High power ultrafast fiber amplifiers

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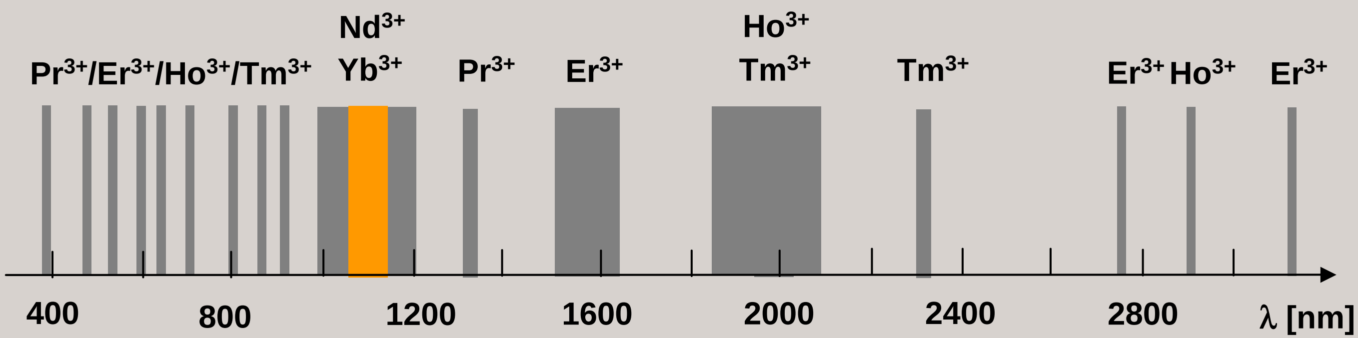
Outline of the talk

- **Interests of Yb-doped fibers as amplifier medium**
  - Interests of fibers
  - Interests of Ytterbium
  - High power double-clad fiber concept
  - Limitations
- **New design of Yb-doped fibers**
  - Microstructured fibers
  - Recent results
- **Suggestion of design**
  - Including Bulk and Fiber lasers
- **The bright future of high power high energy fiber amplifiers**

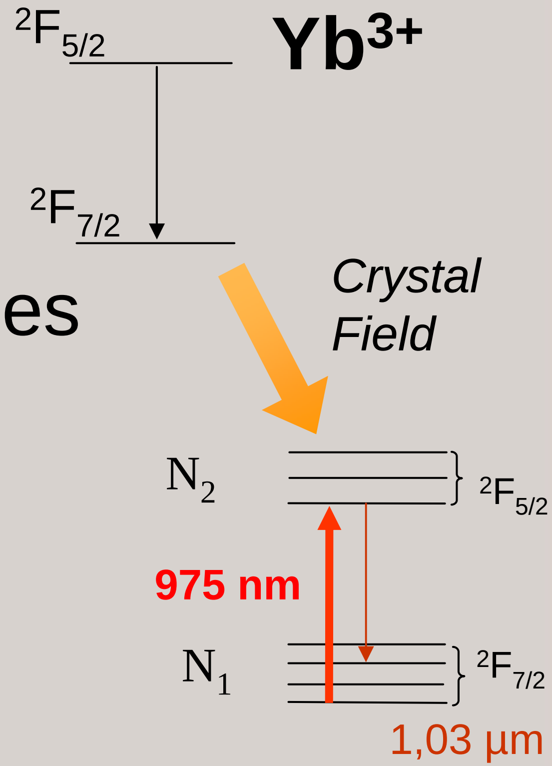
Interests of fibers

- Numerous advantages
  - **Reduced** free-space propagation
  - **No** thermo-optical problems
  - **Excellent** beam quality: $M^2 < 1.2$
  - **High** gain
  - **Large** variety of dopants
  - **Efficient** diode pumping operation



Interests of Ytterbium

- Very simple electronic structure of Yb ions
  - **No** undesired effects
- Weak quantum defect
  - **Reduced** thermal load
- Diode pumping with 976nm diodes
- Broad emission bandwidth



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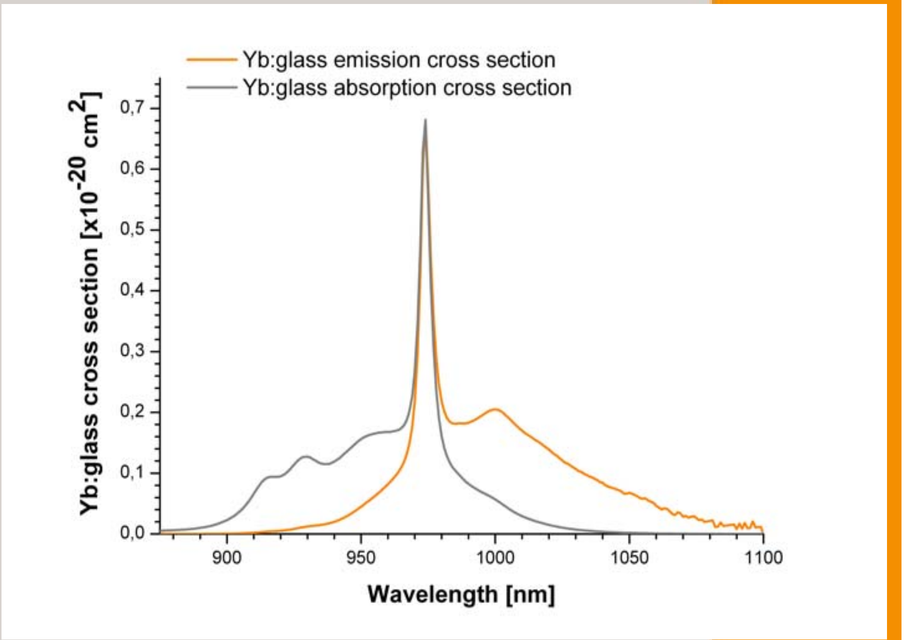

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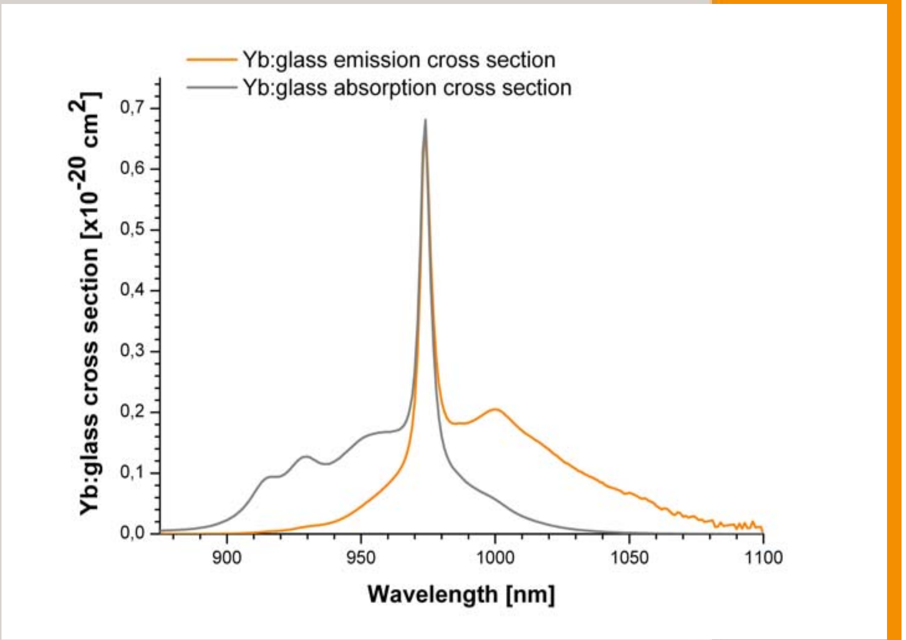

Ideals candidates for the **amplification** of ultrashort pulses

Double-clad concept

- A highly efficient brightness conversion concept
  - Monomode signal core
  - Multimode inner-cladding for multimode diode pumping

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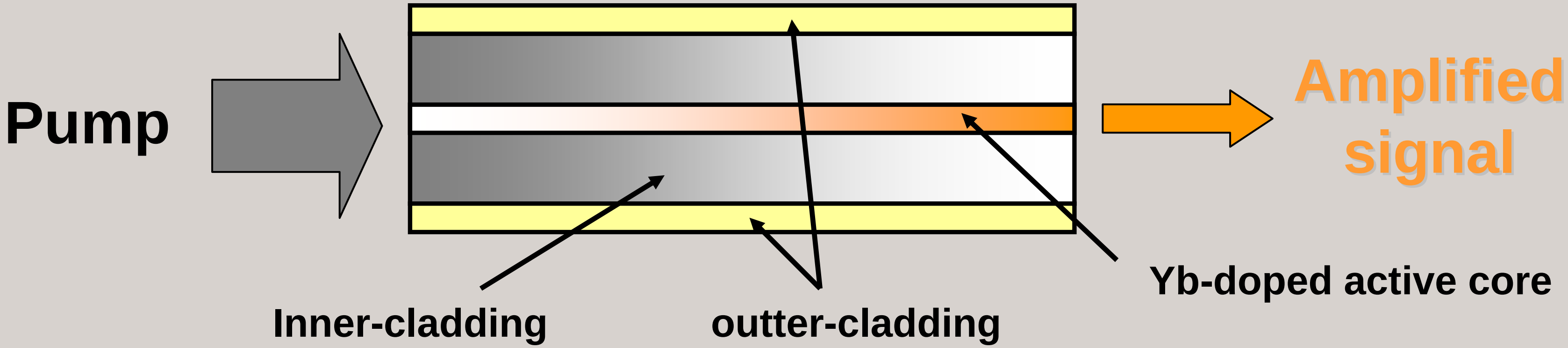

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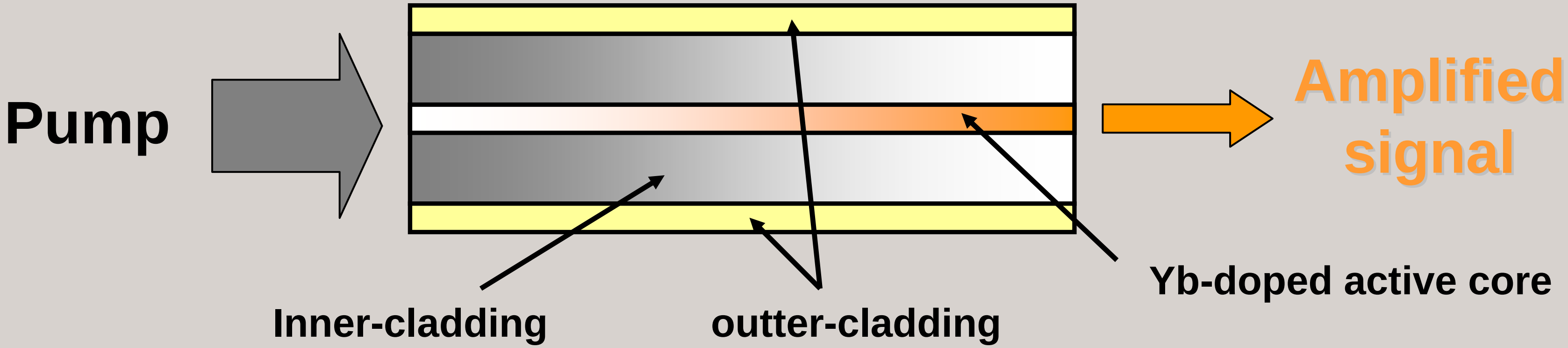

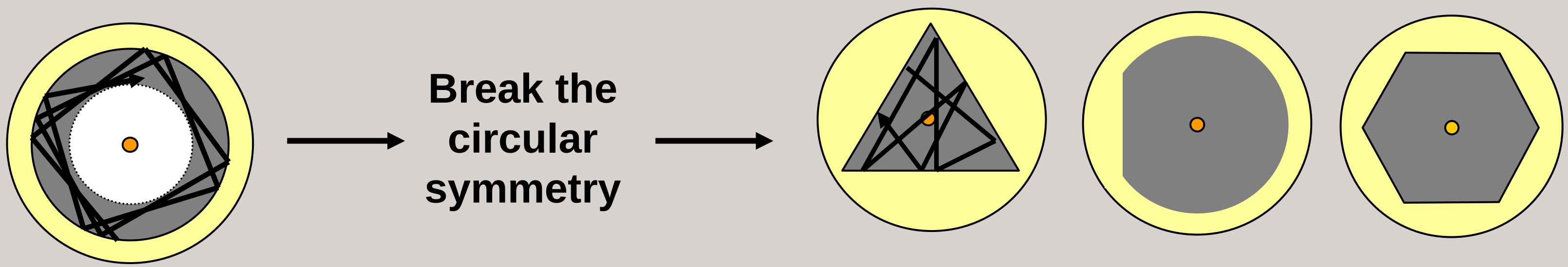

Nonlinearity limitations

- Interaction length in fiber >> than in bulk
  - Nonlinearities are the limiting factors
  - Isotopic media ⟹ lowest order nonlinearity: $\chi^{(3)}$

Nonlinearity limitations

1. **Nonlinear refraction index :** $\tilde{n}(\omega,|E|^2) = n(\omega) + n_2.|E|^2$
   - Self Phase Modulation : SPM
     - Non linear phase shift : $\phi_{NL}(\omega,T) = \gamma.L.|E(\omega,T)|^2$
     - Instantaneous frequency : $\delta\omega(T) = -\frac{\partial \phi_{NL}(z,T)}{\partial T} \propto \frac{L}{A_{eff}}$

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2. **Inelastic scatterings :**
   - Stimulated Raman Scattering : SRS
     - Frequency downshift through vibration of the medium: 13THz

       $$\propto \frac{L}{A_{eff}}$$
   - Stimulated Brillouin Scattering : SBS
     - Stokes shift of ~10GHz

       $$\tilde{g}_B = \frac{\Delta\nu_B}{\Delta\nu_B + \Delta\nu_P} g_B(\nu_B) << 1$$

Fighting Nonlinearities

- Reduced nonlinearities mean:
  - Smaller interaction length L
  - Larger mode field diameter A_{eff}

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⚠ **Multimode** operation

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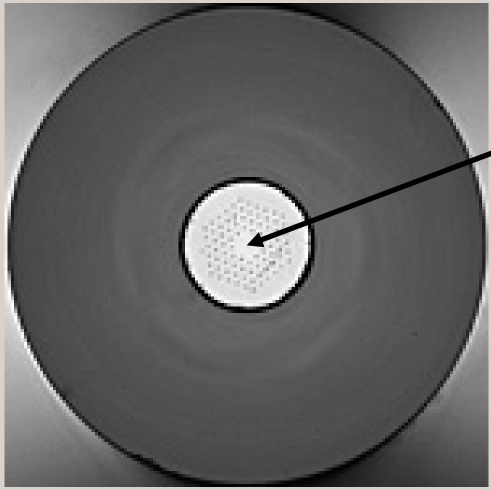
    ⚠ **Multimode** operation

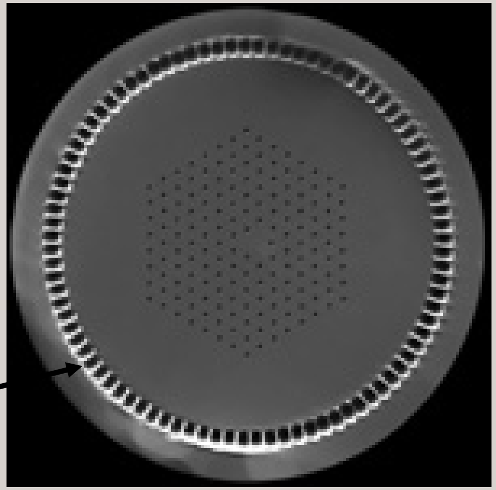
- Diffraction-limited operation with larger core diameter

⇒ **Microstructured Fibers**

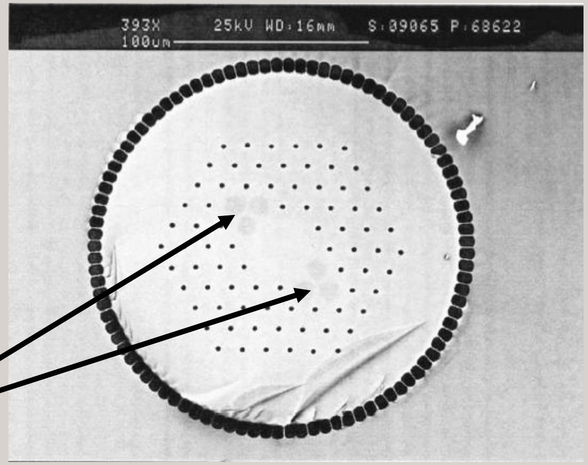
Microstrutured fibers



Up to **50 µm** core diameter with diffraction limited operation **(NA = 0.03)**



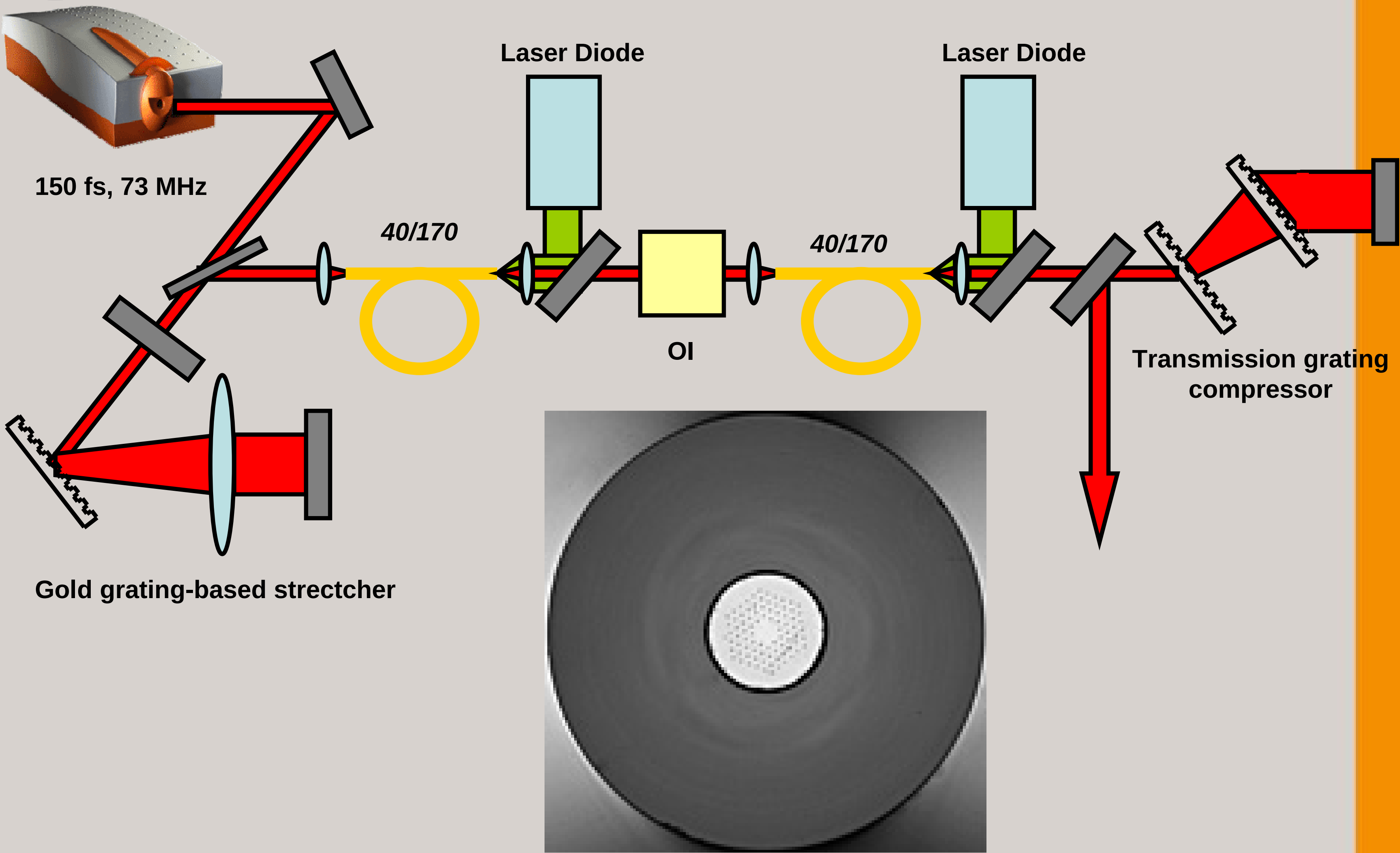
Air-clad for pump propagation **(NA = 0.6)**



Polarization maintaining design for **environmentally stable** operation

CPA-based amplification stage

Recent results (1/3)



F. Röser et al. Optics letters, 30, p2754, 2005

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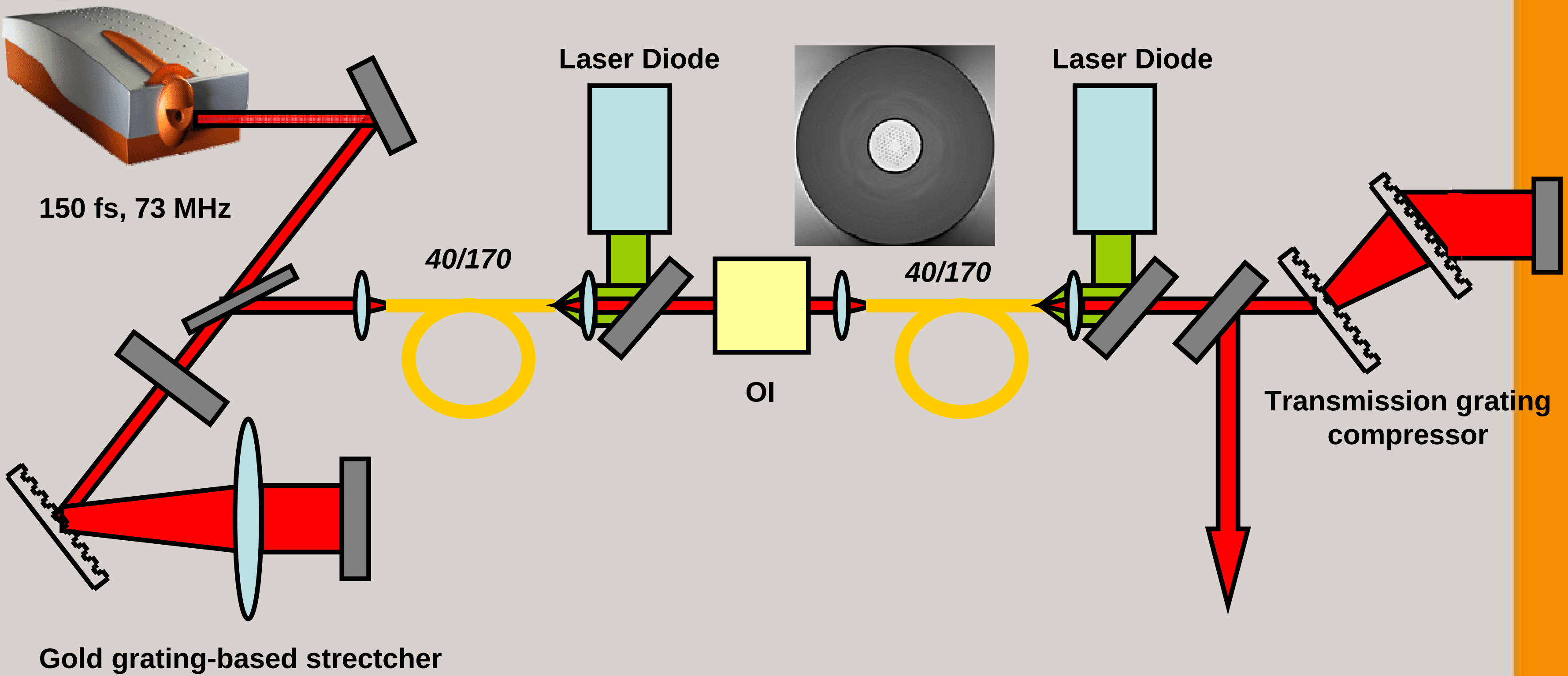

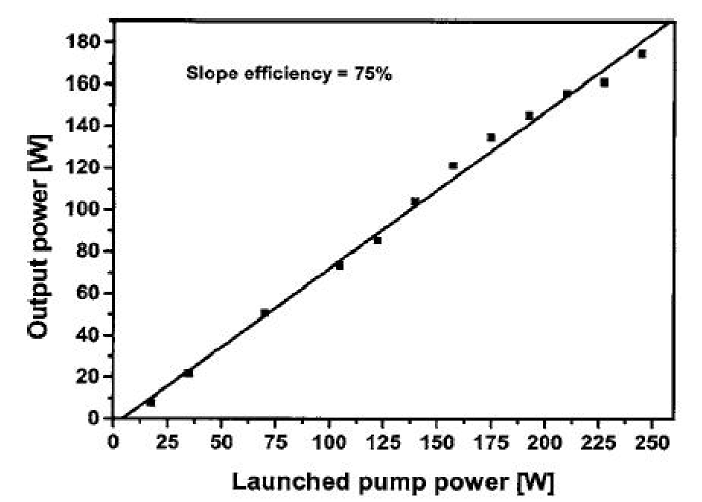

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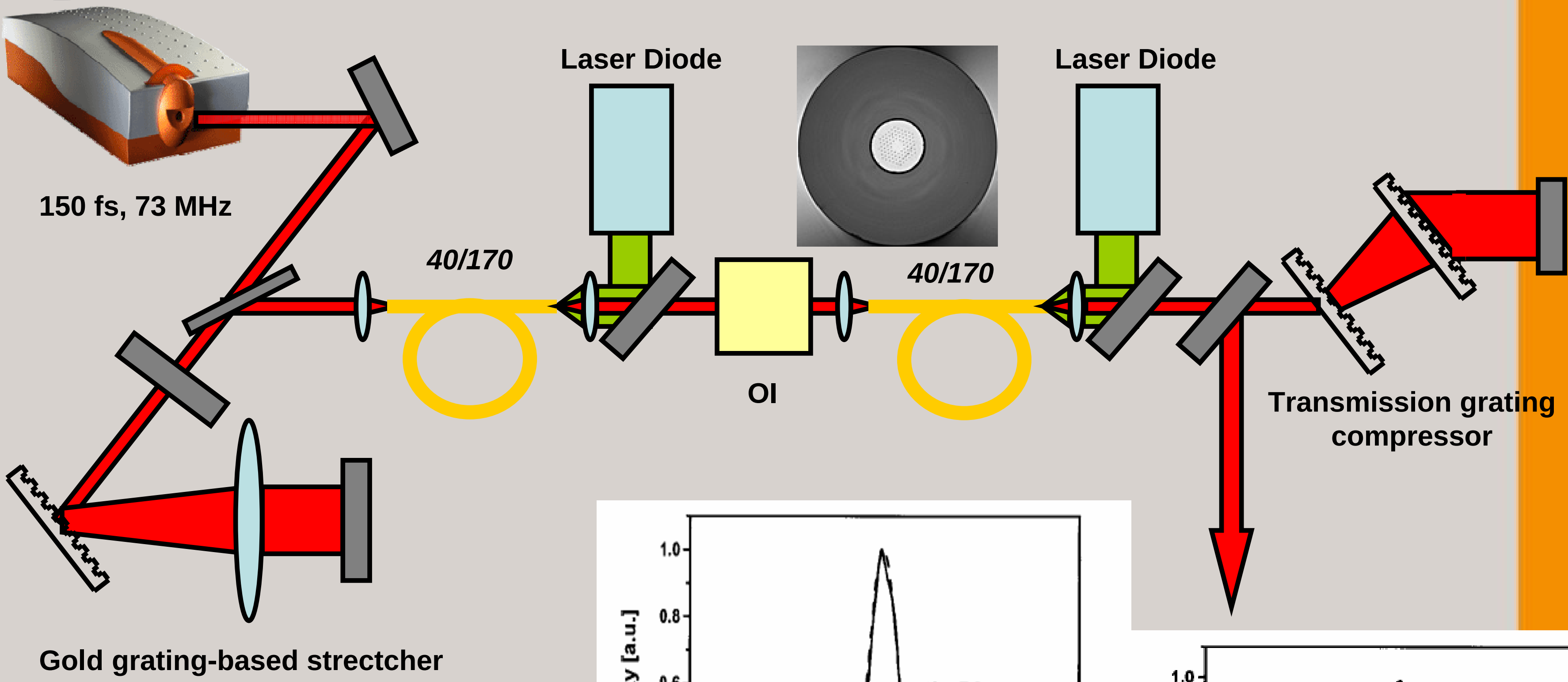

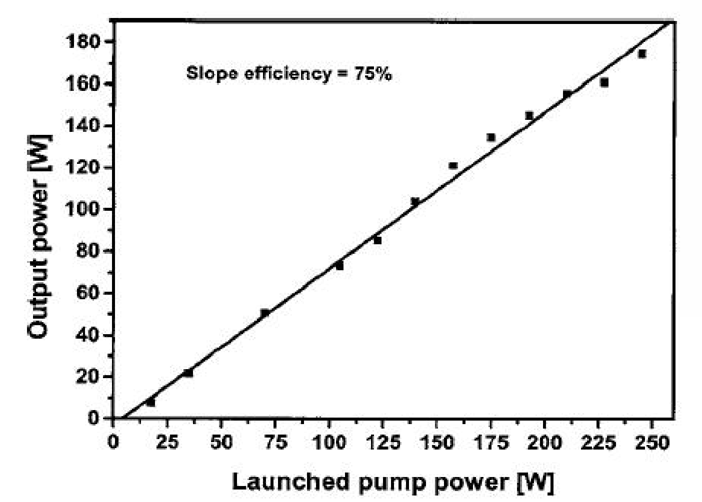

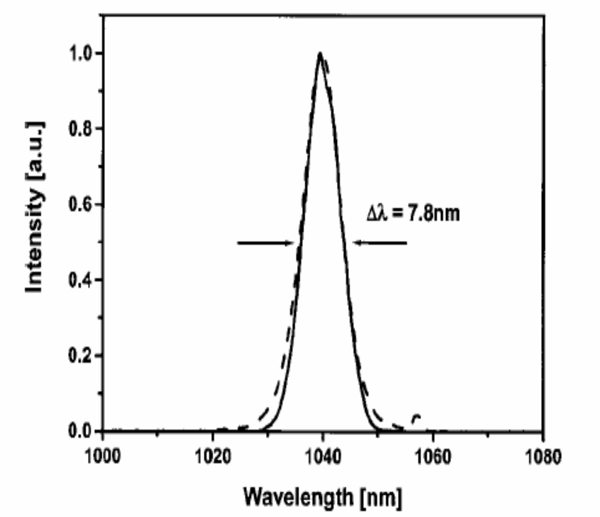

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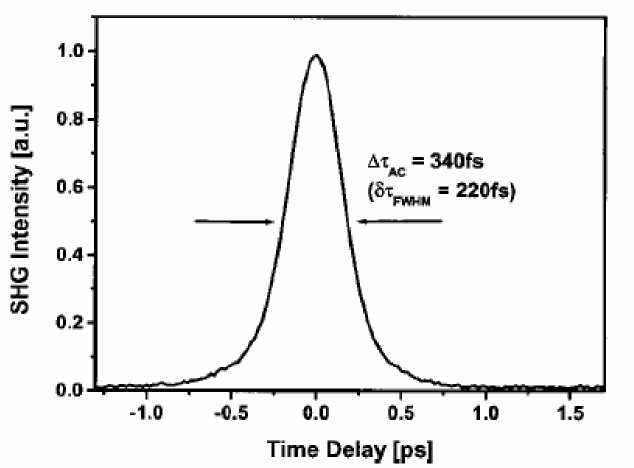

What if we want sub-100fs pulses ?

Recent results (2/3)

- **Parabolic pulse amplification**
  - Initialization of input energy and duration of the pulses
  - **Spectrum** and **Duration** grow and converge to a parabolic shape during the propagation accumulating a purely **linear chirp**
  - Asymptotic solution of NLSE with gain

$$i\frac{\partial\psi}{\partial z}=\frac{\beta_2}{2}\frac{\partial^2\psi}{\partial T^2}-\gamma|\psi|^2\psi+i\frac{g}{2}\psi$$

  - Easy to recompress with conventional grating-based compressor thanks to the linear chirp

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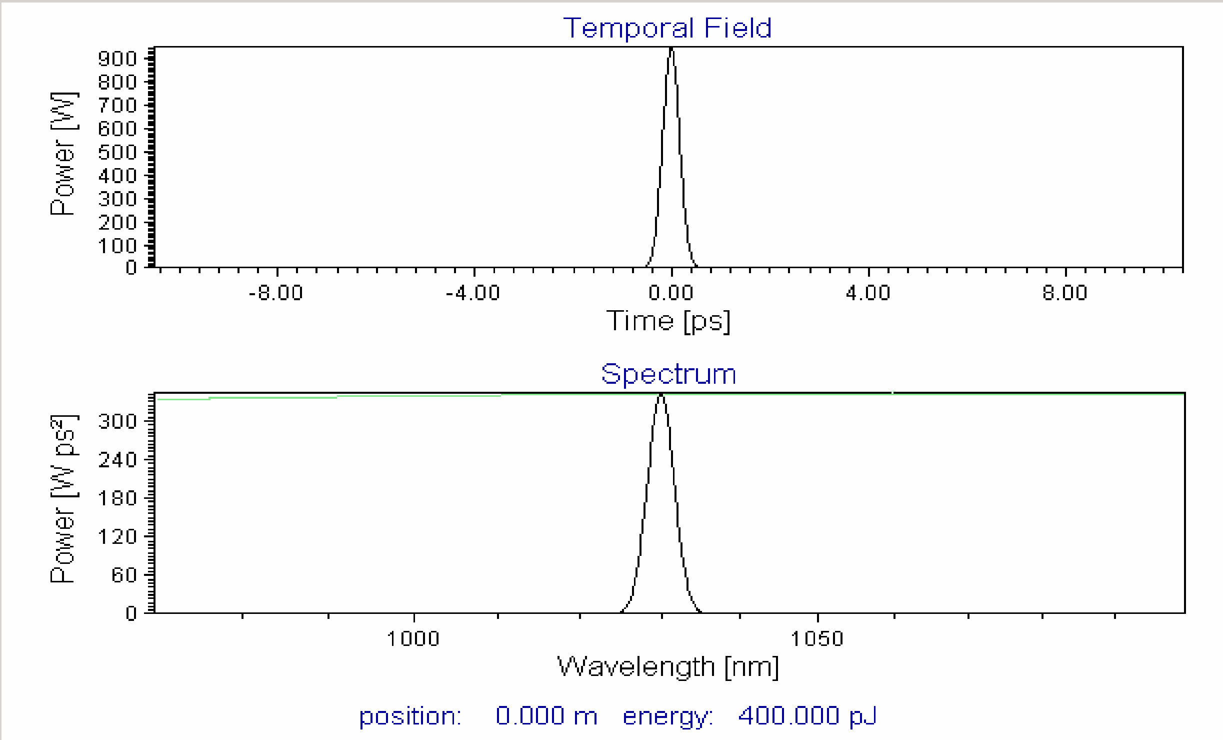
Recent results (2/3)

- **Parabolic pulse amplification**
  - EXEMPLE:
  - Oscillator: 400 fs, 75 MHz, 30 mW i.e. 400 pJ
  - Fiber amplifier: 9m, 23µm MFD, 0.7 m^{-1}



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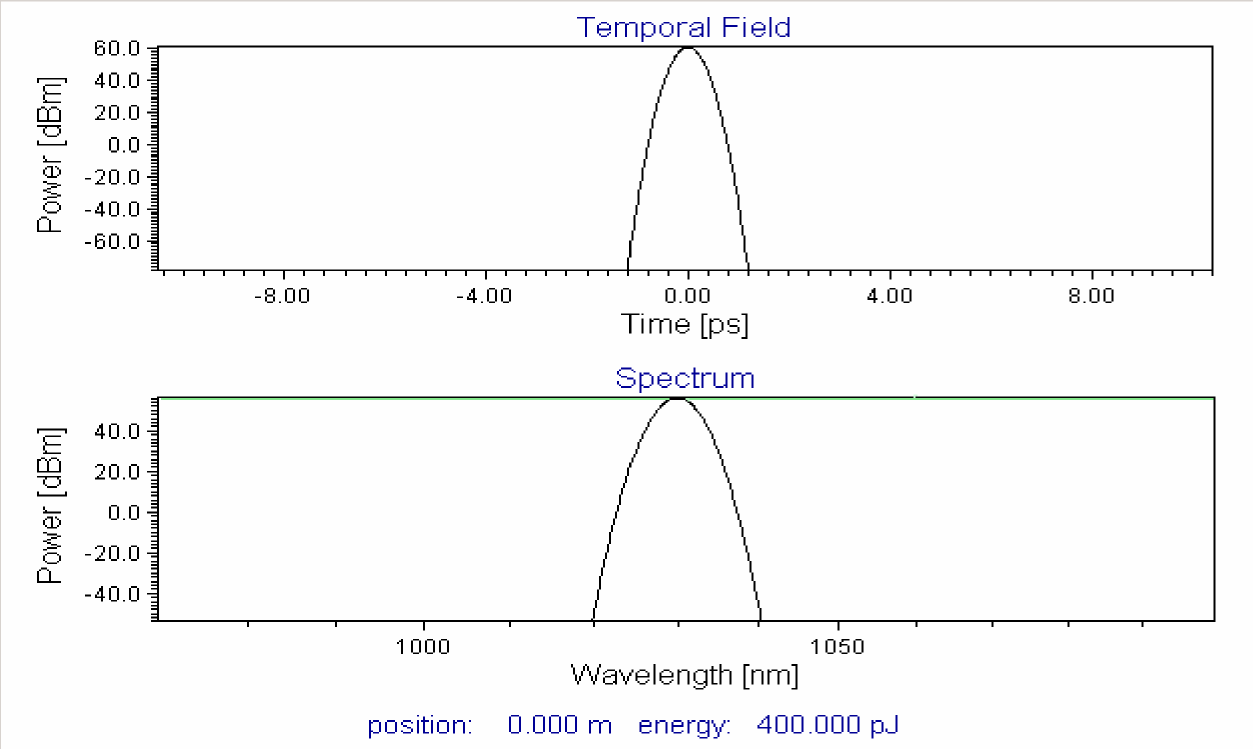

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  - $\Delta\lambda \approx 33nm$ i.e $\Delta t \approx 90\,fs$ assuming $\Delta t.\Delta\upsilon \approx 0.86$

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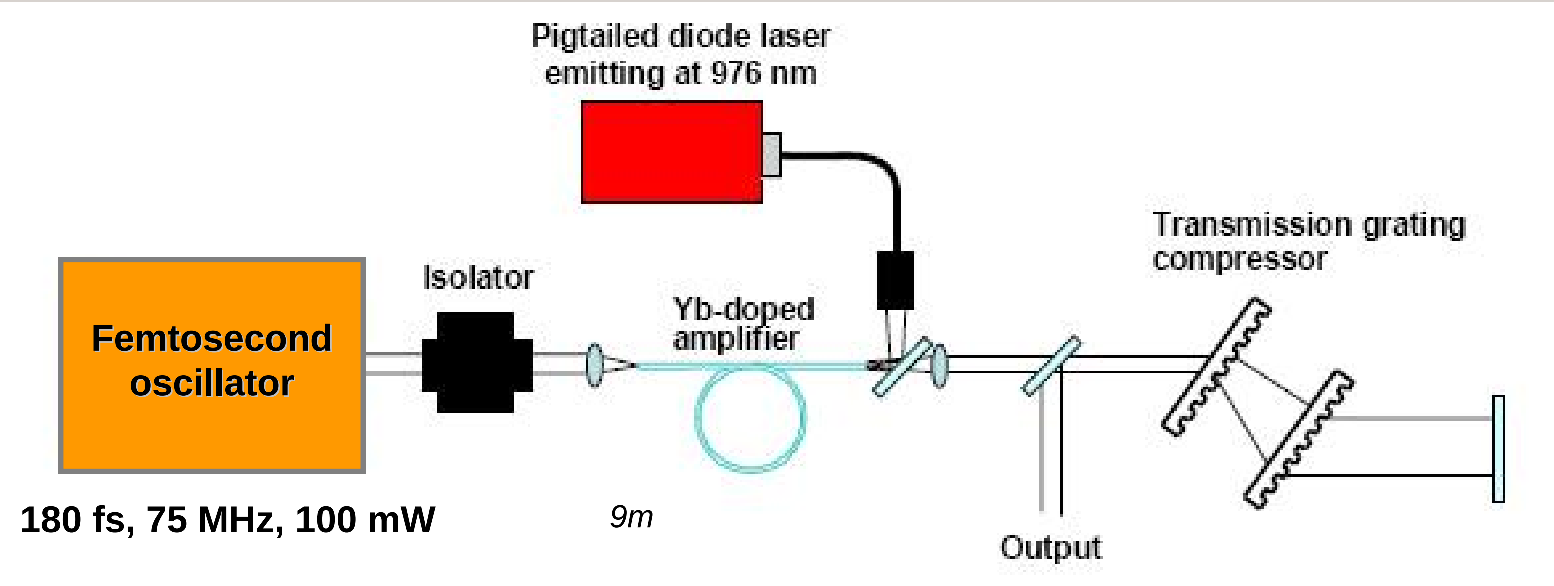
  - Experiment by Limpert et *al.*

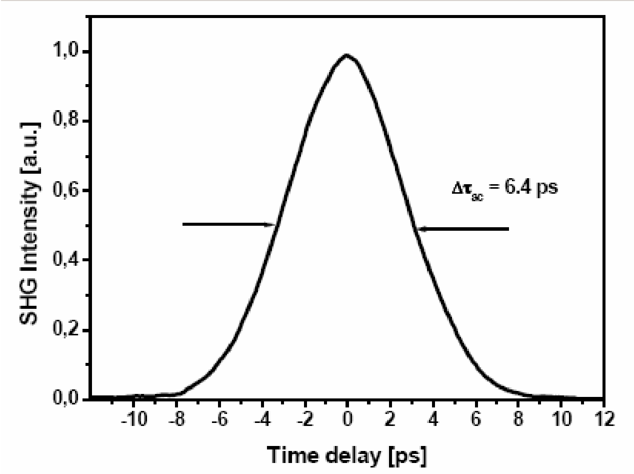


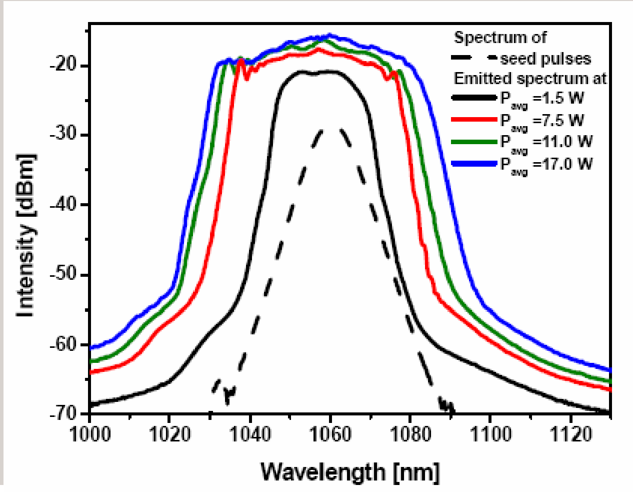
Oscillator

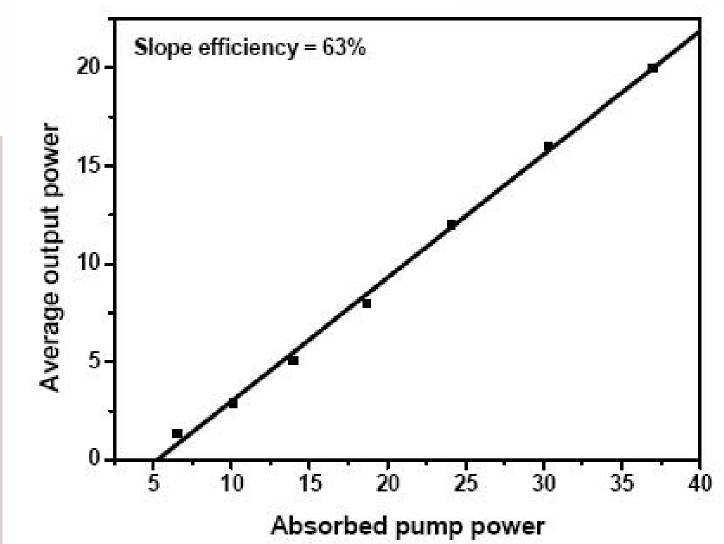
Limpert et *al.* , Optics Express, 10, p628, 2002

Recent results (2/3)

- Parabolic pulse amplification
  - Expériment of Limpert et *al.*







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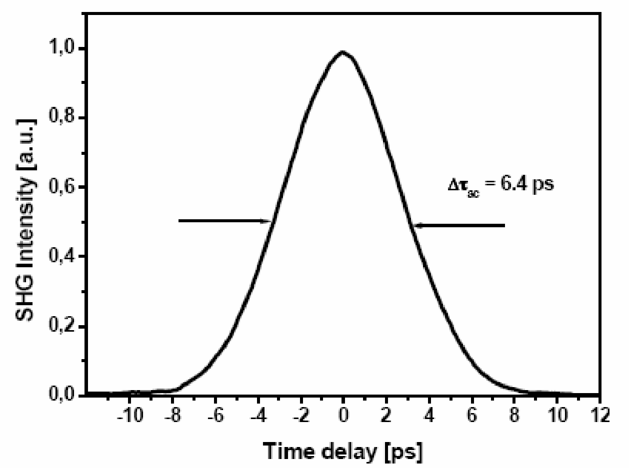
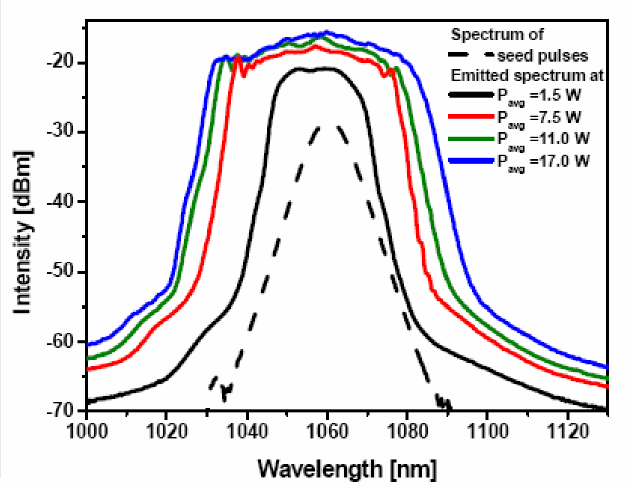
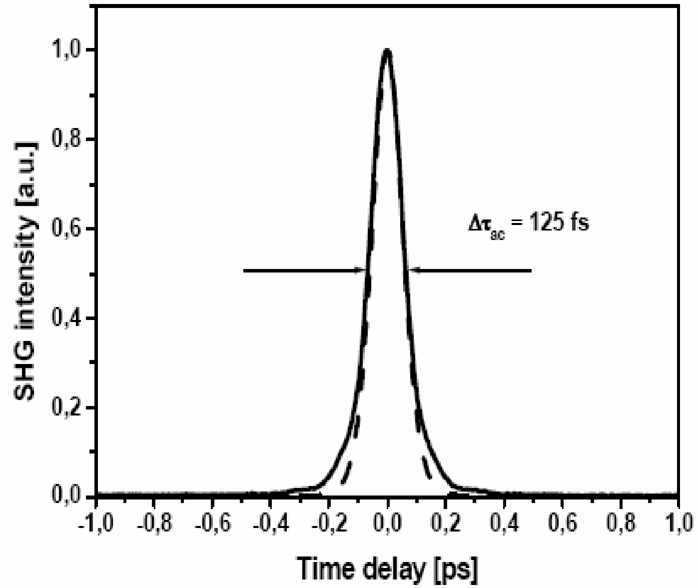






Limpert et *al.* , Optics Express, 10, p628, 2002

Energy scalable ?

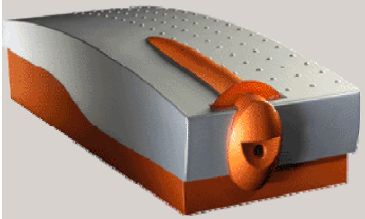
Recent results (3/3)

- Nanosecond pulses amplification :
  - Aculight, Femlight
  - 1 to 2 mJ, 1ns with 60 µm core-diameter fibers
  - >500 W/m power extraction reported by Femlight

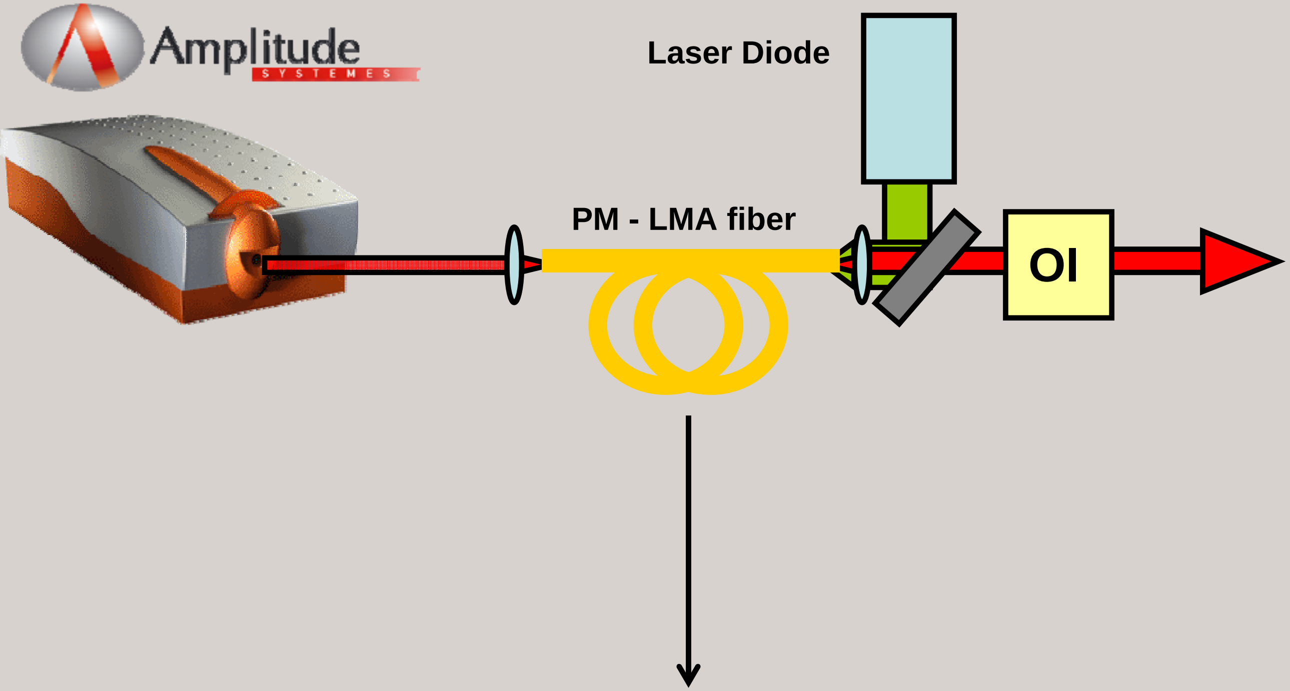
F. Salin et al. Optics Express, 14, p2275, 2006

C. D. Brooks et al. Optics Express, 13, p8999, 2005

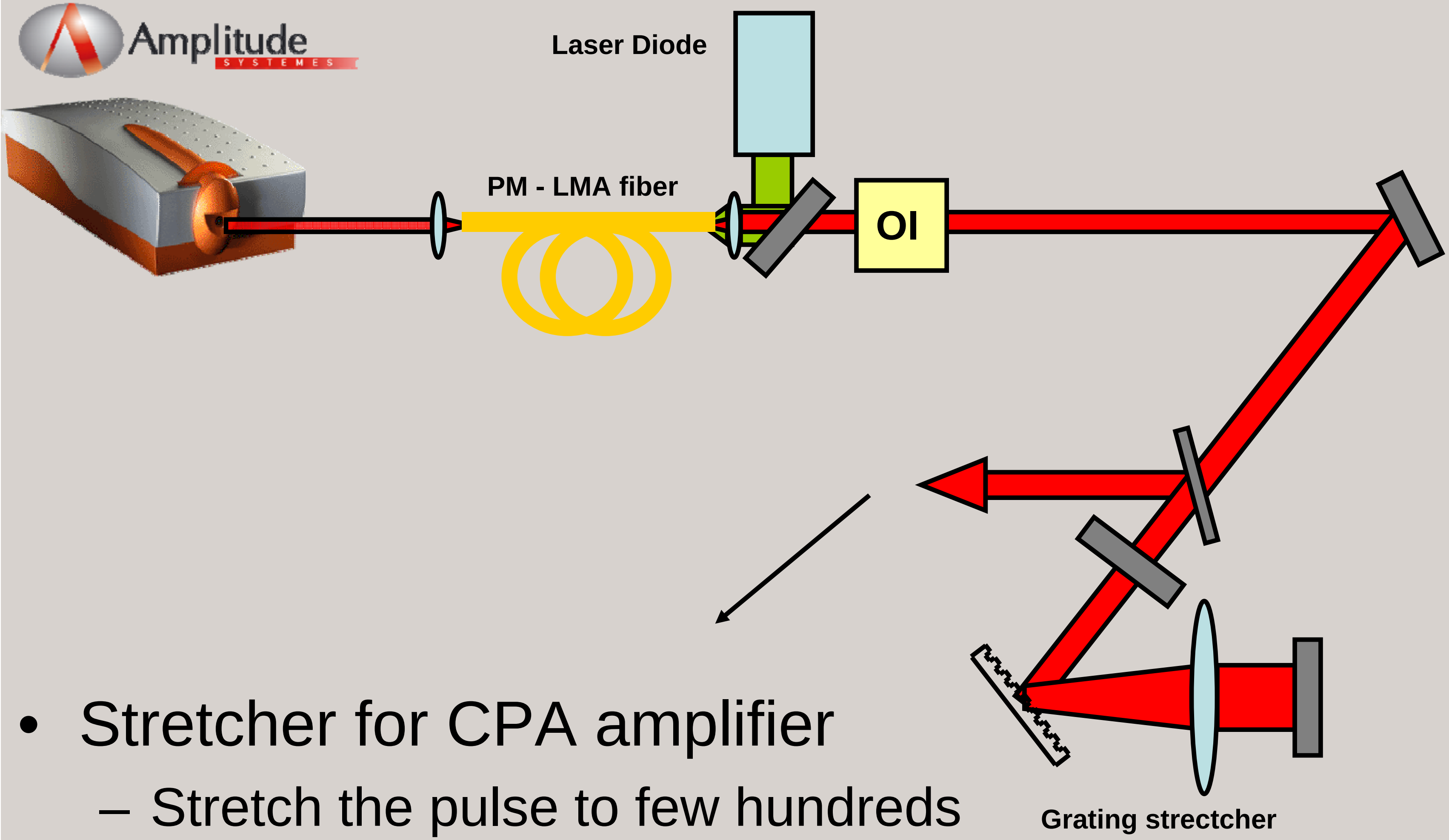
Suggestion of design



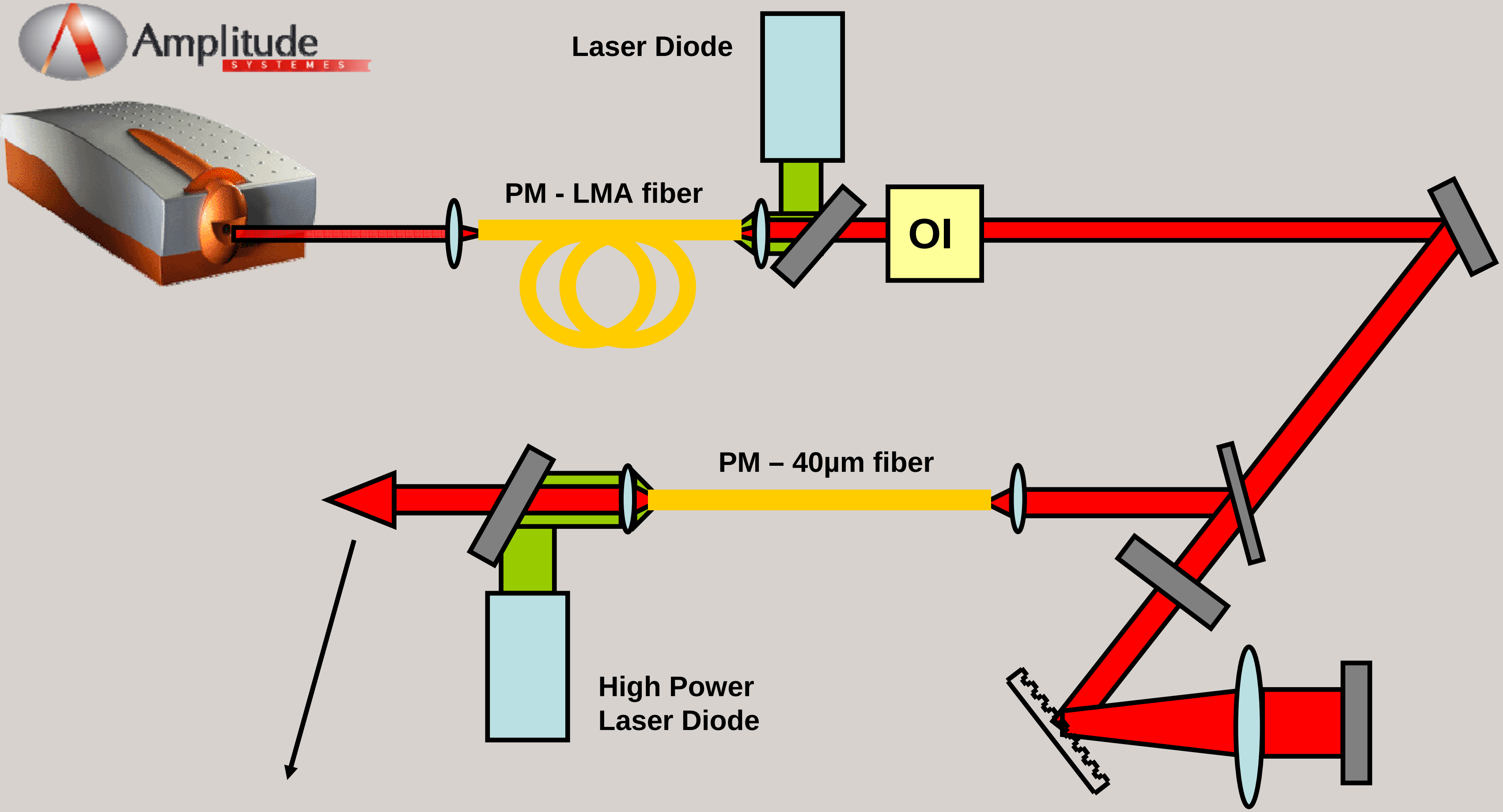
- Low power, long cavity oscillator
  - > 2 W average power
  - Rep rate of 10 MHz
  - < 400 fs pulse duration
  - Synchro-locked : adjusting the length of the cavity



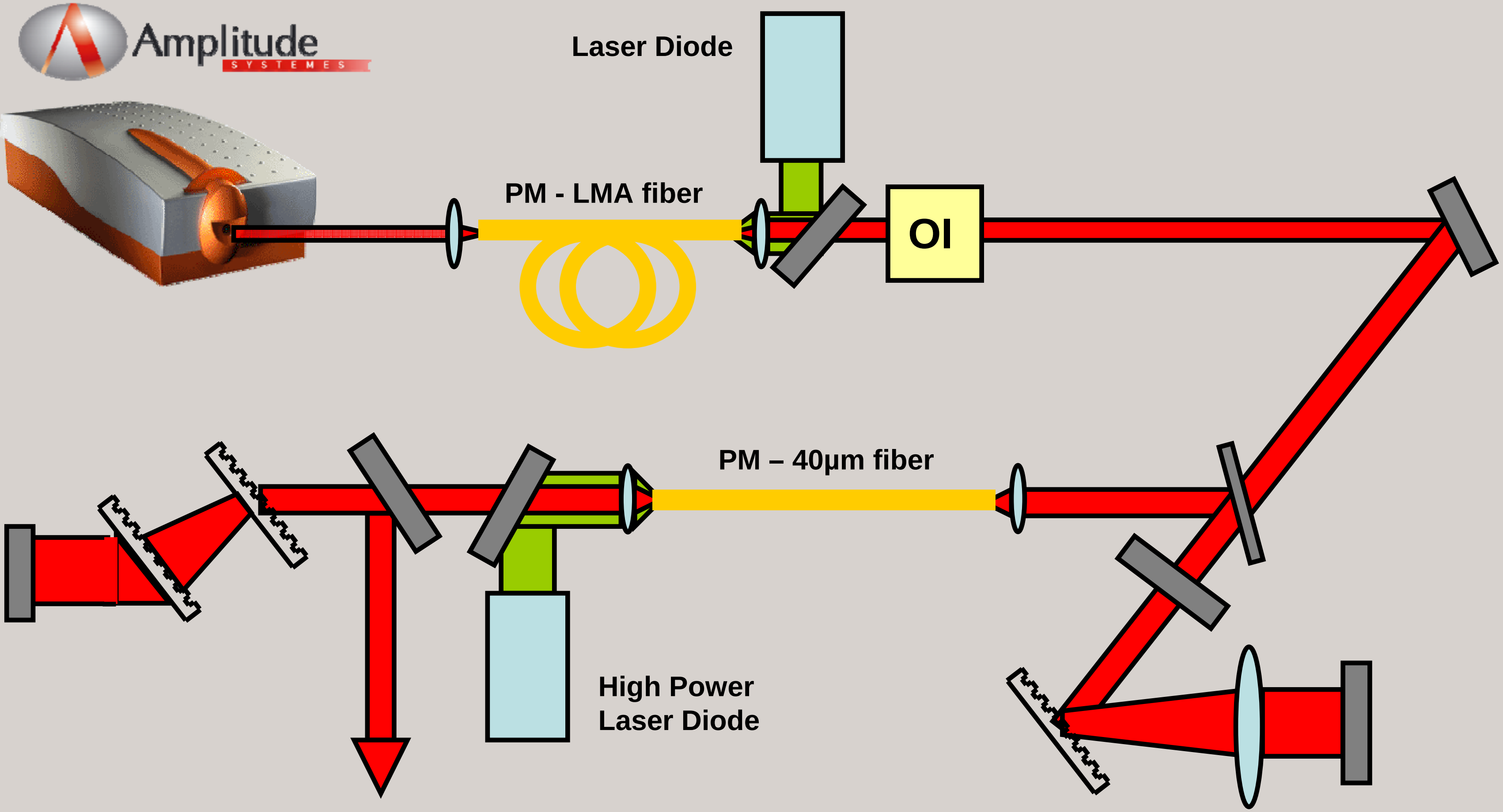
- PM - LMA fiber
  - Length and gain design for parabolic amplification
  - Polarization maintaining fiber



- Stretcher for CPA amplifier
  - Stretch the pulse to few hundreds of ps
  - Avoid nonlinearities in the power amplifier stage



- < 1 m PM 40 µm core diameter microstructured fiber
  - Few tens of µJ @ 10 MHz
  - Pump-power-limited !!



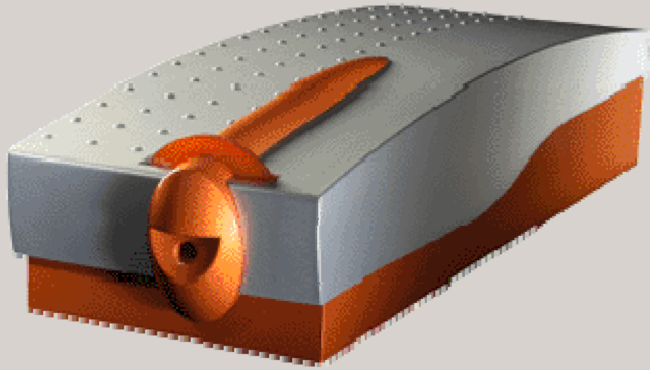
- And hopefully …
  - ~100 fs recompressed
  - Average power is pump-power-limited
  - Polarized and Synchro-Locked

What's coming up ?

- Fiber design
  - Diffraction limited operation already demonstrated in a passive **100 µm** core diameter microstructured fiber
  - New designs of PM microstructured fibers are on the run

- Energy and power improvement
  - **10 mJ, 1ns** may (will ?) be achieved in the coming years
  - **"Kilowatt Femto"** is feasible

Thank you



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