Development of Ultrafast Thin-Disk Lasers with High Average Output Power


- Motivation and Target Specifications
- Ultrafast Thin-Disk MOPA (> 1 mJ, > 1 kW)
- Ultrafast Thin-Disk Oscillators
Motivation and Target Specifications (1 of 2)

From our lectures:
- Intensity and interaction time ⇒ process
- Average laser power ⇒ productivity

Illustration with laser cutting of CFRP:
- Heat conduction along carbon fibers causes matrix damage
- Fast removal of the carbon fibers is needed:

\[ I \approx 10^9 \, \text{W/cm}^2 \text{ for } <10 \, \mu\text{m of damage} \Rightarrow \text{ps pulses} \text{ (or tightly focused cw beam?)} \]

\[ P \approx 3 \, \text{kW to meet productivity goal} \]

Conclusion:
- Develop ultrafast lasers (ps or fs pulses) with kW average output powers

High pulse energy or high repetition rate?

- High-quality **single-pulse ablation**: low fluences and ps pulses

Increase the productivity by
- either increase the repetition rate
  (1 kW = 1 mJ x 1 MHz)
- or increase the pulse energy
  (and the effective beam cross section)

- Heat accumulation limits the repetition rate

Temperature on the surface at same average power of 1.25 W!

Conclusion (again):
- Despite the need of further investigations it seems appropriate to develop ps lasers with > 1 mJ/pulse and > 1 kW average power
Laser Development

What are the options? \((\text{ps}, > 1 \text{ mJ}, > 1 \text{ kW}, < 1 \text{ MHz})\)

- **Fiber** lasers require chirped pulse amplification (CPA) to avoid *non-linear effects*
- **Bulk** solid-state lasers are limited by *thermally induced distortions*
- The **thin-disk** concept fundamentally alleviates both issues

What are the concepts? \((\text{ps}, > 1 \text{ mJ}, > 1 \text{ kW}, < 1 \text{ MHz})\)

- **Mode-locked oscillator**
  **Challenge:** long resonators (150 m for 1 MHz)

- **MOPA with a regenerative amplifier.**
  **Problem:** optical switch limits power, energy and repetition rate

- **MOPA with a multi-pass amplifier**
  **Advantage:** no switching, no CPA
Where It All Began


- Laser spectroscopy on muonic hydrogen ($\mu$-$p$)

- Laser pulses (35 ns) within <500 ns after trigger

- Solution: All thin-disk MOPA with multi-pass amplifier

- Result: the proton (charge) radius is 4% smaller than expected!

Big puzzle for physics!
The Size of the Proton

- Nature Letter 466, 213-216 (8. July 2010), DOI: 10.1038/nature09250
- Science 339, 417-420 (2013), DOI: 10.1126/science.1230016

- Thin-disk multi-pass laser amplifier was very reliable and efficient

  apply this approach to industrial applications
Ultrafast Thin-Disk Multi-Pass Amplifier with >1 kW output


Seed laser:
- 6.5 ps
- 800 kHz
- 80 W

Output:
- 1.1 kW (1.4 kW)
- \( M^2 < 1.25 \)
- Pulse energy: 1.4 mJ (4.7 mJ)
- Pulse Duration: 7.3 ps
- Slope Efficiency: 46%

Set-up of the multi-pass amplifier

- 2316 W of pump power
- Pump diodes 940 nm (969 nm)
- Yb:YAG
- 40 passes
- \( \lambda/4 \) waveplate
- \( \lambda/2 \) waveplate
- Mirror array
- \( M_1 \), \( M_{20-21} \)
- TFP
Further Developments

Based on the present set-up:
- Further power and energy scaling
- Amplification of fs pulses
- Frequency conversion
- Application to materials processing, …

Other related projects:
- **Ti:Sapphire thin-disk fs laser with double-sided cooling**
  in cooperation with Thales Optronique SA (France),
  Element Six Ltd. (UK), FEMTO-ST/CNRS (France), Oxford Lasers Ltd. (UK), and M-Squared Lasers Ltd. (UK),
  coordinated by the IFSW.
- **Crystal fiber amplifier followed by multi-pass thin-disk laser amplifier**
  for ps pulses with cylindrical polarization
  in cooperation with Time-Bandwidth Products AG (Switzerland), CNRS (France), Fibercryst SAS (France), Next Scan Technology B.V. (The Netherlands), GFH GmbH (Germany), SLV Mecklenburg-Vorpommern (Germany), and Class 4 Laser Professionals AG (Switzerland),
  coordinated by the IFSW.

a) Freitag, Negel, Löscher, Wiedenmann

b) Cut in CFRP with ps pulses, up to 3.5 mJ/pulse, and 1 kW average power
Development of Ultra-Fast (fs) Thin-Disk Oscillators

- The prerequisite for an ultrafast oscillator (with kW of output power) is a diffraction limited operation.

- Several promising crystals are being investigated with respect to their suitability for the use in ultrafast thin-disk oscillators with high average powers:
  - Yb:Lu$_2$O$_3$
  - Yb:CaGdAlO$_4$ (Yb:CALGO)
  - Yb:Sc$_2$SiO$_5$ (Yb:SSO)
  - Yb:CaF$_2$
  - Yb:YAl$_3$(BO$_3$)$_4$ (Yb:YAB)
  - Yb:YLF
  - Ti:Sapphire
Testing Suitable Crystals

- Record 670 W output from a Yb:Lu$_2$O$_3$ zero-phonon pumped thin-disk laser with an optical efficiency of 66% to demonstrate power suitability of the material [Laser Phys. Lett. 9, 110 (2012)]

- First demonstration of a Yb:CALGO thin-disk laser (cw and Q-switched) [Opt. Lett. 36 (21), 4134 (2011)]$^{1234}$


In cooperation with
1 FEE GmbH
2 Institut d’Optique, Paris
3 Inst. d. Chimie d. l. Mat. Cond., Bordeaux
4 Amplitude Systèmes

In cooperation with Shanghai Institute of Ceramics
Testing Suitable Crystals

- Record demonstration of 109 W of IR output power with Yb:YAl₃(BO₃)₄ as gain material in thin-disk oscillators
  [Optics Express 21 (22), 25708-25714 (2013)]¹

- First laser demonstration with highly doped Yb:Gd₂O₃ and laser demonstration Yb:Y₂O₃ crystals, grown by an original flux method
  High potential for disk configuration

- Record demonstration of 250 W of IR output power with Yb:CaF₂ as gain material in thin-disk oscillators
  [Opt. Express 22 (2), 1524-1532 (2014)]²⁴

In cooperation with
¹ FEE GmbH
² Institut d’Optique, Paris
³ Inst. d. Chimie d. l. Mat. Cond., Bordeaux
⁴ LZH

… there is room for improvement!
Power Scaling: The Challenge of Thermally Induced Effects

- Compared to other solid-state lasers the unique advantages of the thin-disk laser are the
  + efficient cooling
  + significantly reduced thermal lens
  + high efficiency
  + simple power scalability

- The main challenge for diffraction-limited kW emission arises from the non-vanishing thermal effects:
  - global deformation of the disk ≈ spherical lens
  - local change of refractive index
  - local expansion

\[
\Phi(r) = 2 \cdot \frac{2\pi}{\lambda_l} \int_0^d \left( n_0 + \frac{dn}{dT} \cdot (T(r, z) - T_{Cooling}) - 1 \right) \cdot \left( 1 + \alpha_{th} \cdot (T(r, z) - T_{Cooling}) \right) dz - 2 \cdot \frac{2\pi}{\lambda_l} \cdot z_0(r)
\]

- Solution:
  ✓ Compensate for OPD with an aspherical (actively deformable) mirror
  ✓ Avoid (reduce) the problem in the first place: zero-phonon pumping
Zero-Phonon Pumping: Fundamental-Mode Operation

- **Oscillator** with nearly diffraction limited beam quality ($M^2 < 1.5$)
- Very high optical efficiency of up to 58% at 750 W from **one single disk**!
Aspherical compensation: Fundamental-Mode Operation

- Compensate for the aspherical OPD by a deformable mirror

- Record performance (2012): Oscillator with diffraction limited beam ($M^2 < 1.4$) and 815 W output power from one single disk!
  S. Piehler et al., Opt. Lett. 37 (24), 5033-5035 (December 2012)

Next Steps:
- Combining zero-phonon pumping and deformable mirror
- Mode-locking at kW average power level
Conclusions

- The thin-disk technology is a very suitable approach for ultrafast lasers with high average powers.

- We have demonstrated > 1 kW of average power and > 1 mJ of energy in ps pulses at the same time from a simple multi-pass thin-disk laser amplifier.

- There is a good choice of laser crystals suitable for the development of high-power fs thin-disk laser oscillators.

- Thin-disk laser modules are commercially available from the IFSW www.ifsw.uni-stuttgart.de

As our laser developers say: “no disk, no fun”!
Join us at the next **Stuttgart Laser Technology Forum (SLT’14)** 24. - 25. June 2014
together with the International trade fair for laser material processing in Stuttgart