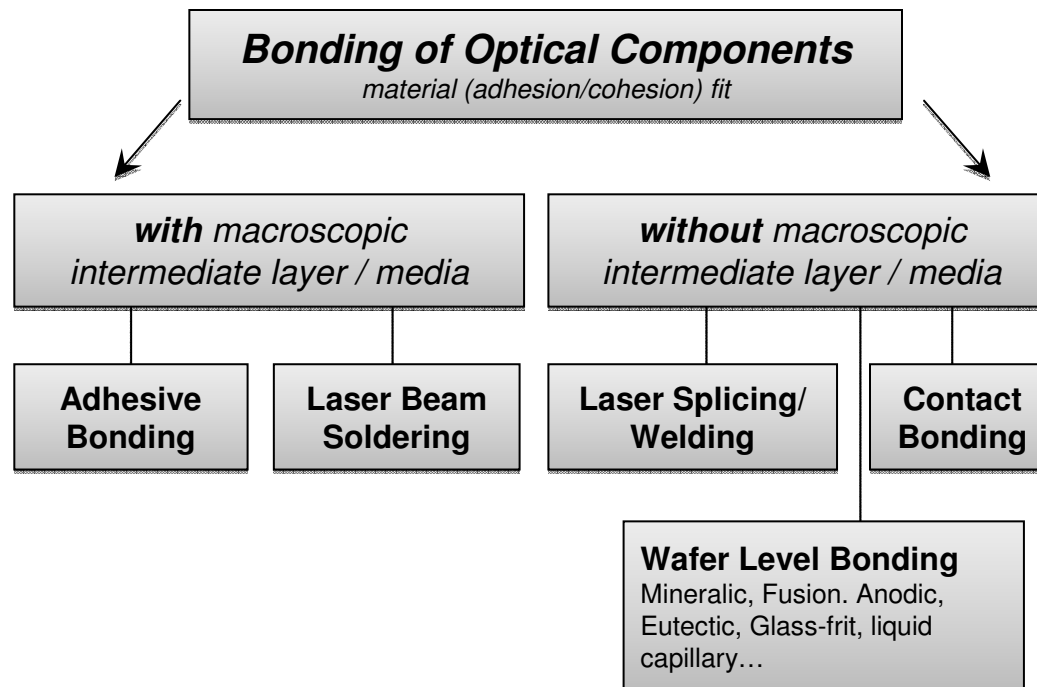
## ■ designing a (Mid-IR) source ...



# Overview of Joining Technologies for Optoelectronic Packaging

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- Bonding of different materials always required
- material , thermal or optical contact desired



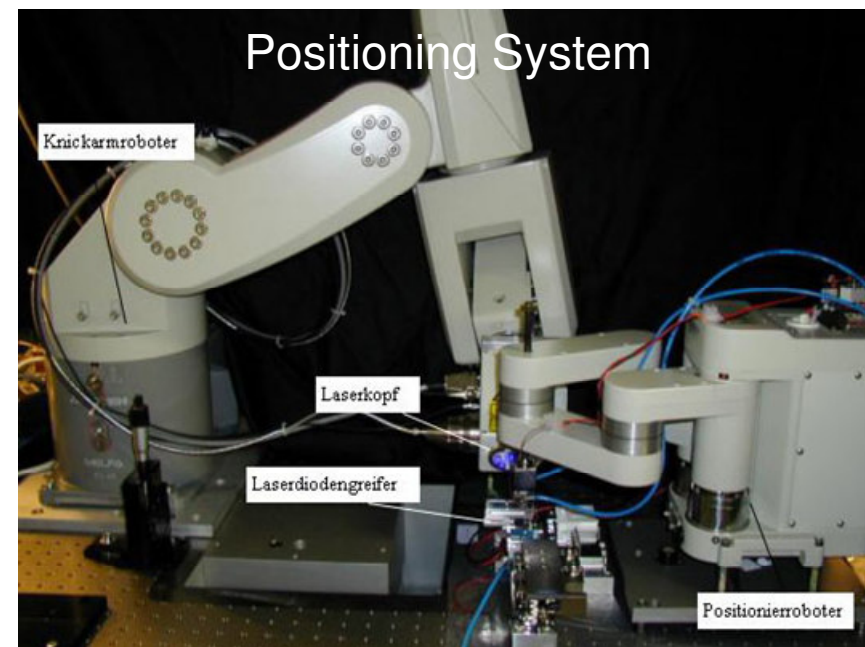
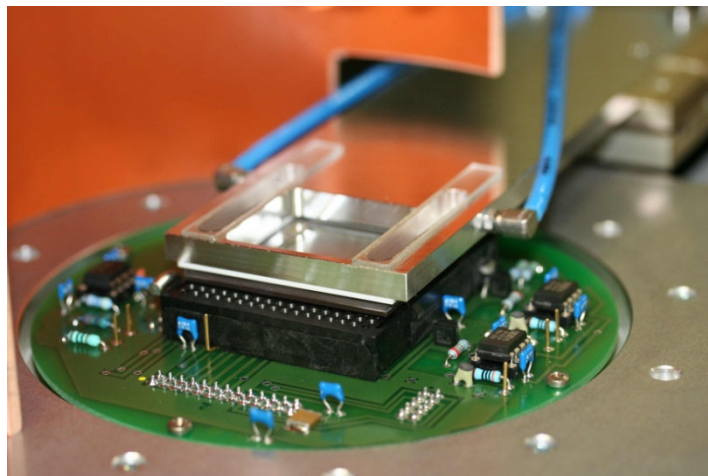


# Bonding and Packaging of Optical Components

## Adhesive Bonding

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- Alignment of a Micro Lens Array to a CCD Sensor
  - 6 degrees of freedom
  - Alignment step wide: 0,1 – 1  $\mu\text{m}$

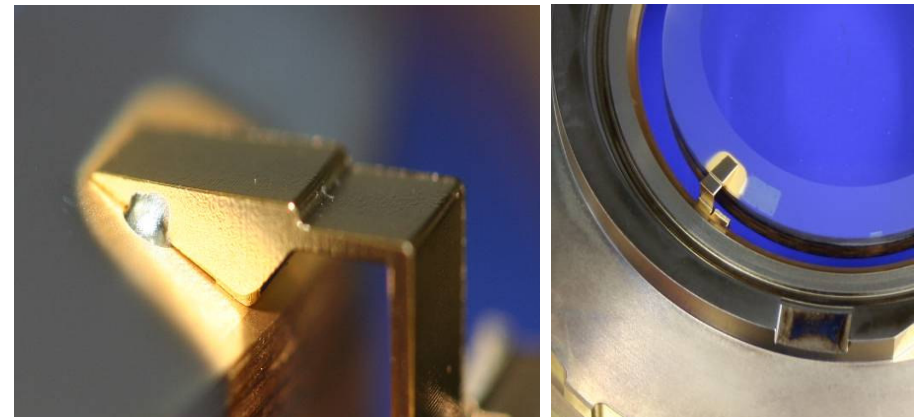


# Bonding and Packaging of Optical Components

## Laser Soldering

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- long term stability
- high temperature stability
- high radiation stability compared to adhesives
- good vacuum compatibility / no outgasing
- high thermal and electrical conductivity
- flux free processing due to sputtered thin film metallization
- flexible and automated assembly



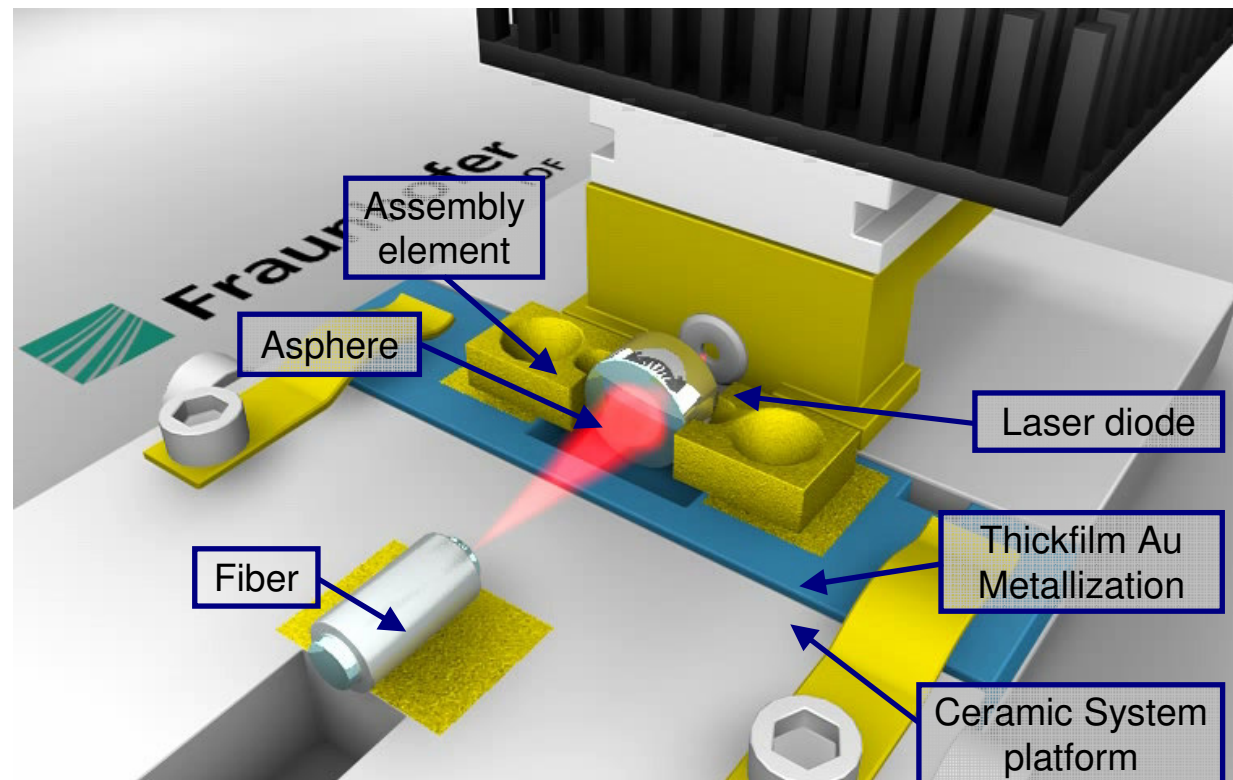
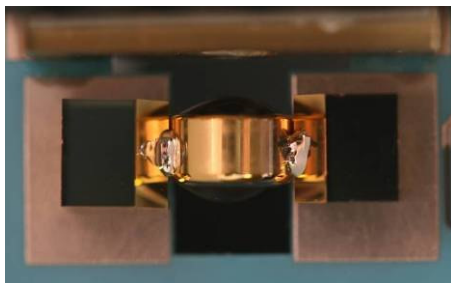
laser beam soldered optics for lithography

# Bonding and Packaging of Optical Components

## Solder Bumping

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- Example of fiber coupled diode

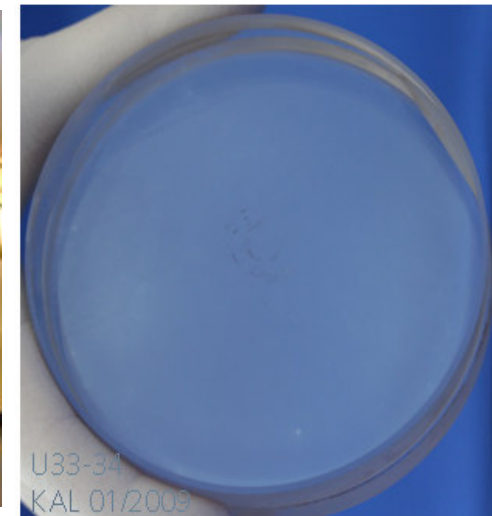
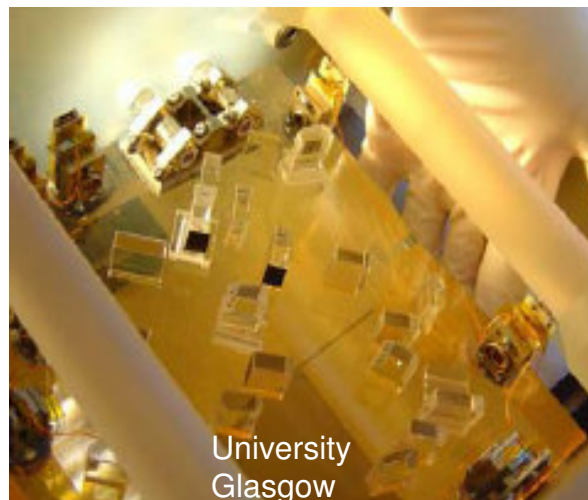
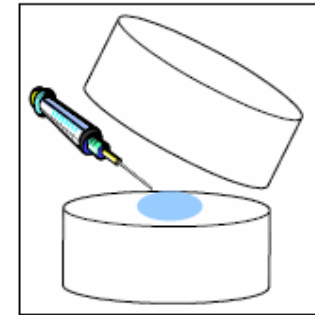


# Bonding and Packaging of Optical Components

## Mineralic Bonding

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- inorganic bonding at low temperatures ( $\leq 200^\circ\text{C}$ ) using special silicate solutions
- e.g. for high precision optical & mechanical systems
- high stability (intermediate layer  $< 200\text{nm}$ )
  - low stress
  - “cold” bonding
  - NO creep
  - NO „out-gassing“



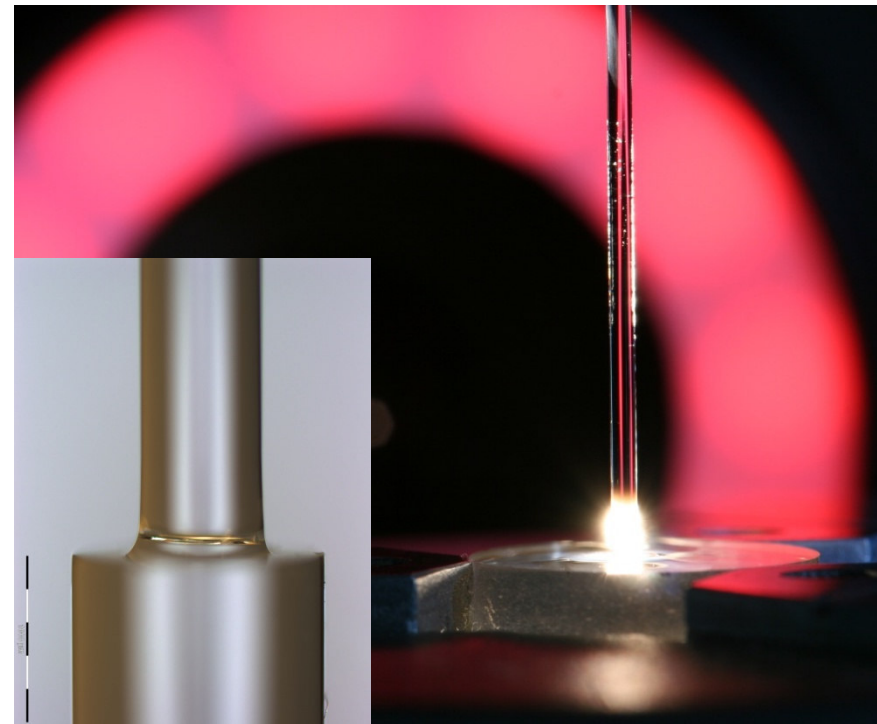


# Bonding and Packaging of Optical Components

## Laser based splicing and tapering

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- Tapering and splicing device as well as process control developed
- easy adaptable
- very precise joints
- computer controlled process with high joining reproducibility
- mechanical stable welded joints
- high purity process without contaminations
- very low optical losses
- no consumables like process gas or filaments



Multimode fiber ( $\varnothing 720\mu\text{m}$ ) with spliced end cap ( $\varnothing 1500\mu\text{m}$ )

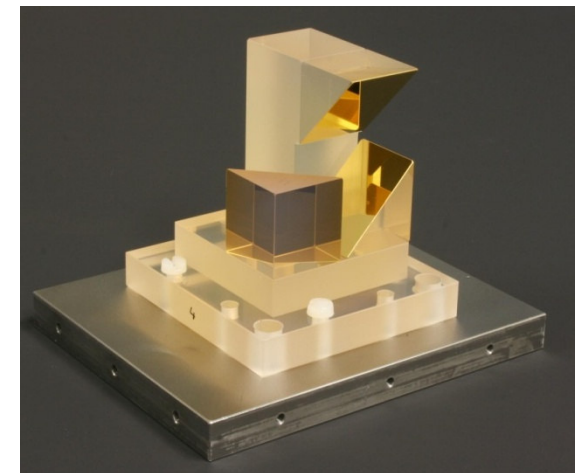
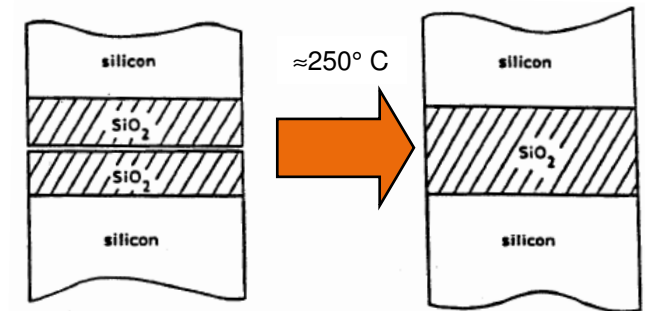
# Bonding and Packaging of Optical Components

## Direct bonding

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- Without additional material – surface activation
- direct bond by a Waals forces
- very small tolerances
- joints are sensitive to shock
- adjustment only within the plane of joining
- assemblies tested under vacuum and cryogenic environment

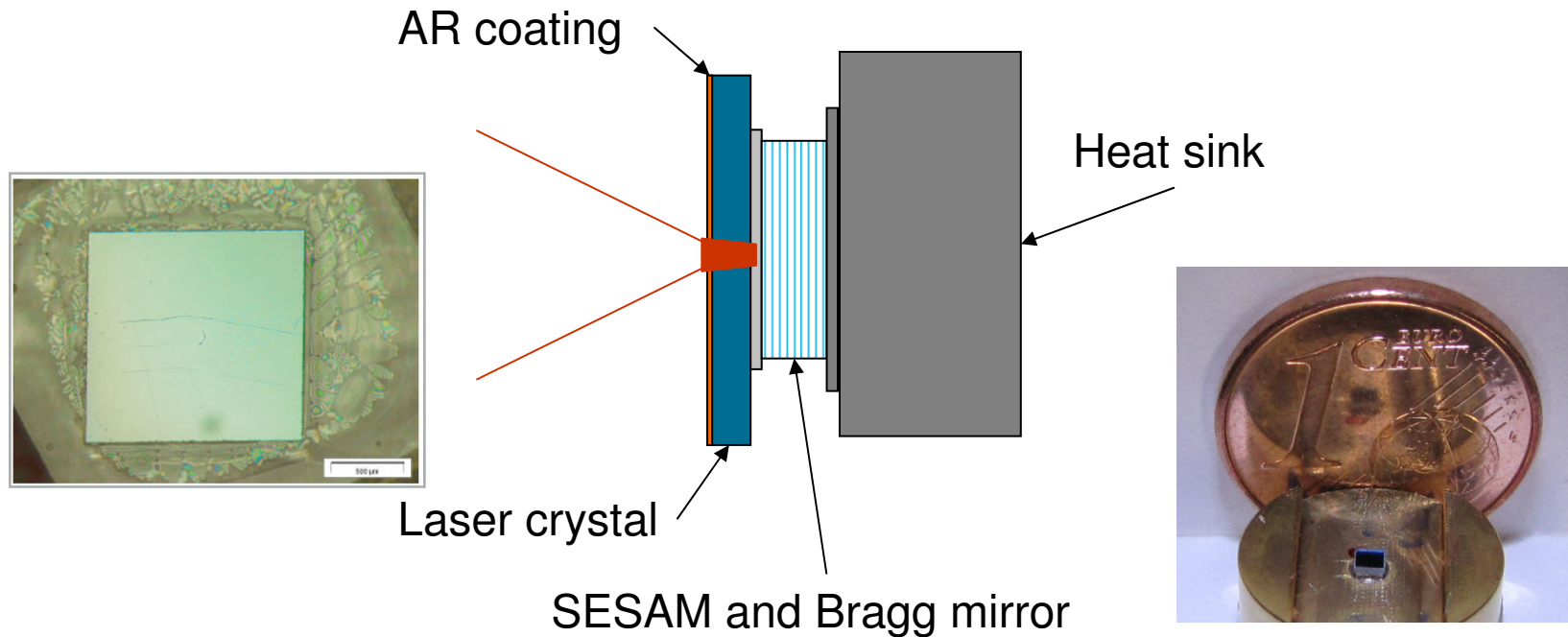


# Scaling of fiber laser systems

## Novel components and laser systems

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### ■ Microchip laser system using bonding technology

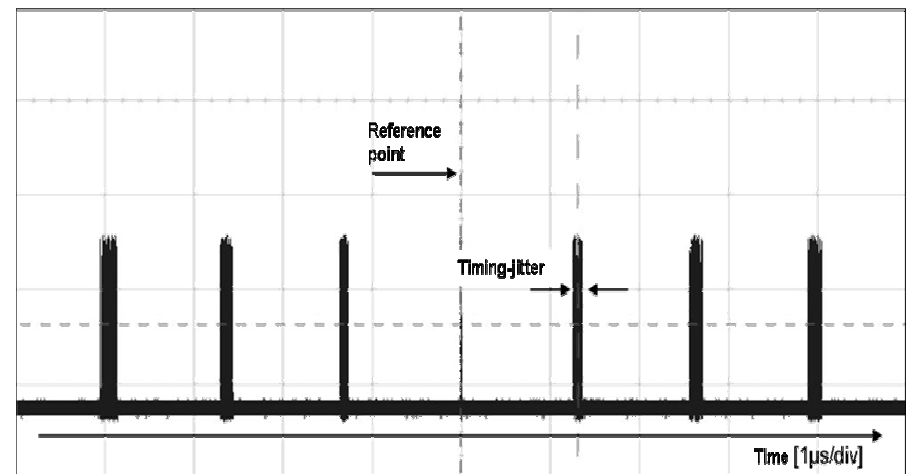
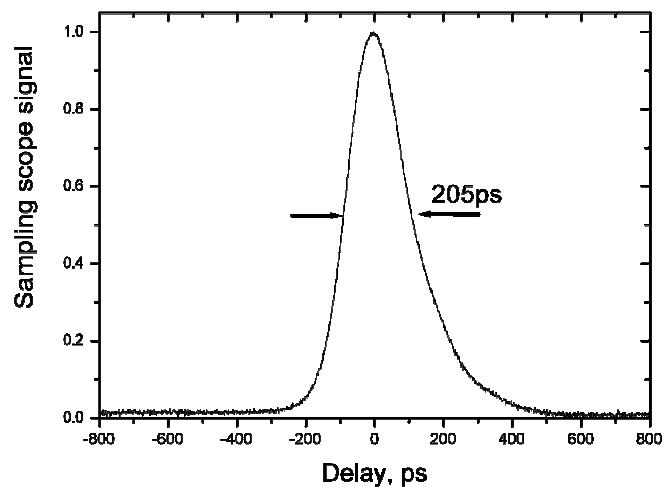


# Scaling of fiber laser systems

## Novel components and laser systems

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- Microchip laser system using bonding technology
  - Unwanted jitter (typical for Q-switched lasers)



200 ps, Slope efficiency of  $\sim 35\%$ ,  $E_p = 120 - 140$  nJ, Repetition rate up to 2 MHz

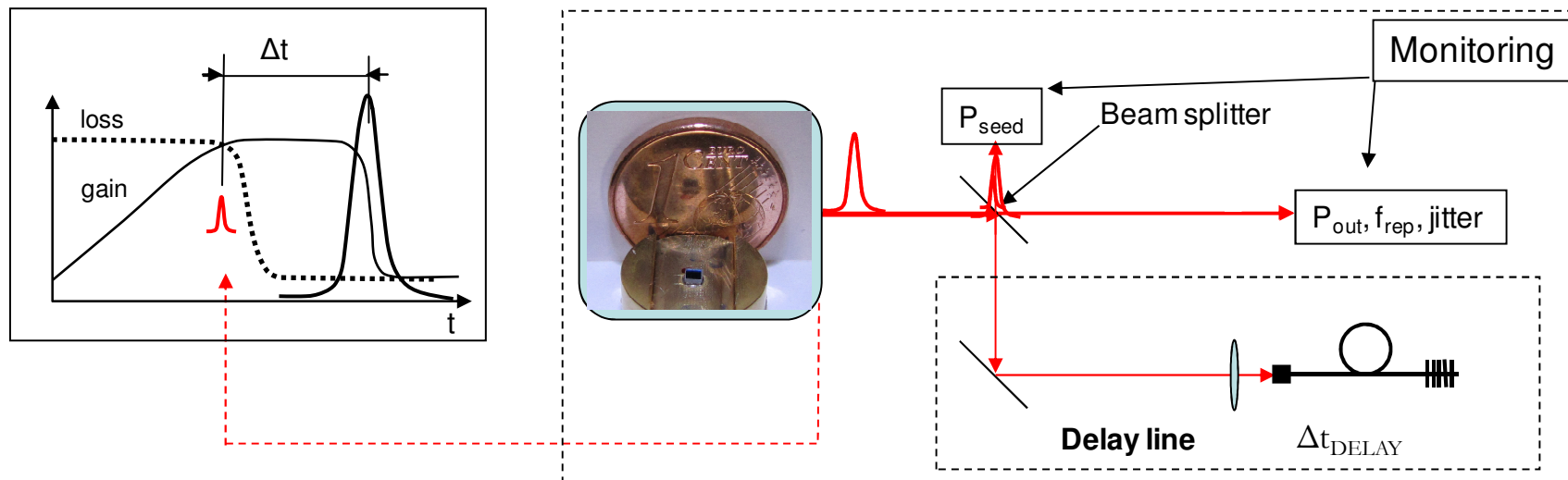


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## Novel components and laser systems

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- Microchip laser system using bonding technology
  - Unwanted jitter (typical for Q-switched lasers)
  - Self-injection seeding



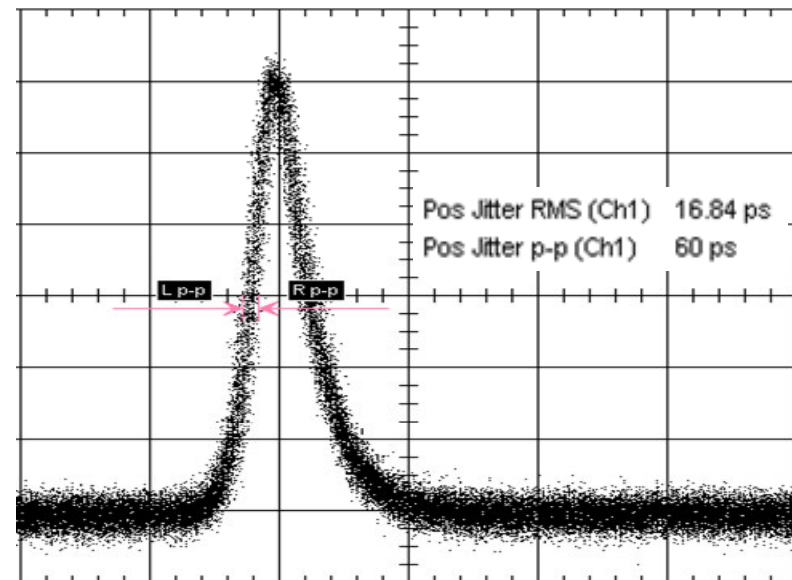
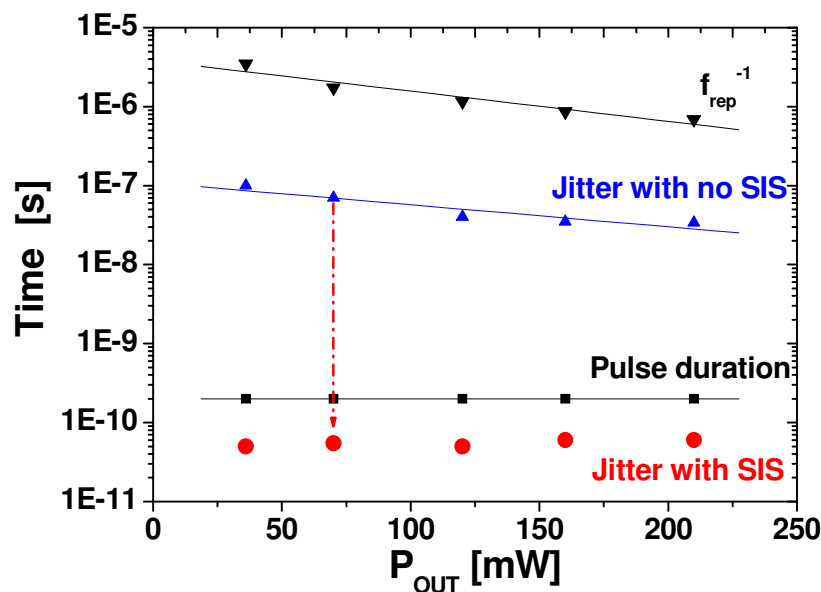
A. Steinmetz et al. *Applied Physics B* (2009) 97: 317–320

# Scaling of fiber laser systems

## Novel components and laser systems

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- Microchip laser system using bonding technology
  - Unwanted jitter (typical for Q-switched lasers)
  - Self-injection seeding
  - Low cost alternative to mode-locked lasers



# Outline



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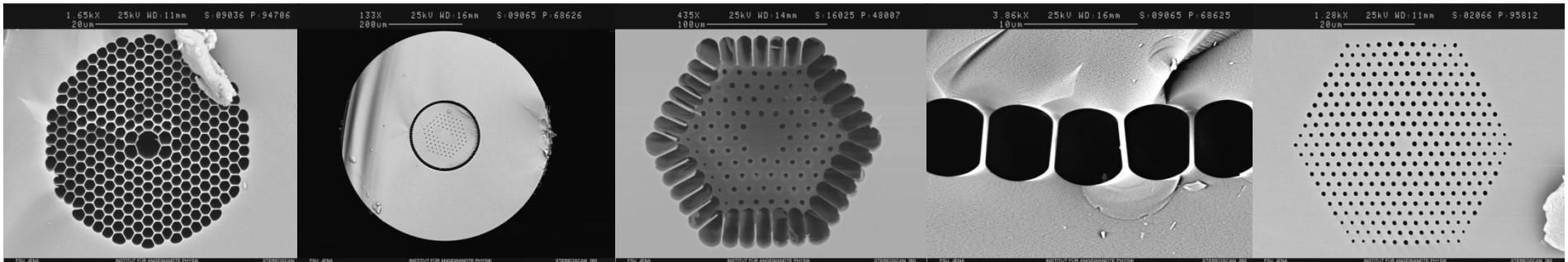
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- packaging and joining technologies
  - Application to microchip lasers
- **novel components**
  - Applications to fiber laser system scaling
- example of MID-IR source
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# Scaling of fiber laser systems

## Novel components and laser systems

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- components:
  - novel fiber designs



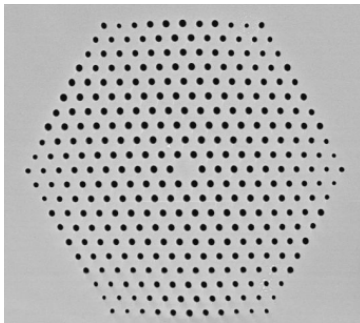
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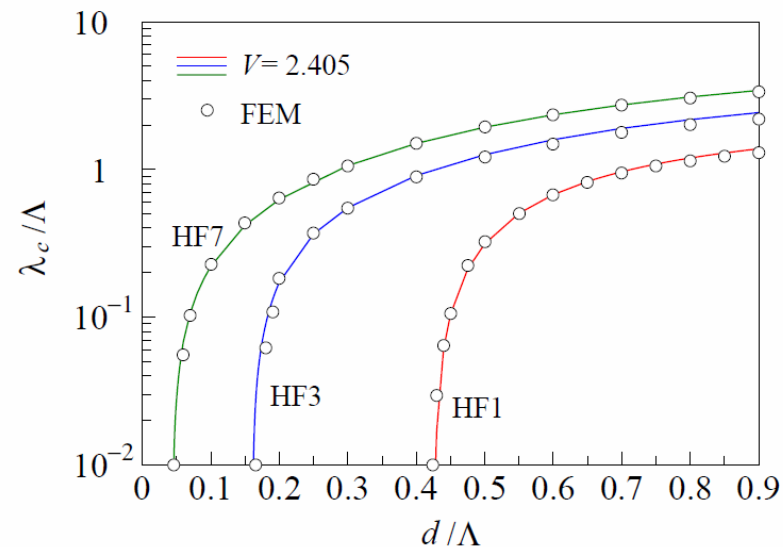
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- components:
  - novel fiber designs = novel optical properties

### endlessly single mode



- MFD independent of  $\lambda$
- SM from 0.5 to 2.5  $\mu\text{m}$



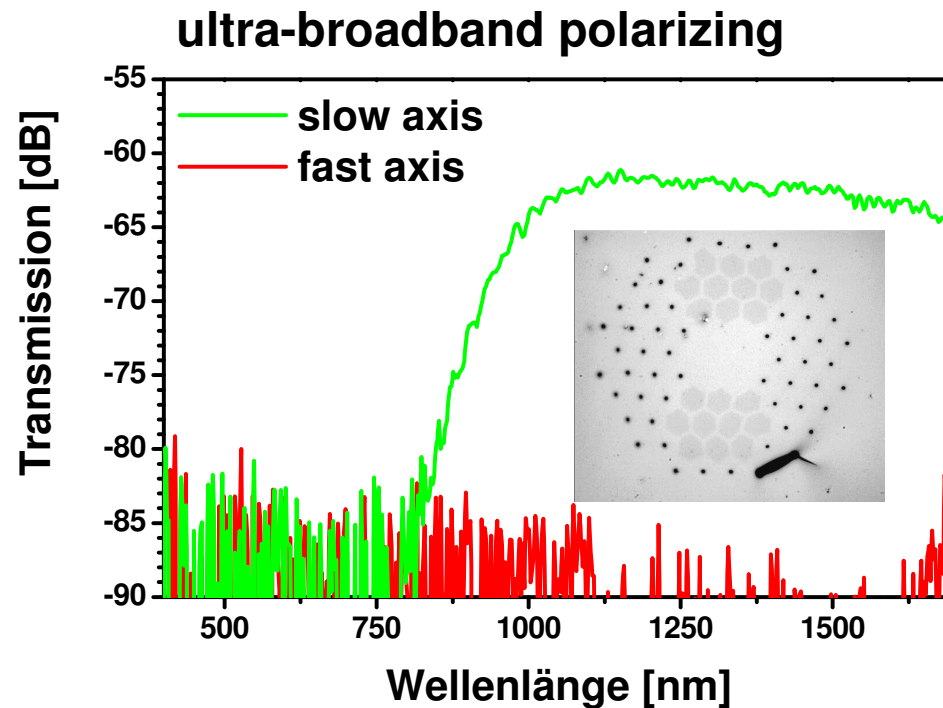
Kunimasa Saitoh, Yukihiro Tsuchida, Masanori Koshiba, and Niels Asger Mortensen, "Endlessly single-mode holey fibers: the influence of core design," Opt. Express **13**, 10833-10839 (2005)

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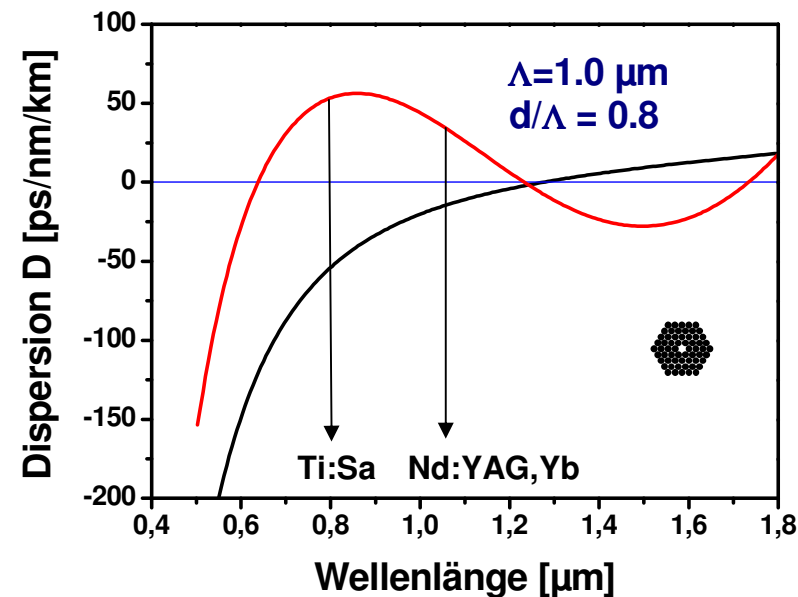
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## Novel components and laser systems

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**extremely large dispersion shifts**



**enhanced nonlinearity**

$$A_{\text{eff}} \sim 1..2 \mu\text{m}^2$$

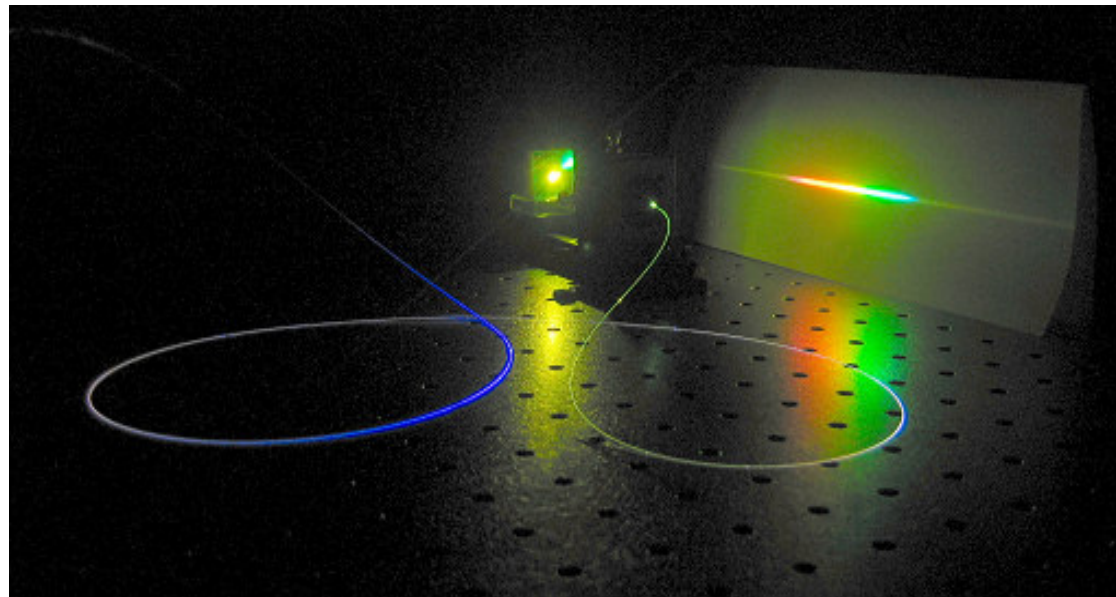
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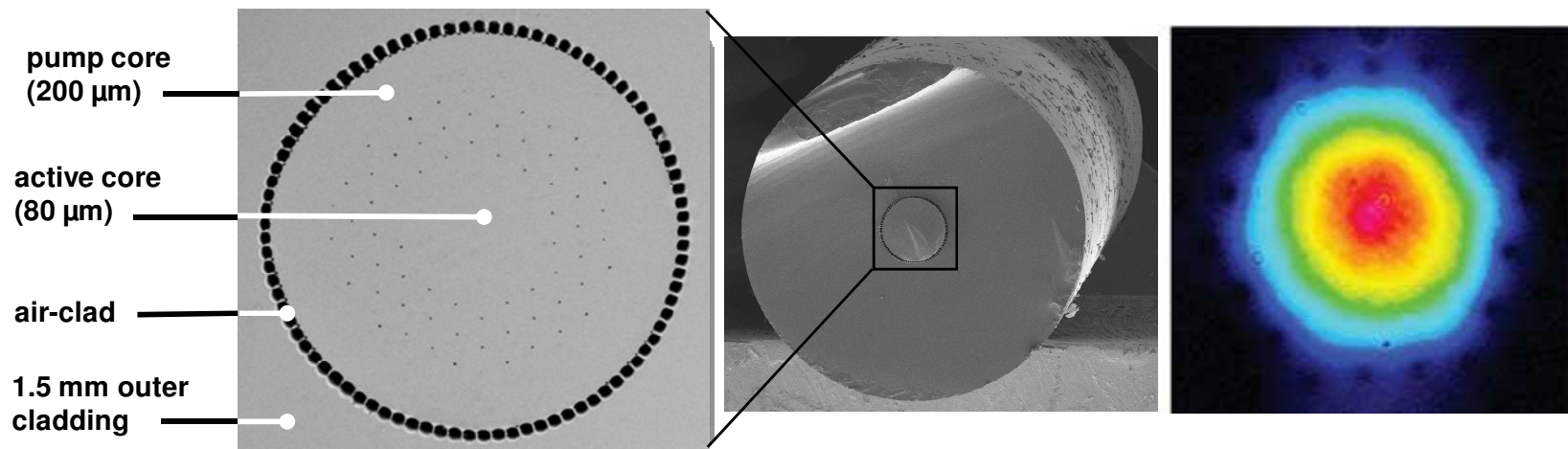
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**extremely low nonlinear interaction**



# Scaling of fiber laser systems

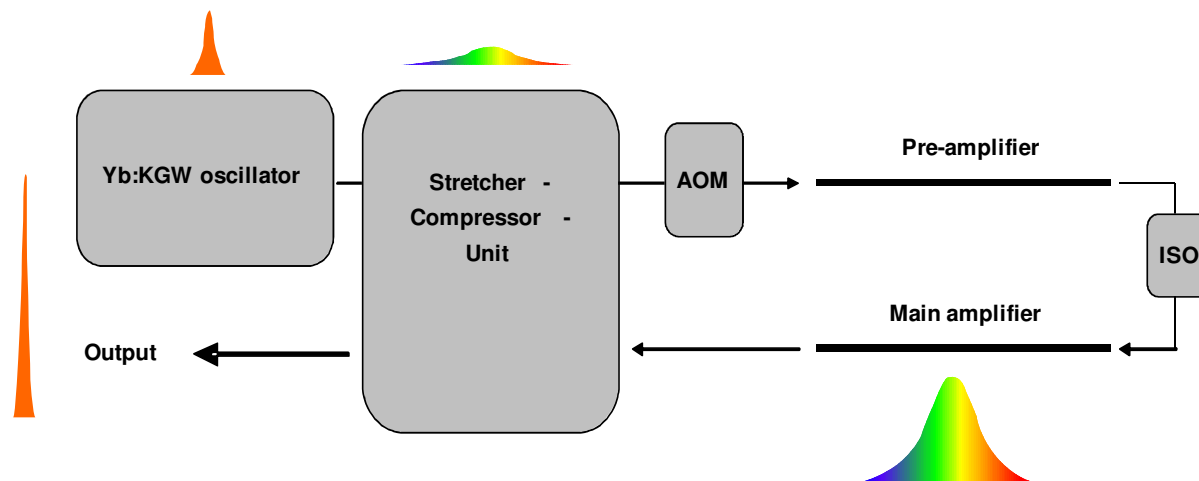
## Novel components and laser systems

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### ■ components:

- novel fiber designs = novel optical properties

**extremely low nonlinear interaction**



- First GW fiber femtosecond system
- First kW average power fiber femtosecond system

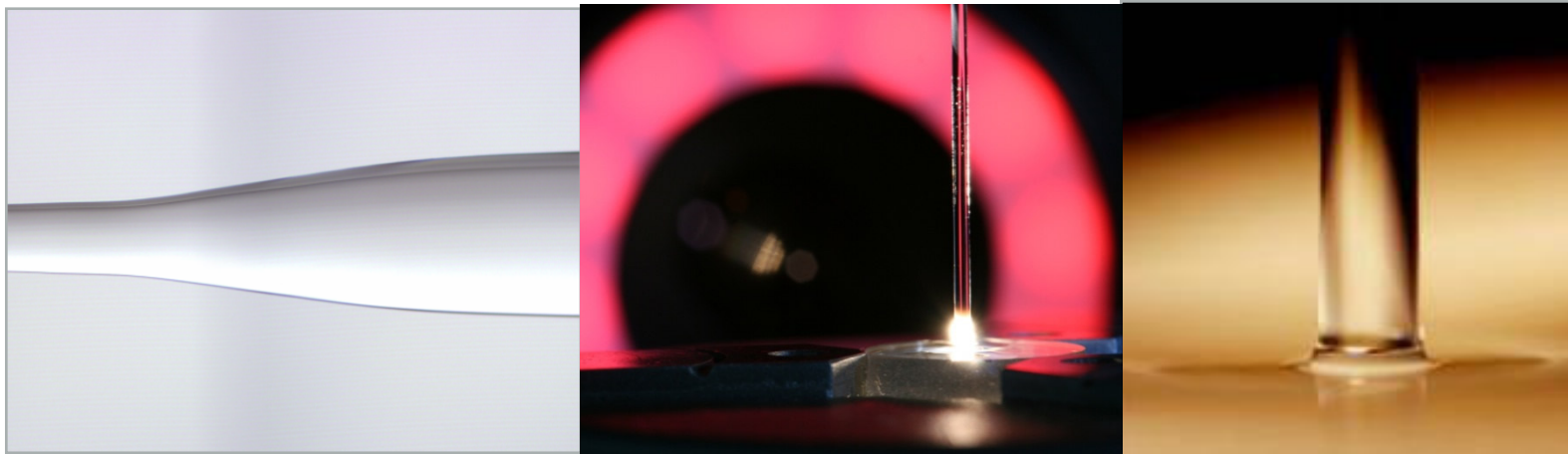
# Scaling of fiber laser systems

## Novel components and laser systems

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- components:
  - novel fiber designs = novel optical properties
  - fiber compatible components

### tapers and endcaps



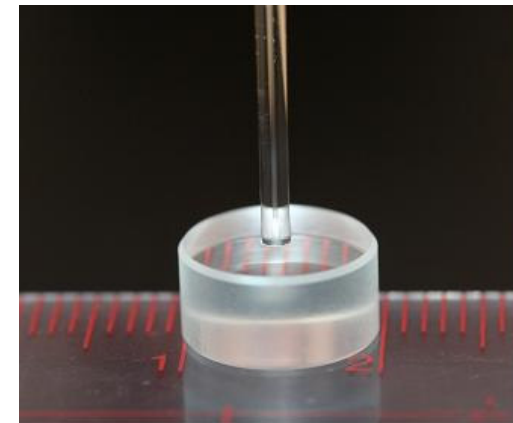
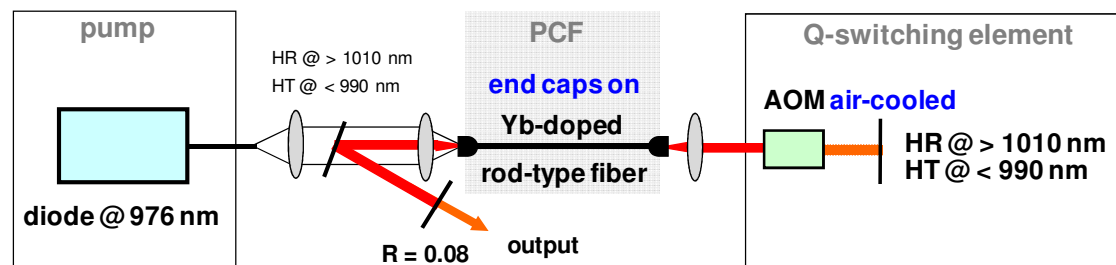
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- mJ, ns fiber laser systems

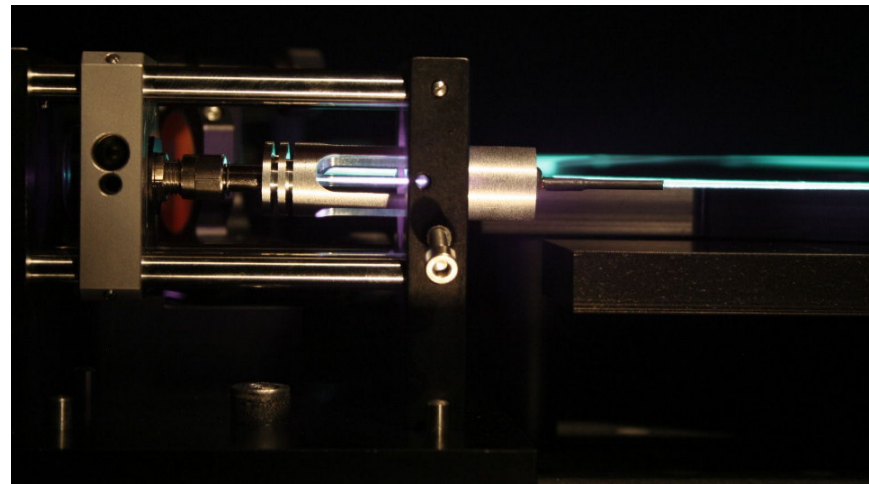
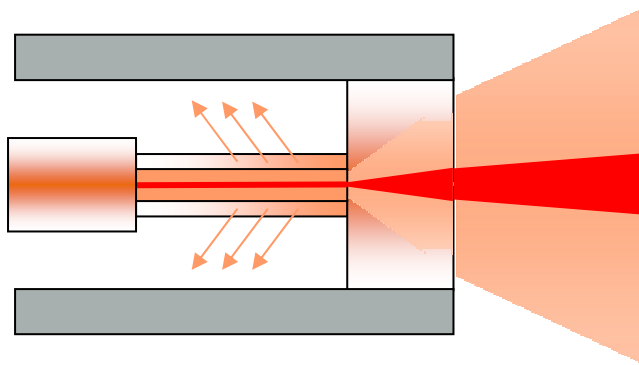
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### mode-stripper and high power connector



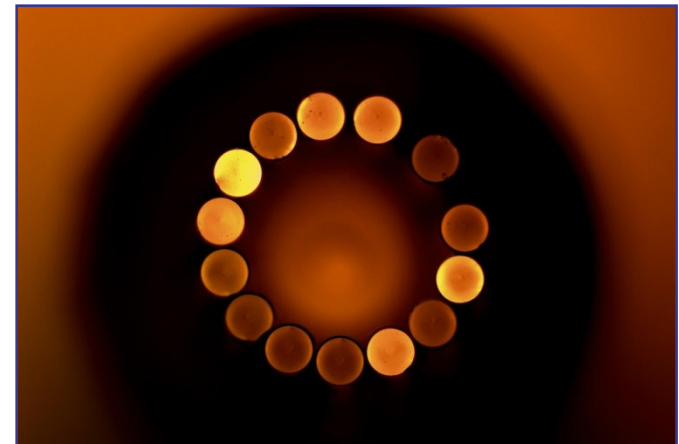
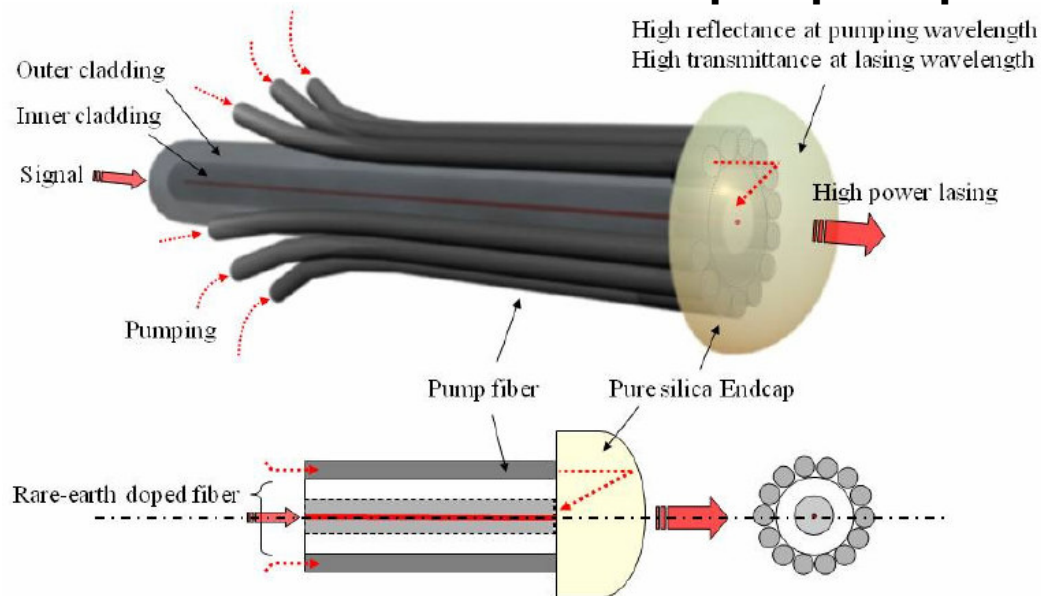
# Scaling of fiber laser systems

## Novel components and laser systems

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- components:
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### Novel pump couplers



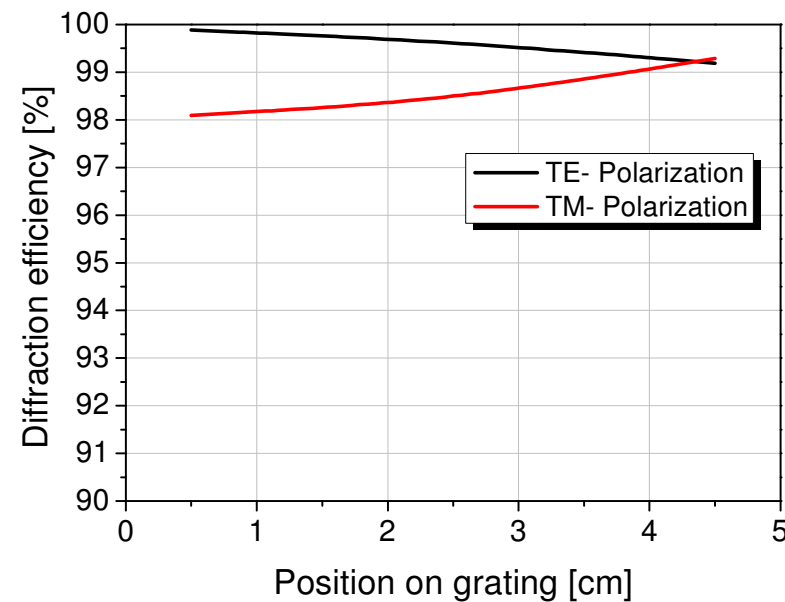
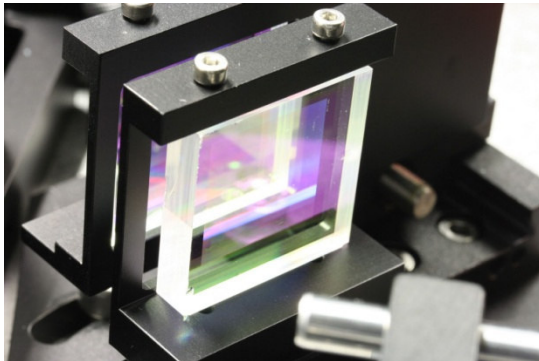


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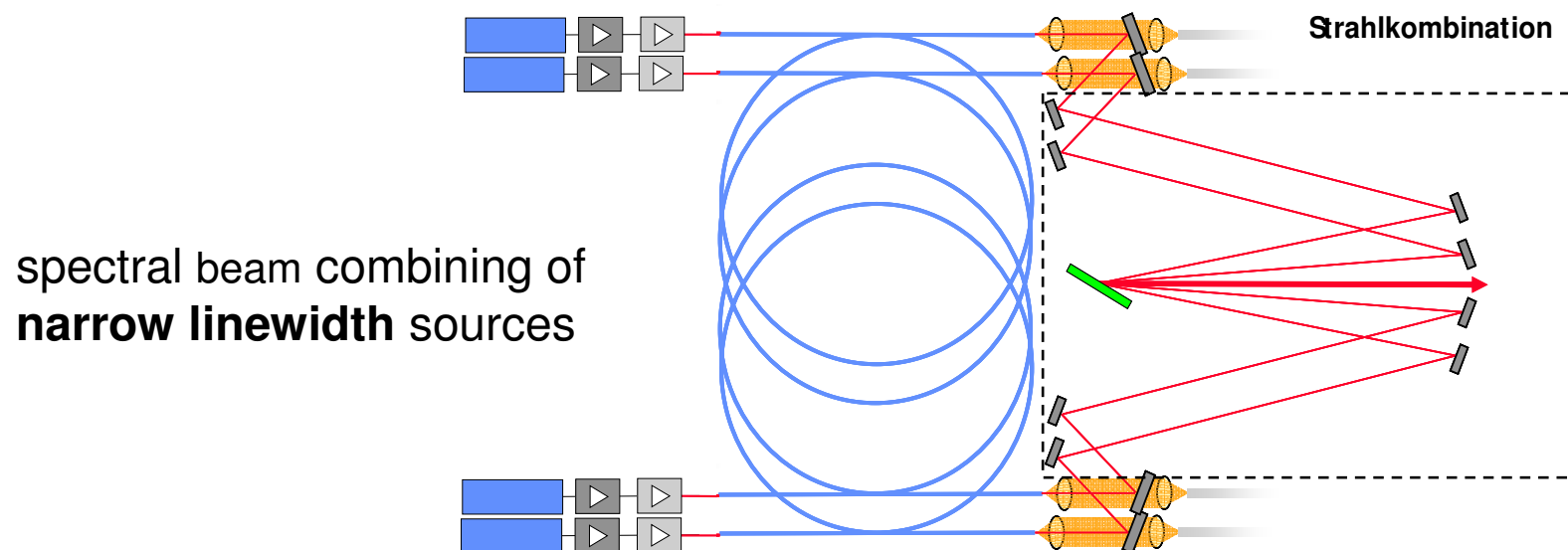


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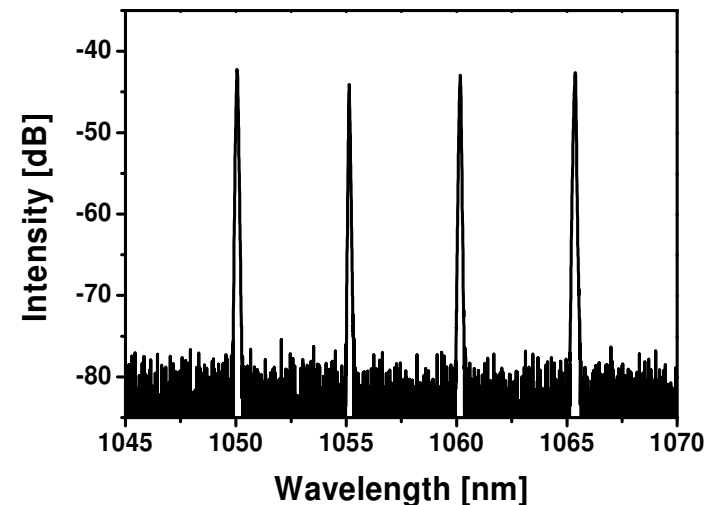
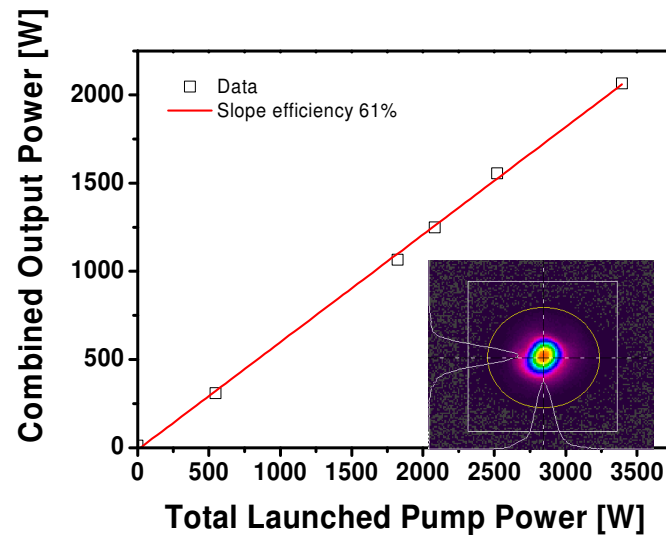


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C. Wirth, O. Schmidt, I. Tsybin, T. Schreiber, T. Peschel, F. Brückner, T. Clausnitzer, J. Limpert, R. Eberhardt, A. Tünnermann, M. Gowin, E. ten Have, K. Ludewigt, and M. Jung, "2 kW incoherent beam combining of four narrow-linewidth photonic crystal fiber amplifiers," Opt. Express 17, 1178-1183 (2009)

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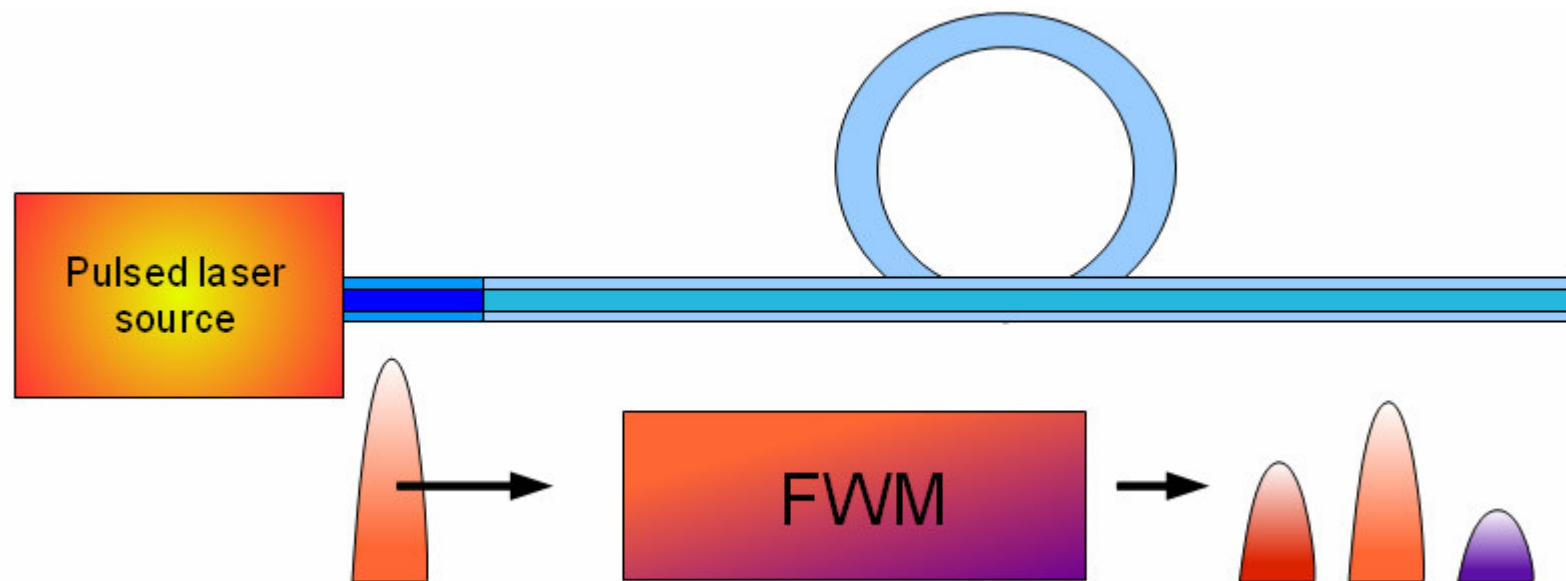
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- possible further directions
- summary

# Scaling of fiber laser systems

## Novel components and laser systems

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- Approach for a fiber based picosecond VIS and MIR source



# Scaling of fiber laser systems

## Novel components and laser systems

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- Approach for a fiber based picosecond VIS and MIR source

### Degenerated FWM

a)	$2\omega_1 = \omega_2 + \omega_3$	Energy conservation
b)	$2k_{\text{pump}} = k_{\text{signal}} + k_{\text{idler}} + \gamma P_1 = 0$	momentum conservation
c)	Low losses at $\omega_1$ , $\omega_2$ and $\omega_3$	No attenuation of the waves
d)	$\text{MFD}_{\text{Signal}} \approx \text{MFD}_{\text{Pump}} \approx \text{MFD}_{\text{Idler}}$	Good overlap of the involved waves

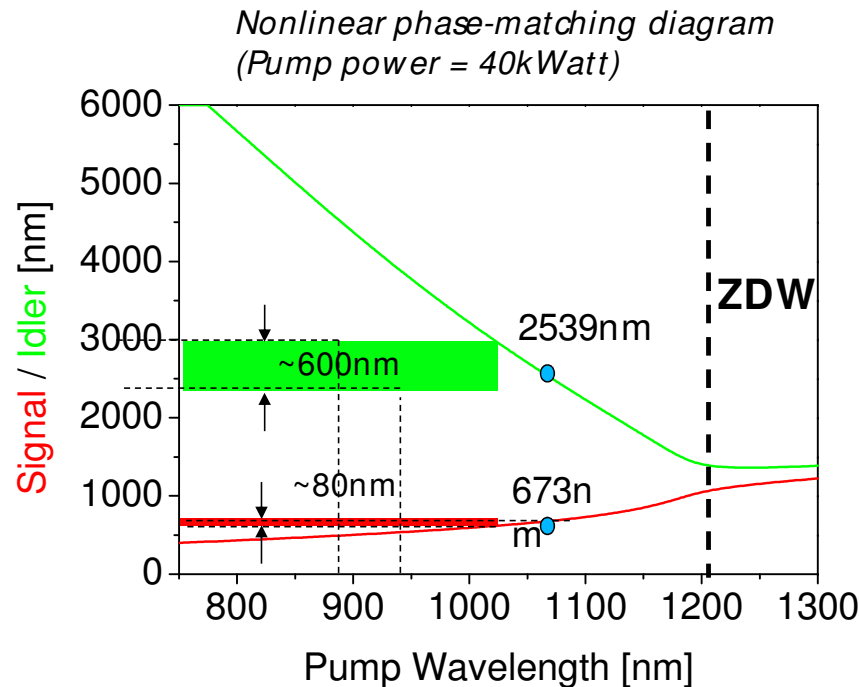
# Scaling of fiber laser systems

## Novel components and laser systems

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### ■ Approach for a fiber based picosecond VIS and MIR source

Condition a)  $2\omega_1 = \omega_2 + \omega_3$  + b)  $2k_{pump} = k_{signal} + k_{idler} + \gamma P_1 = 0$



To get widely separated signals move the pump wavelength far away from the ZDW (in the normal dispersion regime)

Furthermore, the amplification bandwidth is given by:

$$\Omega_A \approx \frac{\gamma P_o}{|\beta_2| \Omega_s}$$

Thus, additionally **to get narrowband signals** we need:

- high dispersion
- high separation of the wavelengths

# Scaling of fiber laser systems

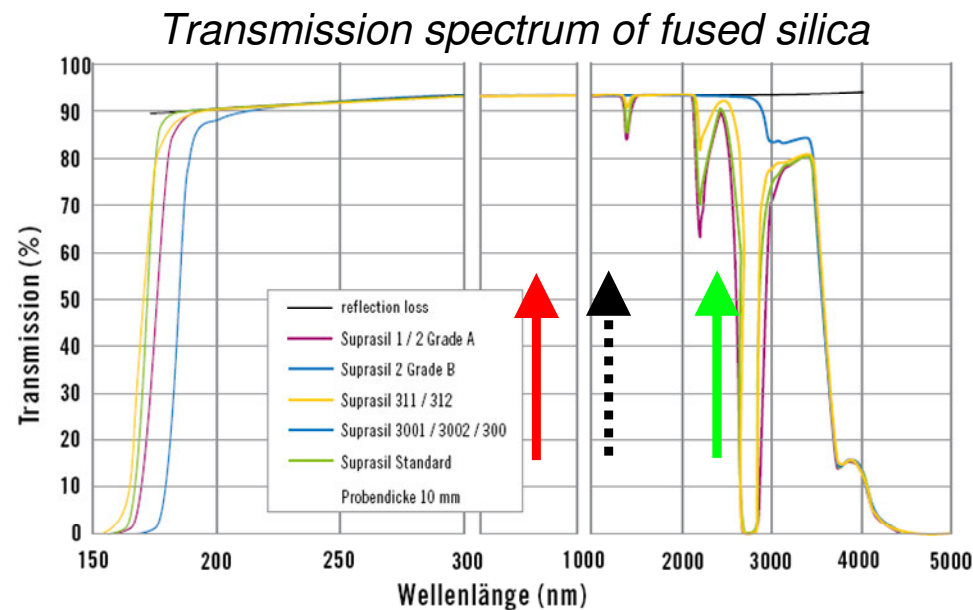
## Novel components and laser systems

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### ■ Approach for a fiber based picosecond VIS and MIR source

Condition c) Low losses at  $\omega_2$  and  $\omega_3$

Analyze the phase-matching condition a) and b) and look for a material which transmission window fullfils c)



IR graded fused silica is a good candidate to use with tunable lasers from 1020-1090nm!

# Scaling of fiber laser systems

## Novel components and laser systems

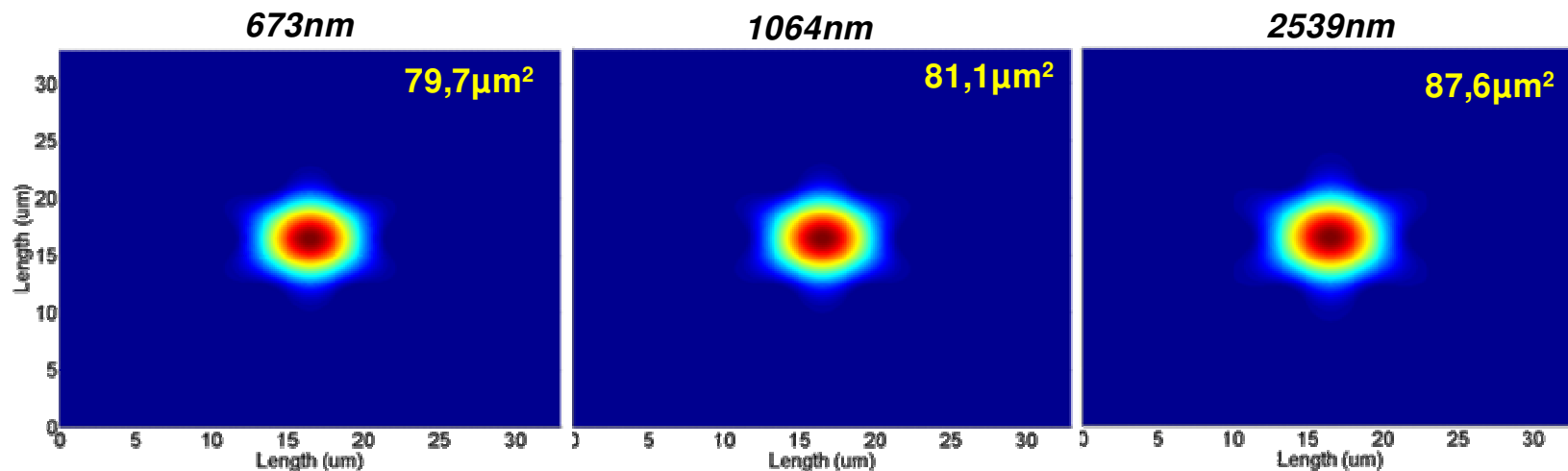
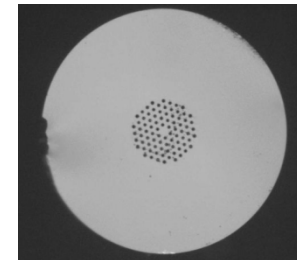
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### ■ Approach for a fiber based picosecond VIS and MIR source

Condition d)  $MFD_s \approx MFD_p \approx MFD_i$

Use an **endlessly single mode design** to ensure good mode field overlap for all involved wavelengths. E.g. an LMA-10 PCF.

Mode field distribution in LMA-10 fiber for signal, pump and idler waves:



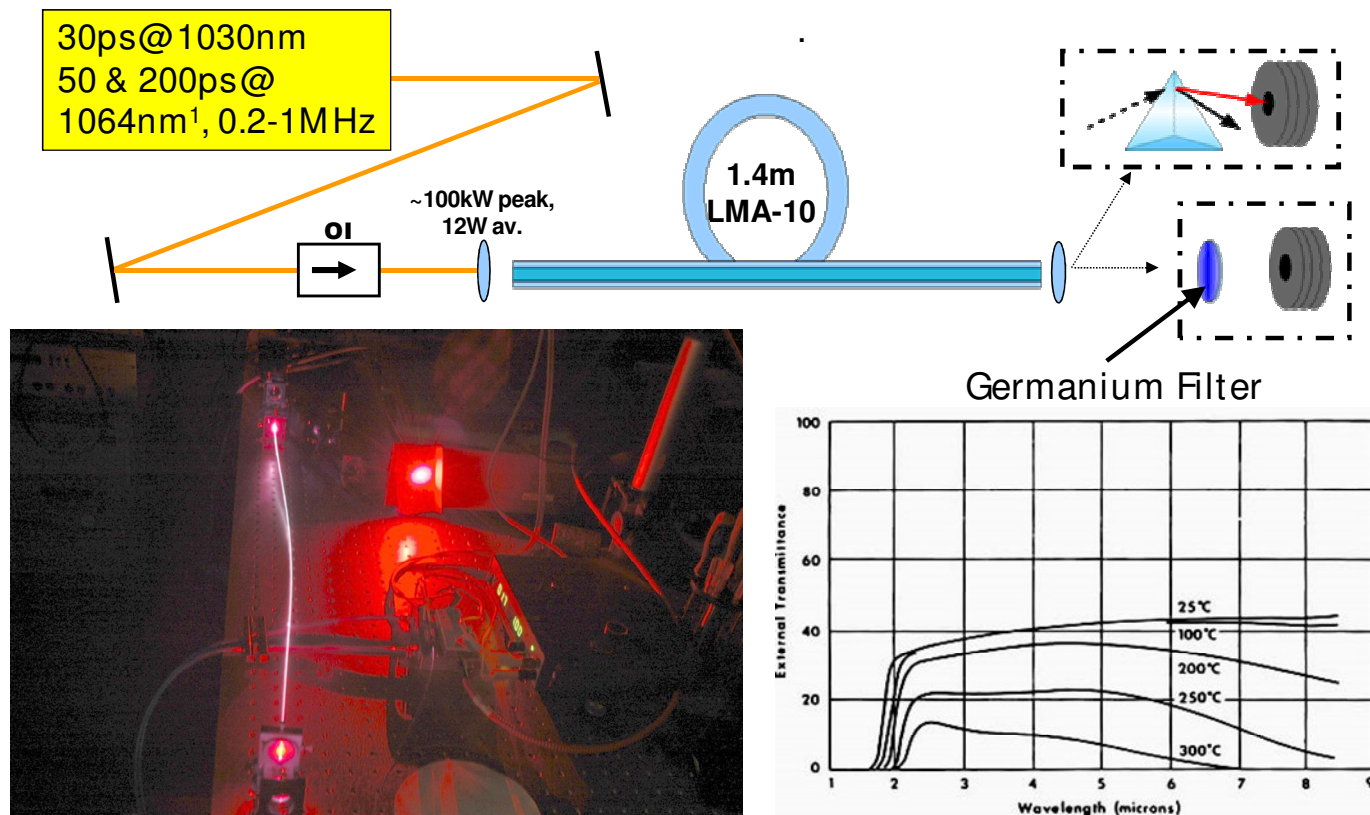


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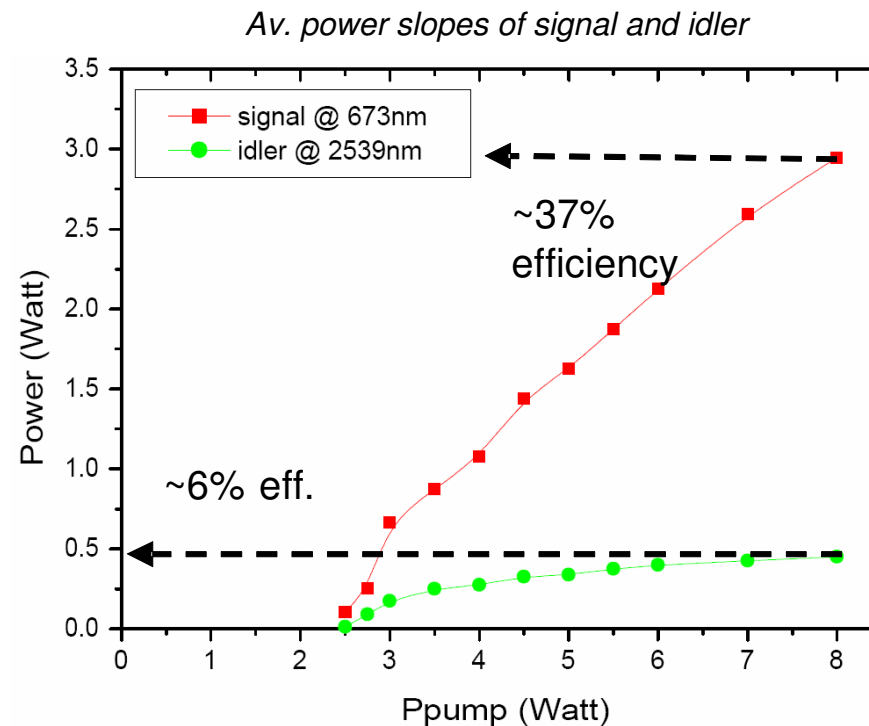
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### ■ Approach for a fiber based picosecond VIS and MIR source

Slopes of the signal and idler wave average power with 200ps pulses and 1MHz rep. rate.



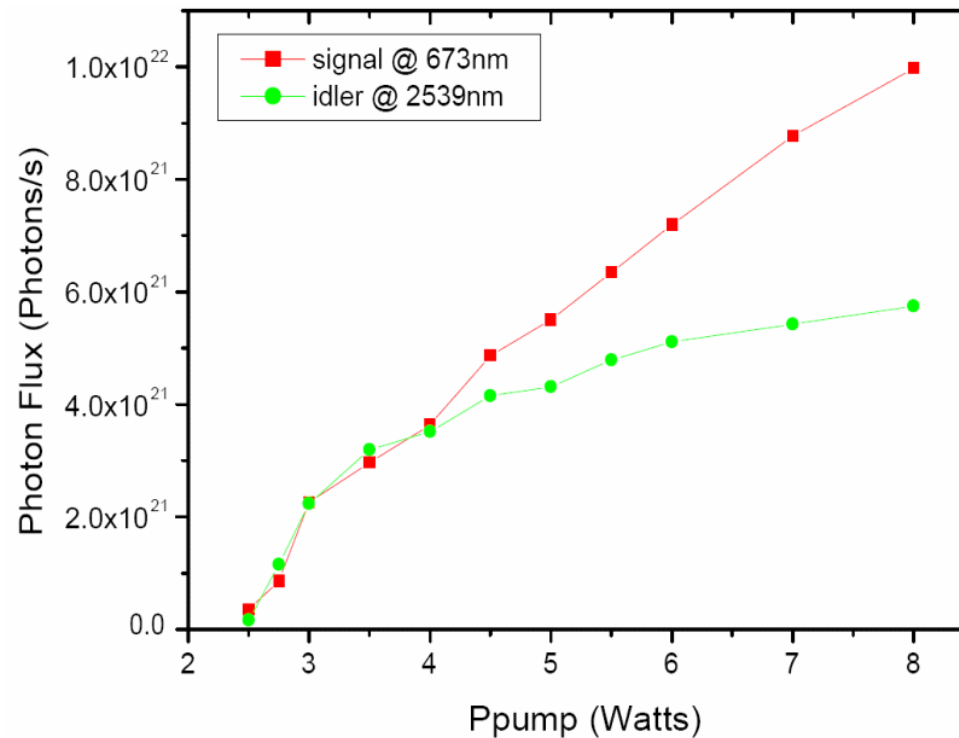
# Scaling of fiber laser systems

## Novel components and laser systems

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### ■ Approach for a fiber based picosecond VIS and MIR source

Slopes of the signal and idler wave average power with 200ps pulses and 1MHz rep. rate.



# Outline



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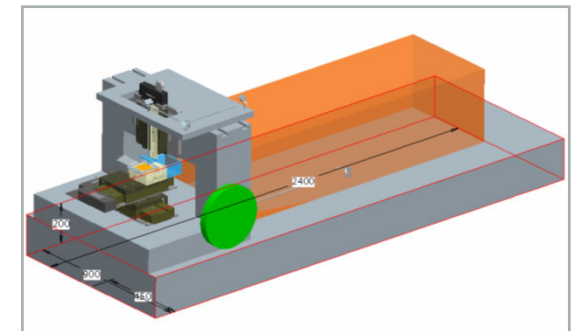
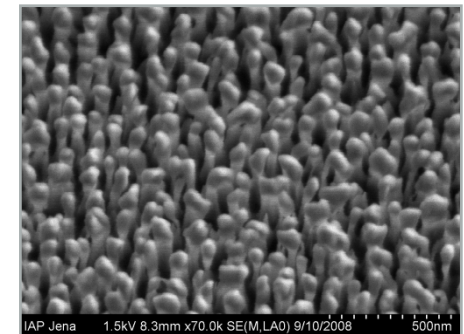
- introduction
- packaging and joining technologies
  - Application to microchip lasers
- novel components
  - Applications to fiber laser system scaling
- example of MID-IR source
- **possible further directions**

# Packaging and Joining Technologies for fiber lasers – further directions

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- using other NLO-elements + high power silica fiber lasers
  - e.g. quasi phase-matching (orientation-patterned GaAs)
  - transparent (low absorption), nonlinear materials + bonding process (for thermal contact)
- anti-reflection properties on MID-IR fibers
  - effective media directly bonded to fiber end facet
- fiber bragg gratings
  - written by femtosecond pulses (for non UV-sensitive fibers)

...



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**SET-171 Mid-IR Fiber Laser Workshop**

**Scaling of fiber laser systems based on novel components and high power capable packaging and joining technologies**

**Thank you for your attention!**

