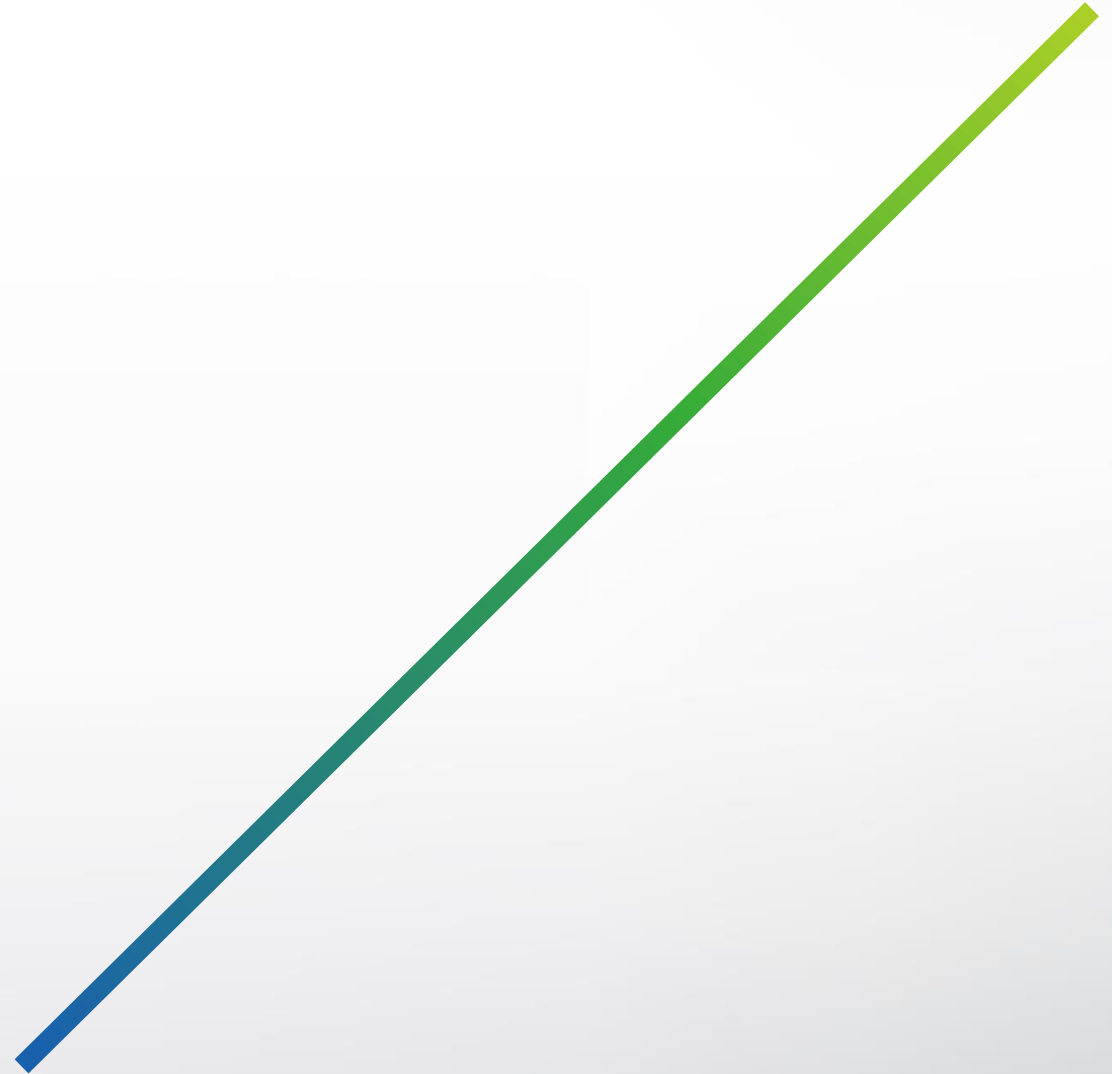


Appolo

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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]

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

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

1. Jaeggi, B. et al. Proc. of SPIE 8243-20, 2012
2. Raciukaitis, G. et al. JLMN 4, 186, 2009
3. Neuenschwander, B. et al. Proc. of SPIE 7584, 2010

Introduction

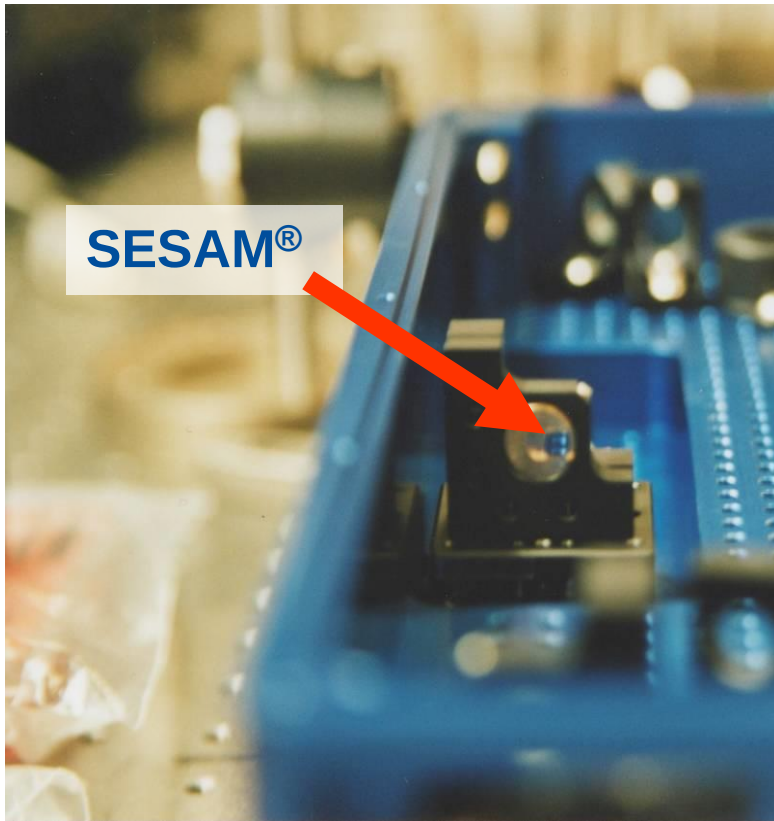
- **Appolo** EU FP7 project <http://www.appolo-fp7.eu/>
- Collaboration between the end-users, research labs and laser manufacturers (21 partners, 8 countries)
- **Requirements for the laser system for high speed surface texturing**
 - high rep rate > 3 MHz,
 - high average power ~ 100 W,
 - ultrashort pulses ≤ 500 fs,
 - compact foot print,
 - low cost,
 - robust system,
 - ...

Appolo – Hub of application laboratories for equipment assessment in laser based manufacturing



Oscillators with SESAM modelocking technology

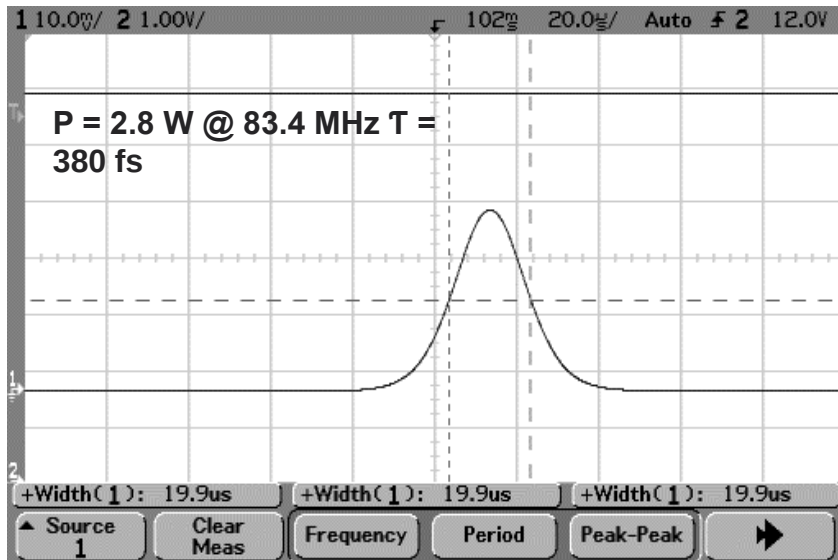
- In order to get ultrafast pulses (picosecond or femtosecond), one needs to achieve the effect of modelocking in a laser.
- At Lumentum (TBP) we use our proprietary SESAM[®] (SEmiconductor Saturable Absorber Mirror) technology developed by Prof. U. Keller at ETH Zurich.



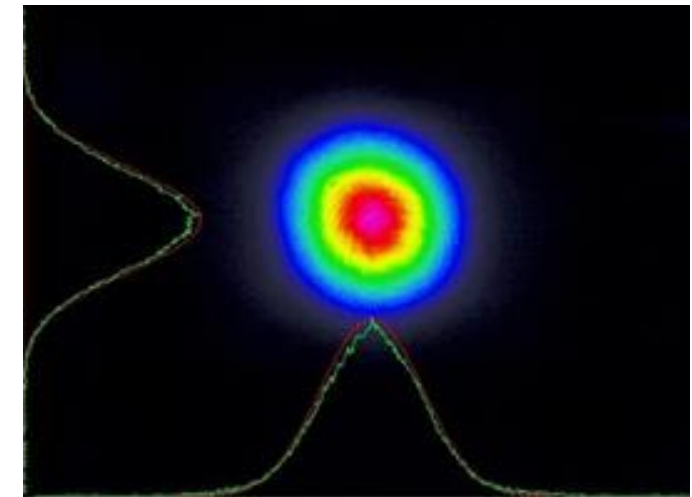
- “Nonlinear mirror” – has higher reflectivity for pulsed light than for continuous light, i.e. laser “naturally” prefers pulsed light.
- “Simple” piece of semiconductor gives reliable ultrafast laser performance, allowing for a broad range of precision pulsed laser systems.

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.



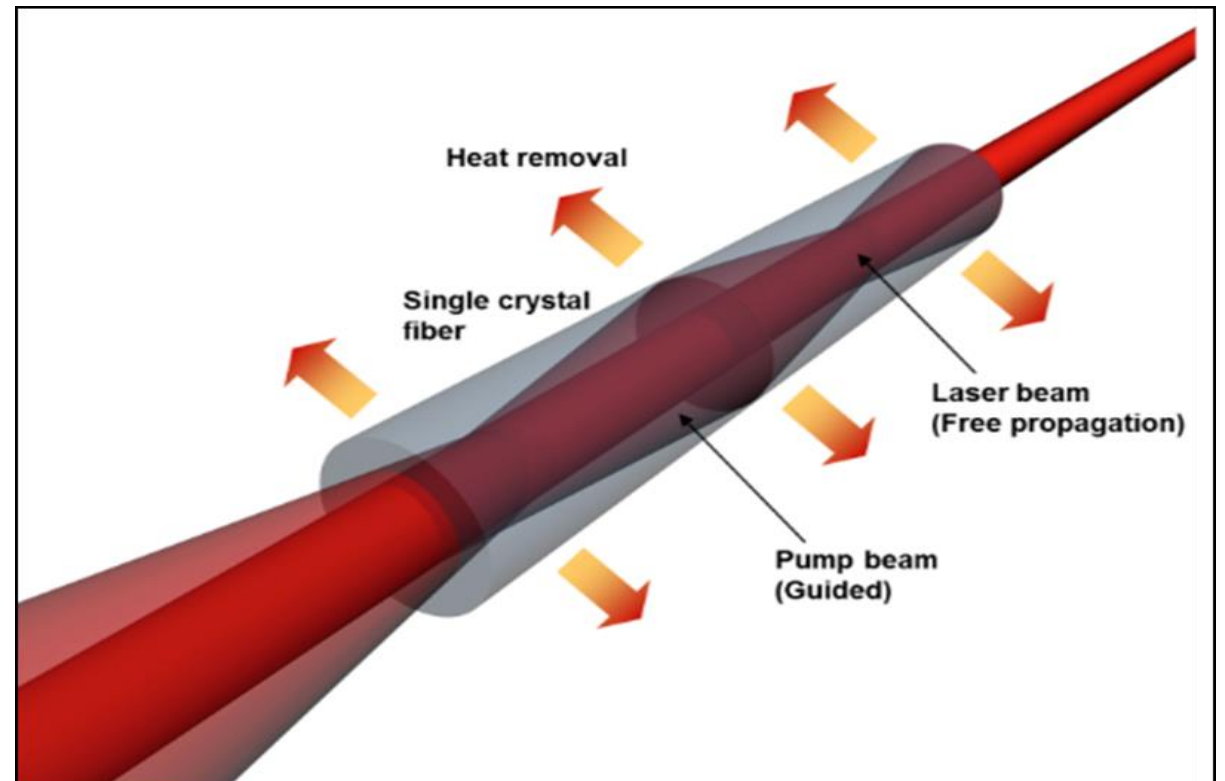
Beam profile measured at 200 mm distance from the housing at 2.8 W.

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.

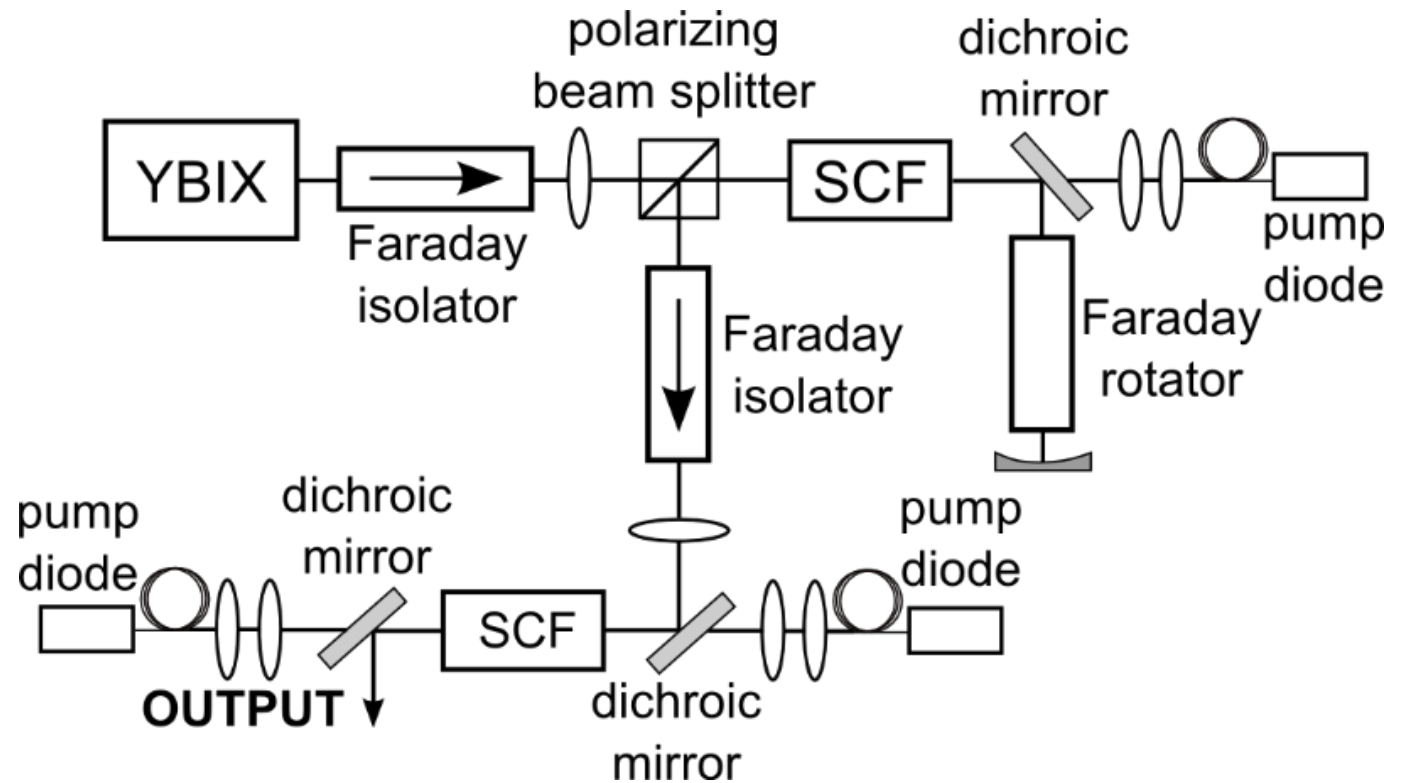
Laser System Design: Amplifier using Single Crystal Fiber

- 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



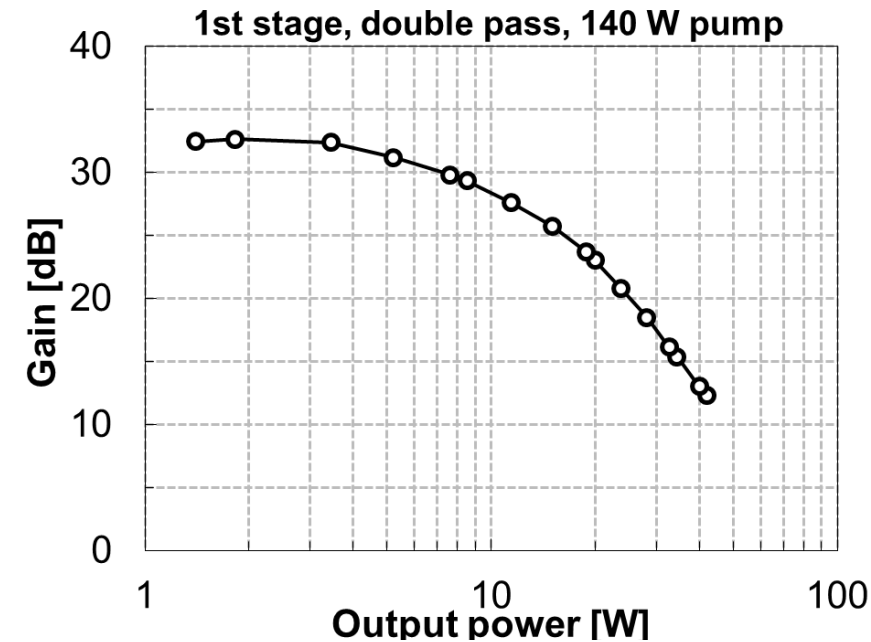
picture credits : property of Fibercryst SAS

Laser System Design



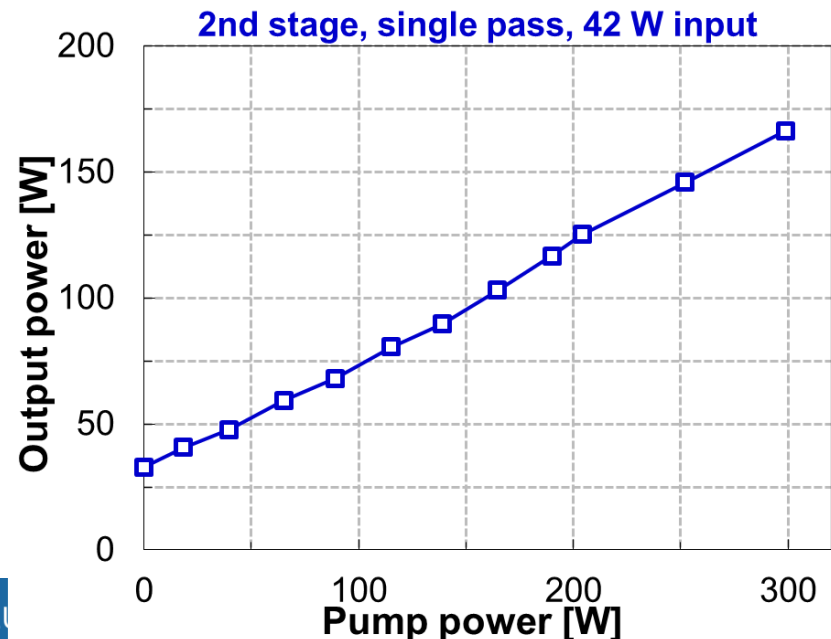
- No CPA
- **1st stage amplifier:**
 - Double-pass signal configuration using the retro-reflective mirror and Faraday rotator
 - **High brightness 105- μ m fiber-coupled pump diode, 140 W, 940 nm**
- **2nd stage amplifier:**
 - Single-pass signal configuration
 - **Bidirectional pumping:** 105- μ m fiber-coupled diode, 140 W, 940 nm and 200- μ m 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 %**

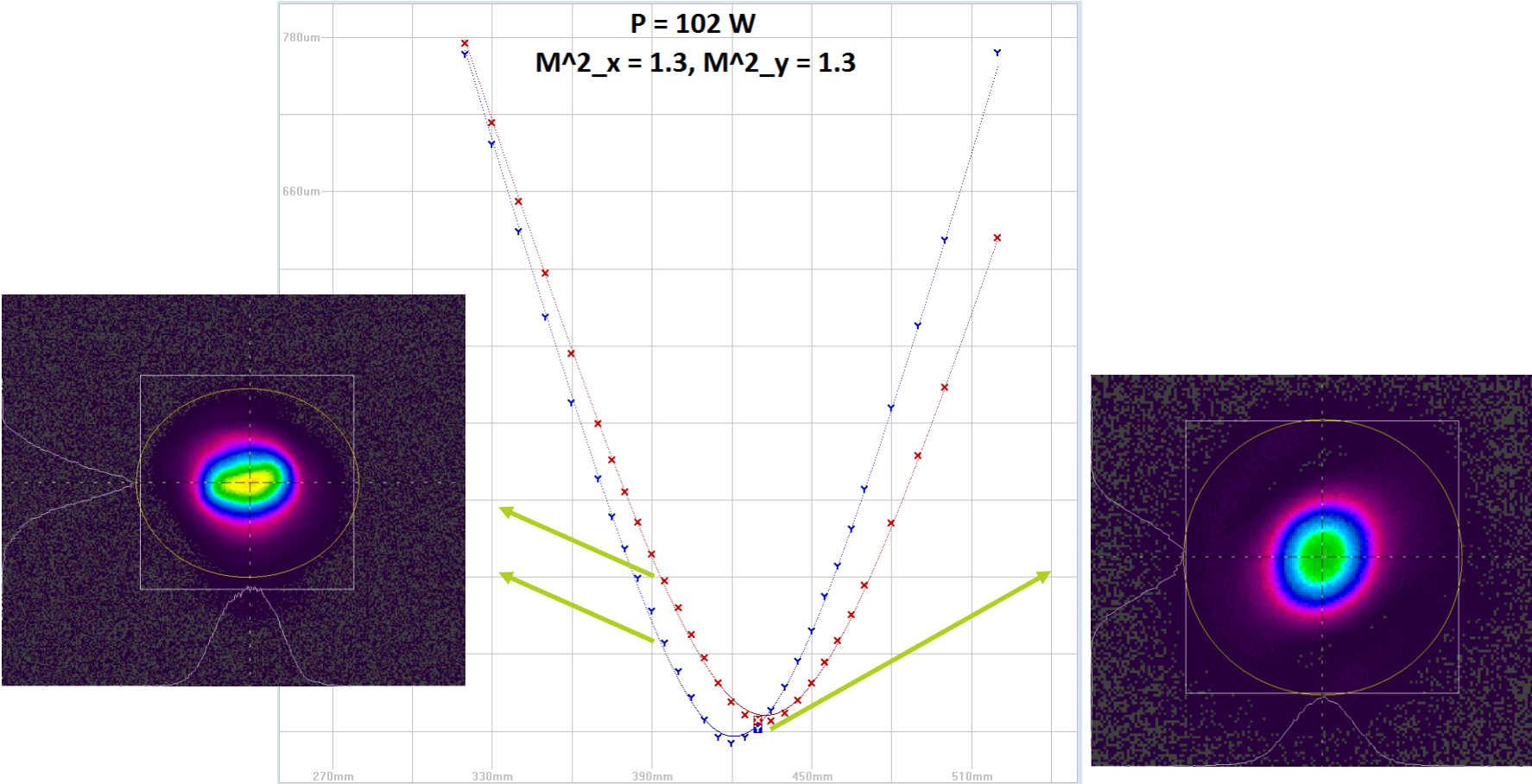


- **2nd stage amplifier:**

- 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**

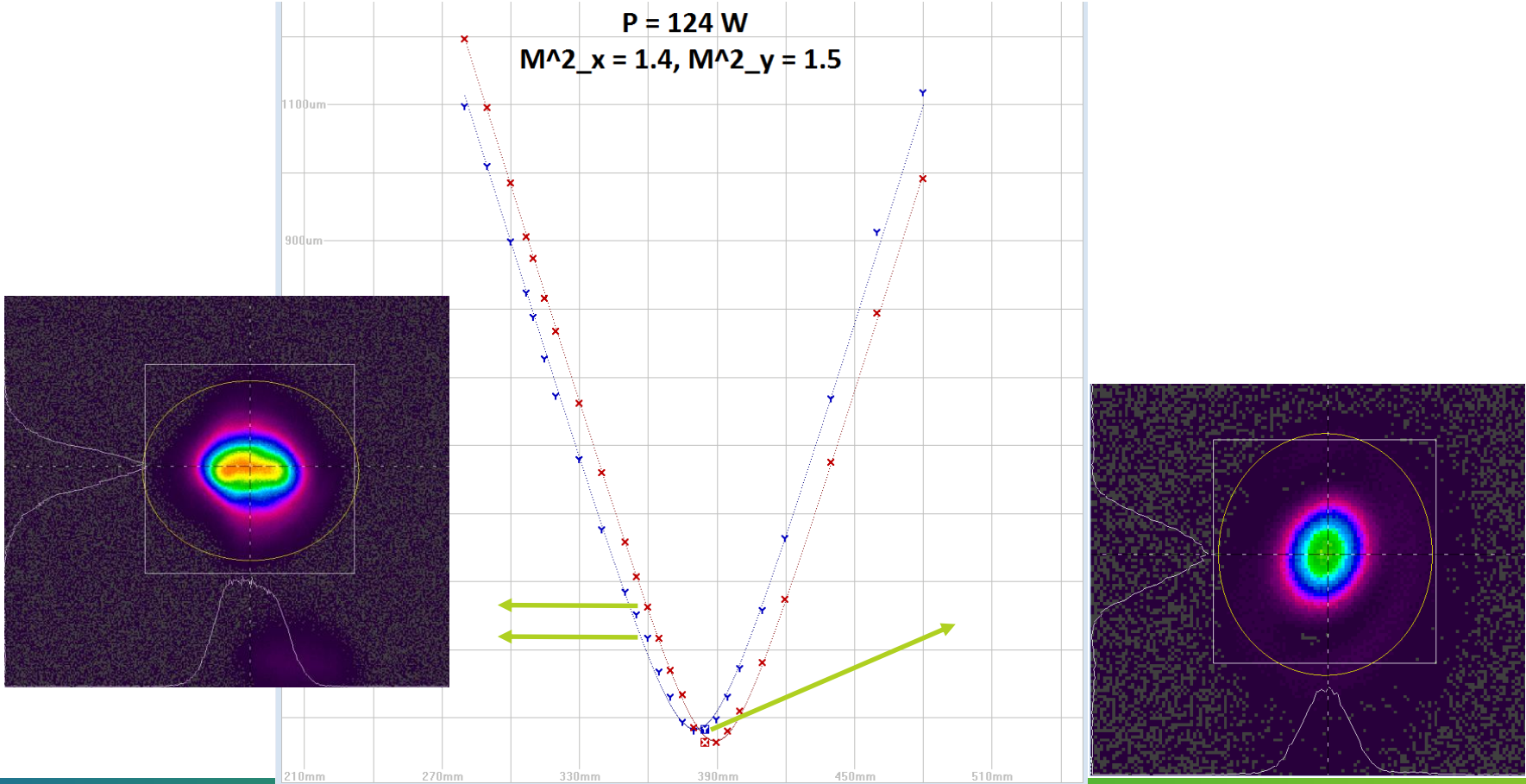
Beam quality

Beam quality factor, M^2			
Oscillator	@ 102 W output	@ 124 W output	@ 162 W output
< 1.1, 1.1	1.3, 1.3	1.4, 1.5	1.9, 1.9



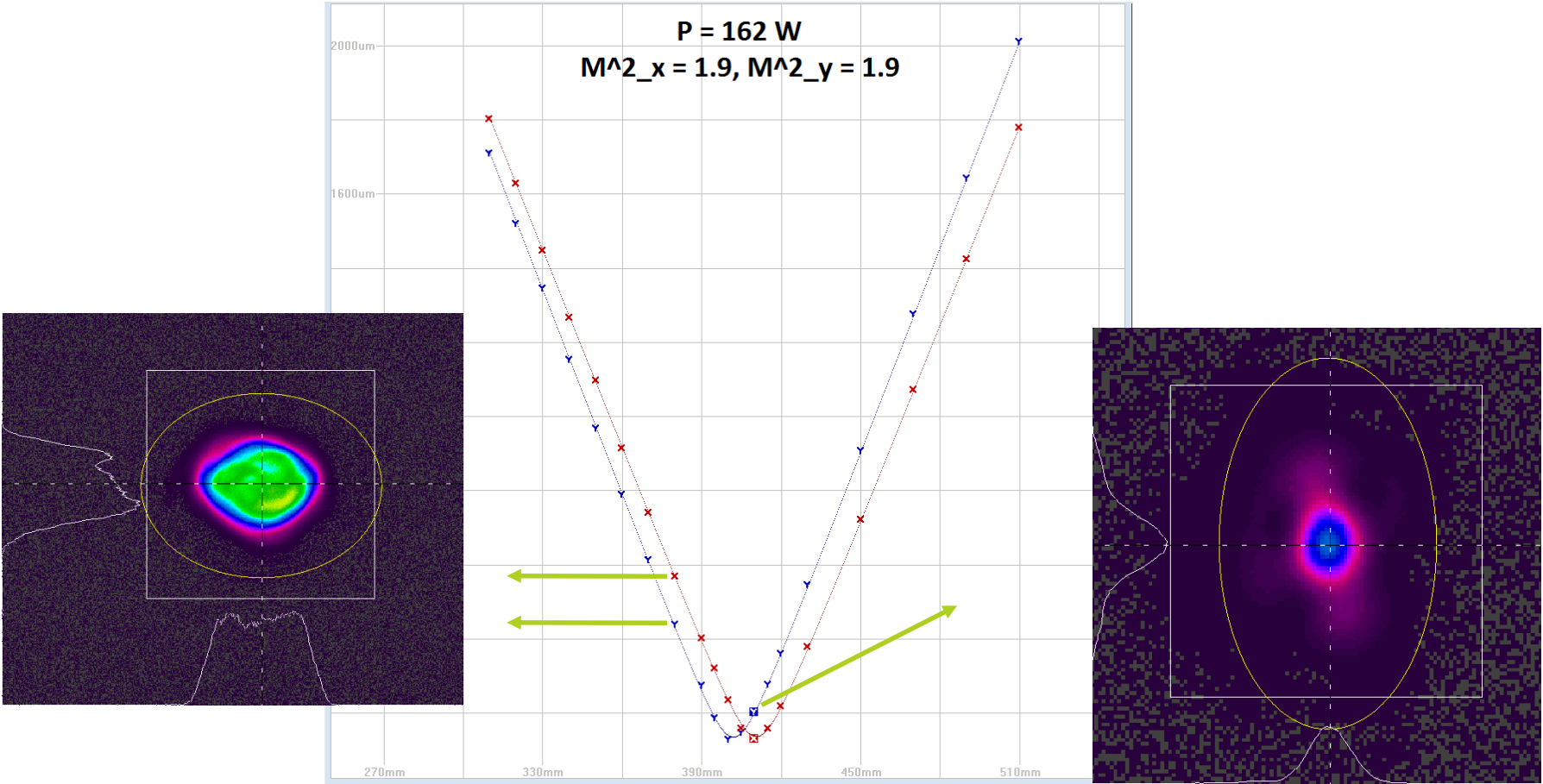
Beam quality

Beam quality factor, M^2			
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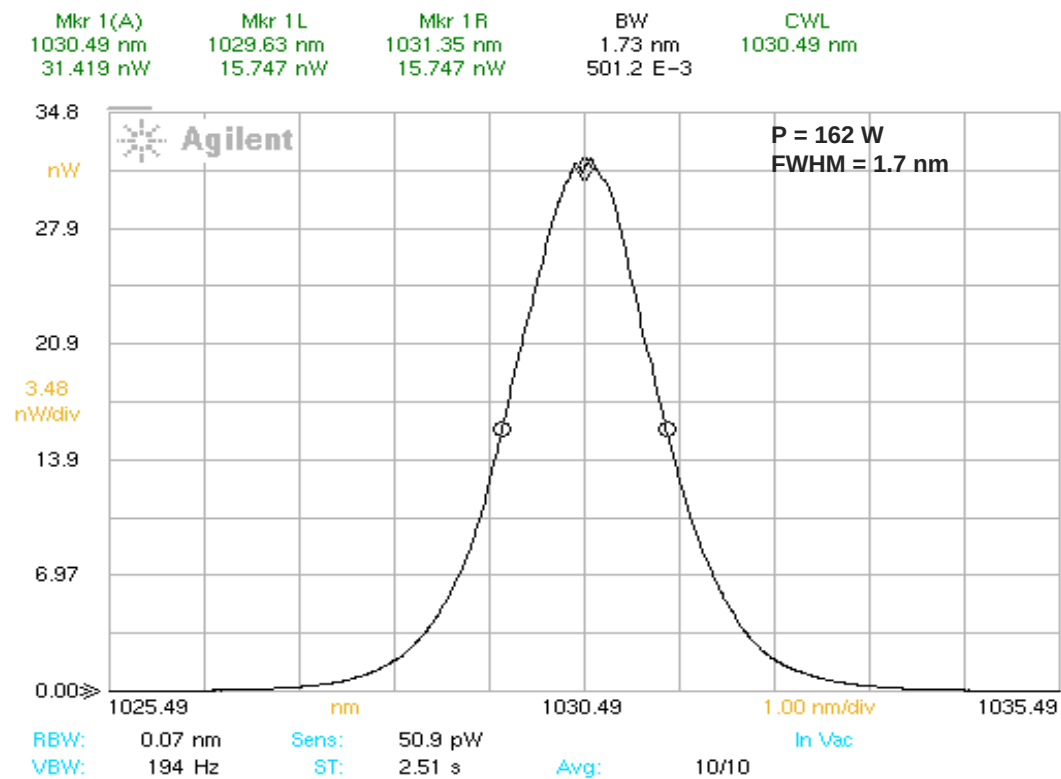


Beam quality

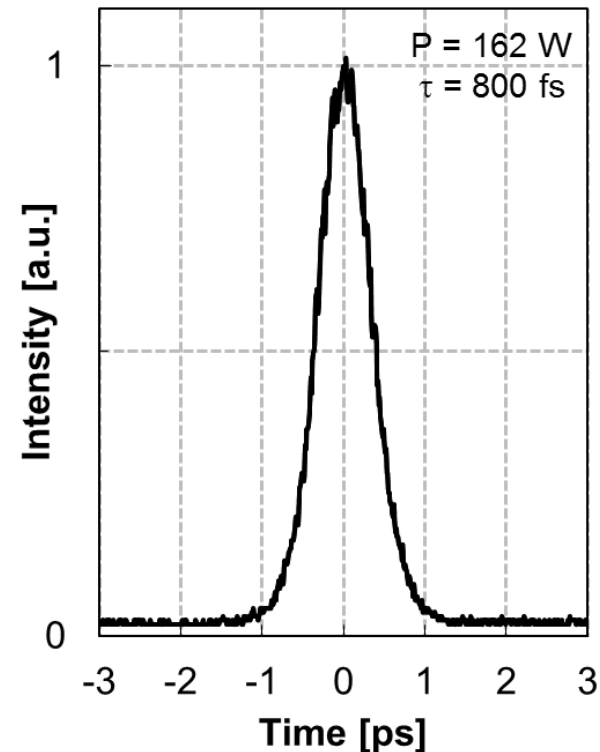
Beam quality factor, M^2			
Oscillator	@ 102 W output	@ 124 W output	@ 162 W output
< 1.1, 1.1	1.3, 1.3	1.4, 1.5	1.9, 1.9



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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