Appolo

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Introduction

- **Ultrashort pulse lasers** are a proven tool for high quality laser micromachining.

- The **high throughput** requirement is the key factor for the wider industrial acceptance.

- Minimum surface roughness is achieved with a spatial overlap of two consecutive pulses of 50-75 % [1].

- **High repetition rate** lasers operating at > 1 MHz are needed for the high throughput.

- For a given material, there is an **optimal fluence (pulse energy)** at which maximum specific removal rate (removal rate per average power) is achieved [2,3].

\[
P_{\text{average}} = E_{\text{pulse}} \times f_{\text{rep}} \Rightarrow \text{to work at high rep rates high average power is needed}
\]

=> Demand for laser systems with high average power and high repetition rate.

2. Raciukaitis, G. et al. JLMN 4, 186, 2009
Introduction

- **Appolo** EU FP7 project [http://www.appolo-fp7.eu/](http://www.appolo-fp7.eu/)

- Collaboration between the end-users, research labs and laser manufacturers (21 partners, 8 countries)

- **Requirements for the laser system for high speed surface texturing**
  - high rep rate $> 3$ MHz,
  - high average power $\sim 100$ W,
  - ultrashort pulses $\leq 500$ fs,
  - compact foot print,
  - low cost,
  - robust system,
  - ...
Appolo – Hub of application laboratories for equipment assessment in laser based manufacturing

http://appolo-fp7.eu/
Oscillators with SESAM modelocking technology

- In order to get ultrafast pulses (picosecond or femtosecond), one needs to achieve the effect of modelocking in a laser.
- At Lumentum (TBP) we use our proprietary SESAM® (SEmiconductor Saturable Absorber Mirror) technology developed by Prof. U. Keller at ETH Zurich.

- “Nonlinear mirror” – has higher reflectivity for pulsed light than for continuous light, i.e. laser “naturally” prefers pulsed light.

- “Simple” piece of semiconductor gives reliable ultrafast laser performance, allowing for a broad range of precision pulsed laser systems.
Laser System Design: Oscillator

- **MOPA:** YBIX oscillator + 2-stage SCF amplifier

- **Why YBIX?**
  - Robust SESAM® mode-locking
  - High peak power
  - Ultrashort pulses, 200 fs

- **Customized YBIX oscillator parameters:**
  - 2.8 W, 83.4 MHz, 1030.3 nm, FWHM = 2.4 nm, < 400 fs, M2<1.1

![Autocorrelation trace of 380 fs at 2.8 W.](image1)

![Beam profile measured at 200 mm distance from the housing at 2.8 W.](image2)
Laser System Design: Amplifier choice?

- Need high rep rate 1-10 MHz, high power ~100 W, and sufficient pulse energy 20-50 μJ
- To be simple, compact, low cost, reliable…

- Semiconductor material has very short upper state lifetime preventing the generation of μJ pulse energies

- Fiber amplifier: high gain in one stage (20-30 dBs), but due to high nonlinearities, for μJ pulse energy, one needs chirped pulse amplification (CPA), which is bulk optics, resulting in increased complexity, cost, size and reliability

- Bulk (crystal) solid-state amplifier: broadband materials enabling fs pulses are low gain. ~40 dBs gain would require 3-4 stages of amps.
Laser System Design: Amplifier using Single Crystal Fiber

- Why single crystal fiber (SCF)?
  - A short rod fiber or a thin and long crystal
  - Direct amplification of femtosecond pulses avoiding the standard CPA technique
  - Designed for a pump light guidance and a free-space propagation of a laser signal

- SCF: 1 mm diameter 1% doped Yb:YAG rod

`picture credits: property of Fibercryst SAS`
Laser System Design

- No CPA

1st stage amplifier:
- Double-pass signal configuration using the retro-reflective mirror and Faraday rotator
- High brightness 105-µm fiber-coupled pump diode, 140 W, 940 nm

2nd stage amplifier:
- Single-pass signal configuration
- Bidirectional pumping: 105-µm fiber-coupled diode, 140 W, 940 nm and 200-µm fiber-coupled diode, 200 W, 940 nm
Gain Curves

- **1st stage amplifier:**
  - Small signal gain: >32 dB
    - Highest small signal gain with SCF so far
  - Maximum output power: 42 W
  - Extraction efficiency: 28 %

- **2nd stage amplifier:**
  - Maximum output power: 162 W
    - Highest average power of femtosecond pulses achieved with SCF so far
  - Extraction efficiency: 42 %
    - Highest value achieved with SCF so far
# Beam quality

## Beam quality factor, $M^2$

<table>
<thead>
<tr>
<th>Oscillator</th>
<th>@ 102 W output</th>
<th>@ 124 W output</th>
<th>@ 162 W output</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 1.1, 1.1</td>
<td>1.3, 1.3</td>
<td>1.4, 1.5</td>
<td>1.9, 1.9</td>
</tr>
</tbody>
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**Graph:**

- **Graph Title:** $P = 102$ W
- **Equation:** $M^2_x = 1.3$, $M^2_y = 1.3$
### Beam quality

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For an output power of 124 W, the beam quality factor, $M^2$, is $1.4, 1.5$. 

- $P = 124$ W
- $M^2_{x} = 1.4, M^2_{y} = 1.5$
## Beam quality

### Beam quality factor, $M^2$

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P = 162 W  
$M^2_x = 1.9$, $M^2_y = 1.9$
Spectrum and Pulse Duration

Optical spectrum centered at 1030.5 nm with 1.7 nm full width half-maximum at maximum output power of 160 W.

Autocorrelation trace of 800 fs at maximum output power of 160 W.
Summary and Outlook

- **Compact laser system that delivers >100 W femtosecond pulses** with only 2 amplifier stages
- High brightness pumping results in the **highest small signal gain (close to 33 dB)** achieved so far
- We implemented **bidirectional pumping scheme of SCF amplifier** for the first time, and this allowed us to reach 160 W with 2 amplifier stages
- **Highest average power of femtosecond pulses achieved with SCF**

- Currently working on beam quality improvement of 160 W beam and pushing further for higher
- Combine pump diodes and pump harder to achieve higher output average power
THANK YOU for your attention!

- My colleagues at Lumentum, especially Dr. Vesna Markovic

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