Optical frequency divider based on passively mode-locked diode-pumped solid-state laser technology

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Outline

- General architecture of fs DPSSL
- Typical laser parameters
- Results obtained with different lasers (CEO stabilization, RIN, microwave generation, timing jitter)
- Radiation tests
- Vibration test
- Next steps
- Conclusions
General laser architecture

- Diode-pumped solid-state passively mode-locked femtosecond laser (femtosecond DPSSL)

![Diagram of laser architecture]

600 mW @ 976 nm

Er:Yb:glass 2 mm

10 x GTI: -100 fs²

OC: 1.7%

Passive mode-locking achieved with Semiconductor Saturable Absorber Mirror (SESAM)

- Self-starting
- Robust
- Reproducible mode-locked state
# Laser typical overall parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>Repetition rate</td>
<td>40 – 1000 MHz</td>
<td>Typical 100 MHz</td>
</tr>
<tr>
<td>Output power</td>
<td>&gt; 100 mW</td>
<td>Directly out of the oscillator.</td>
</tr>
<tr>
<td>Pulse duration</td>
<td>&lt; 200 fs</td>
<td>Soliton</td>
</tr>
<tr>
<td>Wavelength</td>
<td>1040 nm &amp; 1560 nm</td>
<td>Yb and Er doped gain media</td>
</tr>
<tr>
<td>Size</td>
<td>200 x 300 x 75 mm³</td>
<td>Typical for 100-MHz rep rate, laser head only</td>
</tr>
<tr>
<td>Power consumption</td>
<td>&lt; 10 W</td>
<td>Laser head</td>
</tr>
<tr>
<td>Weight</td>
<td>3 kg</td>
<td>Typical for 100-MHz rep rate, laser head only</td>
</tr>
</tbody>
</table>
Carrier-envelope offset frequency stabilization

**Yb:KYW laser**

- **System architecture:**
- **186 MHz, 113fs pulses, 300mW**
- **SC suitable for optical stabilization with Yb, Ca, Sr lattice clocks as well as In+, Al+, Hg+, and Sr+ ion clocks**

Carrier-envelope offset frequency stabilization

Yb:KYW

- Feedback through pump diode injection current
- Integrated phase noise: 300 mrad [0.1Hz to 1 MHz]

Low phase-noise microwave generation with DPSSL

Yb:KYW laser

- Laser stabilized on Al$^+$ optical reference cavity for microwave generation
- Result: curve (i)
- STE-QUEST microwave phase noise specifications (●):

<table>
<thead>
<tr>
<th>Frequenz (Hz)</th>
<th>Spektrale Phasenrauschdichte (PSD) (dB/√Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-90</td>
</tr>
<tr>
<td>10</td>
<td>-110</td>
</tr>
<tr>
<td>100</td>
<td>-115</td>
</tr>
<tr>
<td>1000</td>
<td>-120</td>
</tr>
<tr>
<td>10000</td>
<td>-120</td>
</tr>
</tbody>
</table>

10-GHz carrier frequency

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Carrier-envelope offset frequency stabilization

Yb:glass

- 200-mW average output power and 110-fs solitons at 1047 nm directly out of the oscillator at a repetition rate of 100 MHz
- $f_{CEO}$ detected with SNR above 40 dB in 100 kHz rbw
- No fiber amplifier required
- Simple and compact system
Carrier-envelope offset frequency stabilization

Yb:glass

- $f_{\text{CEO}}$ integrated phase noise: 736 mrad [0.001 Hz to 1 MHz]
- Long-term stability observed but will be characterized more carefully
- Very low RIN (shot-noise limited measurement)
Timing jitter of Er:Yb:glass lasers

Balanced optical cross-correlator measurement

- Er:Yb:glass lasers emits at 1557 nm

BOC provides:
- Immunity to amplitude noise
- High discriminator slope
- No limitation due to photodetection shot noise
- Requires two identical lasers
Timing jitter of Er:Yb:glass lasers

- Integrated jitter of **80 as** when integrated from 10 kHz to 5 MHz
- Several measurements with different acquisition methods give same result
- Measurement noise floor reached for frequencies above 300 kHz
- Quantum limit: **2.5 as** [10 kHz to 5 MHz]

![Graph showing jitter PSD and phase noise L(f) vs frequency](image)
RIN of Er:Yb:glass lasers

![Graph showing RIN of Er:Yb:glass lasers with frequency on the x-axis and RIN (dBc/Hz) on the y-axis. The graph compares Laser 1, Laser 2, shot-noise 1, and shot-noise 2.]
Radiation tests

Proton irradiation

- Tested solitary crystals: Yb:KYW, Yb:glass & Er:Yb:glass with dose corresponding to 5 years mission
- Tested solitary SESAMs
- Devices tested in fs lasers before and after irradiation
- About 2 weeks lag between irradiation and tests in fs lasers
- No degradation of SESAMs or laser gain media observed
Vibration tests

- Ariane 5 shock tests and random vibration tests performed up to the qualification level
- Ariane 5 vibration levels selected because most stringent among launchers
- Shock tests had no impact
- Random vibration tests:
  - Acceptance test: one direction ok, other direction 5% power drop
  - Qualification test: laser broken
- Technology already not far from being compliant! Only incremental design necessary
Future tests in the framework of the STE-QUEST assessment study

- **Gamma irradiation** of a *switched-on* laser with continuous-monitoring of “vital” laser parameters
- **Proton irradiation** of a *switched-on* laser with continuous-monitoring of “vital” laser parameters
- If time available: demonstration of long-term carrier-envelope offset frequency locking
Conclusions

- Passively mode-locked fs DPSSL technology has demonstrated ultra-high performances in particular:
  - Low relative intensity noise
  - State-of-the-art robust carrier-envelope offset frequency stabilization
  - Ultra-low pulse-to-pulse timing jitter
  - Low phase-noise microwave generation
  - Turn-key capability
  - High mechanical stability
  - Robustness against radiations (to be confirmed in a running laser)
- STE-QUEST assessment study will allow to
  - Investigate the radiation hardness of a working laser
  - Demonstrate the long term carrier-envelope offset frequency stabilization

Promising technology for a space-qualified high-performance optical frequency comb
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