Tunable millijoule laser based on Yb:CaF$_2$ : from nanosecond to femtosecond

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• Company activity
• Technology and products
• Motivations
• Experimental results
• Conclusion
- Created in 2000

- >100 employees in ultrafast lasers

- 20M€ turnover

- Products sold in more than 20 countries

- Industrial and scientific lasers

- Applications in medical, semiconductor, pharmaceutics
- A broad range of technologies
  - Ti:Sapphire lasers
  - Yb solid-state lasers
  - Yb fiber lasers
Ti:Sa high intensity lasers

Technology :
Ti:Sa: short pulses (30fs) reduces the required energy for a given peak power
Green pumps @10Hz: cost effective flash-pumped technology
Temporal contrast is a key issue

- 0.1-1PW commercially available (3-30J 30fs)

Applications :
- Electron acceleration
  Compact accelerators, wake-field regime
- Proton acceleration,
  Cancer therapy
- Interface with LINAC, synchrotrons, future of X-FEL
Applications

- High order harmonic generation,
  Attosecond physics
- Photoinjectors for LINAC
- Femtochemistry, femtosecond spectroscopy
Nanosecond pulses (3.3 ns)

- Large Heat Affected Zone (HAZ)
- Lack of reproductibility
- Need to adapt wavelength to material

Femtosecond pulses (200 fs)

- Low ablation threshold
- Limited HAZ
- Efficient and stable process
- Interaction with transparent materials is possible through multiphoton absorption

Typical heat transfer dynamics ~5 ps from electrons to lattice
Multiphoton process allows interaction with any material

High quality micromachining of metal, glass…
Technology
A new generation of ultrafast lasers

• We want:
  – A compact, reliable, high performance femtosecond laser

• We need:
  – Direct diode pumping
  – Broadband laser material
  – Efficient optical scheme

• We use:
  – Ytterbium as the active ion
  – All solid-state system
  – Small footprint optical cavities
Ytterbium lasers: The new generation of Femtosecond laser!

- Direct diode pumping capability

**Traditional femtosecond lasers:**

- Direct diode pumping capability

**Amplitude Systemes femtosecond lasers:**

- Direct diode pumping capability
Femtosecond intense lasers: nonlinear issues
Use of Chirped Pulse Amplification architecture (CPA)

**Oscillator:**
- self starting using Semiconductor Nonlinear Mirror
- compact using diode-pumping & dispersive mirrors
- Crystal based: pure soliton pulses, 10-500nJ energy
- Fiber based: compact, lower energy

**Amplifiers:**
- regenerative amplifiers using crystals (thermal limitations)
- single stage amplifiers using fibers (nonlinearity limitations)

Use of **hybrid architecture** to exploit benefits of both fiber and crystal technology
## Crystal based solid state lasers

<table>
<thead>
<tr>
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<th>Oscillator</th>
<th>Amplifier</th>
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<tr>
<td><strong>Pulse energy</strong></td>
<td>20 to 500nJ</td>
<td>Up to 2mJ</td>
</tr>
<tr>
<td><strong>Stability, reliability</strong></td>
<td>Vibration &gt;5G</td>
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<td>Thermal test: 15°C – 35°C</td>
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<td>Long term stability (12h): &lt;0.5% RMS</td>
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<tr>
<td><strong>Average power</strong></td>
<td>1 to 5 W</td>
<td>Up to 8W</td>
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Fiber lasers

High power fiber lasers

- **Active core**
- **Cladding**
- **Mirror**

**Table:**

<table>
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<tr>
<th>Feature</th>
<th>Performance</th>
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<tbody>
<tr>
<td>Average power</td>
<td>😊</td>
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<tr>
<td>High exchange area:</td>
<td>&gt;20W femtosecond laser</td>
</tr>
<tr>
<td>Vibration &gt;5G</td>
<td>😊</td>
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<tr>
<td>Pulse energy</td>
<td>😞</td>
</tr>
<tr>
<td>Non linear effects:</td>
<td>😞</td>
</tr>
<tr>
<td>20μJ for PCF</td>
<td>😞</td>
</tr>
<tr>
<td>300μJ for rod type fiber</td>
<td>😞</td>
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</tbody>
</table>
Products
- Clean room production:
  - From mechanical assembly to quality control
- High production capacity
- Vibration and temperature cycling

**Production**

- Mechanical assembly
- Laser quality control
- Oscillator alignment workstations
Product range

- t-Pulse & Mikan series
- Satsuma series
- Tangerine series
- s-Pulse series

Amplitude Systems

www.amplitude-systemes.com
Applications:

- Glass marking & engraving
- Biology: Multiphoton excitation
- Multi-photon polymerisation
- Lab-On-Chip direct writing
- Picosecond acoustics…
Applications:
• Micro-machining
• Glass marking & engraving
• Chemical & material analysis

**s-Pulse series**
- Up to 8W
- Up to 2mJ energy per pulse
- Industry ready
- Up to 300kHz repetition rate

**Satsuma series**
- Up to 10W & 20μJ
- Ultra compact
- Industry ready
- Up to 5MHz repetition rate

**Tangerine series**
- Up to 20W & 100μJ
- Pulse duration <100fs up to 10ps
- Industry ready
- Up to 2MHz repetition rate
Sensitivity to environment

Temperature fluctuations

Average power

Temperature (°C)

Output power (W)

Time (hours)
**Pointing stability**

**Pointing stability long-term**: < 10µrad rms over 2 heures (divergence 700µrad)

**Pointing stability short-term**: approx. 2 µrad rms over 5 mn
Energy performances

Example: s-Pulse HP

CW pumping allows any rep rate
No need for compressor readjustment

Versatile source: well adapted for ablation process optimisation
Applications

- MEDICAL DEVICE MFG
- IMAGING
- EYE SURGERY
- INSTRUMENTATION
- MICRO-MACHINING
- PHARMA
- DISPLAY
- SCIENTIFIC RESEARCH
- SEMICONDUCTOR
- NANOTECHNOLOGY
- PHOTOVOLTAIC
Strong R&D activity

Motivations:
- Shorter pulses for specific materials ablation
- Higher power for higher process speed
- Higher intensity for new applications

Recent results:
- Sub-100fs post-compression (60fs 300µJ @ 5kHz)
- High energy femtosecond fiber laser (60W 600µJ 300fs)
- Thin disk Yb:YAG picosecond laser source (20W 500µJ <1ps)
- Thin disk laser based on Yb:Calgo
- High average power cryocooled Yb:CaF\textsubscript{2} laser
- Femtosecond Yb:CaF\textsubscript{2} lasers
Post-compression in LMA fiber / gas capillary:
1. Spectral broadening by SPM in fused silica / gas (nitrogen)
2. Monomode guiding
3. Dispersion compensation (dispersive mirrors)

Allows to achieve sub-100fs pulse duration with
- >50% overall transmission
- Compact architecture

Low energy 500nJ 400fs $P = 1.2\text{MW}$

High energy 600µJ 500fs 5kHz $P = 1.2\text{GW}$

Femtosecond laser $\rightarrow$ Isolator $\rightarrow$ LMA fiber $l \sim 1-3 \text{ cm}$

Gas capillary $l \sim 15 \text{ cm}$ $\rightarrow$ GTI mirrors

250nJ 40fs $P > 5\text{MW}$ !

300µJ 60fs $P > 5\text{GW}$ !
Thin disk Yb:Calgo

Experimental setup

Power performances

CW tunability
Coherent combining

Up to 650µJ 300fs at 100kHz
Using 2 rod-type fibers, >90% combining efficiency
Fully passive architecture : high robustness
Cryo-cooled Yb:CaF$_2$

Demonstration of 97W pumped with 245W
Collaboration between LCFIO, CIMAP and Amplitude Systemes
Moderate thermal lensing
Yb:CaF$_2$ : broadband material

Multisite

Charge compensation

Crystalline reorganization

Clusters

Broad bands

Experimental demonstrations (room temperature):

• Tunability CW : 1018 – 1072 nm

• Femtosecond oscillator : 150 fs @ 1043 nm

• High energy amplification : 190 mJ 190 fs @1Hz
  *Siebold et al, Opt Lett, 33, 2770 (2008)*

• High rep rate CPA laser: 0,7 mJ 180 fs @100-10kHz

Interest for higher intensities and high repetition rate
Experimental setup

Zero-line pumping for lower heat deposition

Yb:CaF\(_2\) : 2.5 to 4.5\% doping concentration, 3 to 5mm thickness

Conductively cooled on a water cooled baseplate
Energy vs repetition rate

Typical performances: Energy vs repetition rate

Pulse duration: 10ns (roundtrip time)
High extracted energy for moderate pump power (<10W)
Optimum repetition rate ~ 300 Hz

Energy (mJ) vs Repetition rate (Hz)

Average power (mW)
Excellent beam quality: $M^2 = 1.10 \times 1.07$
Spectral investigations

Qswitched output spectrum depends on pumping conditions

Spectral gain measurement confirms broadband spectral gain
Up to 3mJ extracted at 100Hz for 10W pumping

Tunable between 1030 and 1065nm, max @1050nm!
Discussion

Optimum of energy at 1050nm
trade-off between gain and extractable energy

Specific to Quasi Three Level nature

1030nm

Extractable energy

Transparency level

1050nm

Excited ions
Improved design for 5mJ regenerative amplification (17W CW pump power)

Seeded by fiber oscillators
• Compacity and integrability
• Investigate 2 different spectral ranges : 1034nm and 1053nm

Diffraction grating stretcher & compressor :
• Flexible and compact architecture
• ~300ps stretched pulses
Injection at 1034nm

Oscillator #1: injection with $\lambda_0 = 1034\text{nm}$
Amplification @ 1038nm, with 8.8nm bandwidth
2.5mJ recompressed energy (3.6mJ before compression) @100Hz
Recompressed pulses: 250fs
Injection at 1053nm

Oscillator #2: injection with $\lambda_0 = 1053\text{nm}$
Amplification @ 1048nm, with 6nm bandwidth
3.2mJ recompressed energy (4.8mJ before compression) @100Hz
Recompressed pulses: 320fs
Extension to 1053nm

Interest for damage threshold tests in the femtosecond regime 1053nm required for specific components (gratings, filters…) 100Hz allows long term testing

Use the same oscillator centered at 1053nm
Use spectral shaping before amplification

2mJ compressed energy @1053nm @100Hz
Recompressed pulses : 600fs for 3,5nm bandwidth
**Conclusion & Outlook**

Broadly tunable ns laser from 1030-1065nm at millijoule level

- good seeder for high energy lasers
- 10GW class femtosecond lasers at 10-300Hz
- enlarging the laser portfolio
- 2mJ 600fs achieved @1053nm
- for Nd:glass laser components qualification

**Outlook:**

*Improve the thermal management for higher average power*
Thank you for your attention!

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