STE-QUEST Workshop

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

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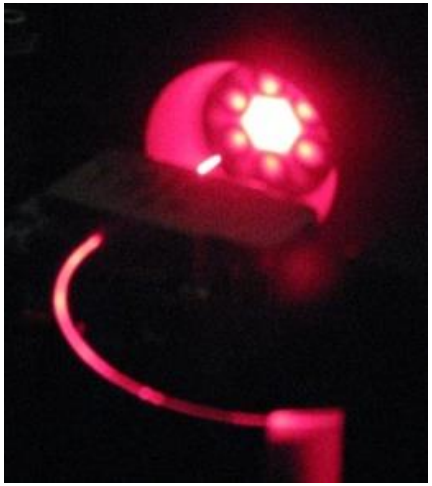


Outline

- 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)

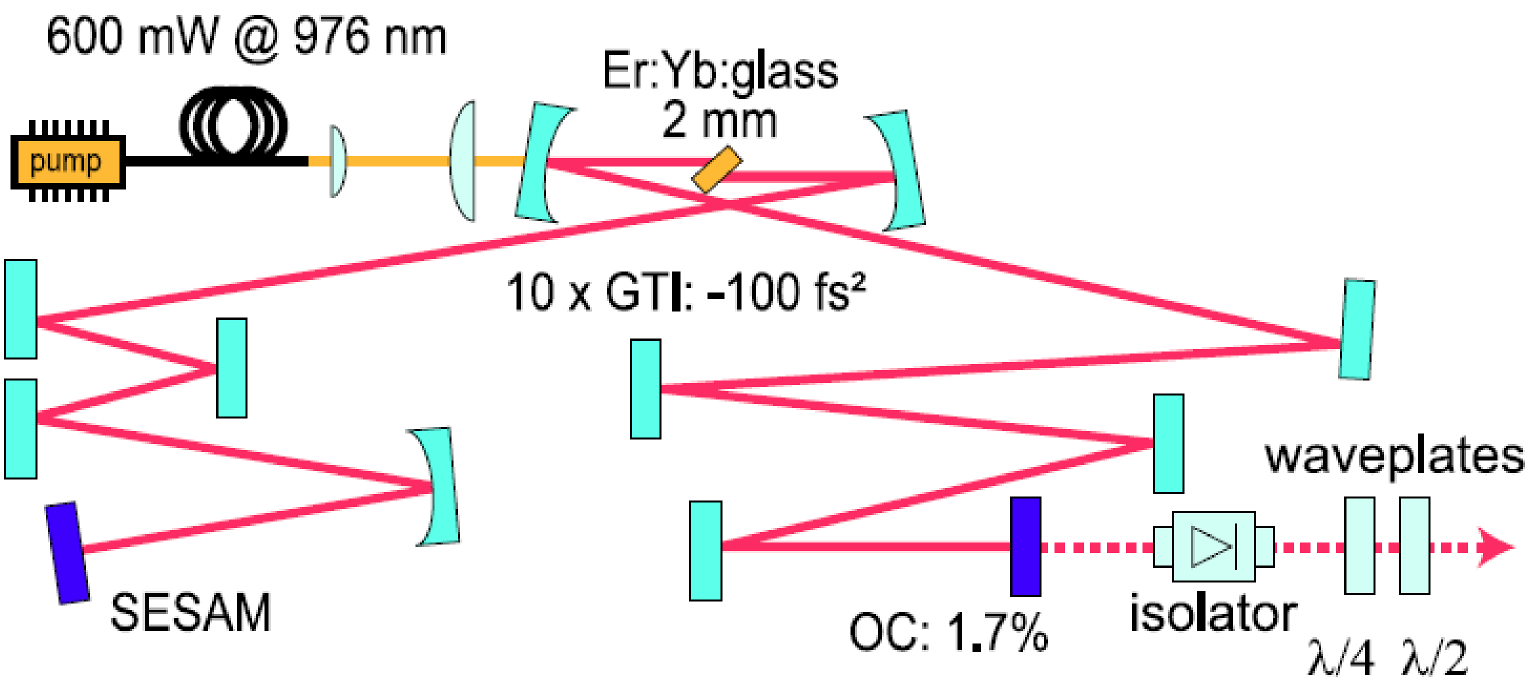
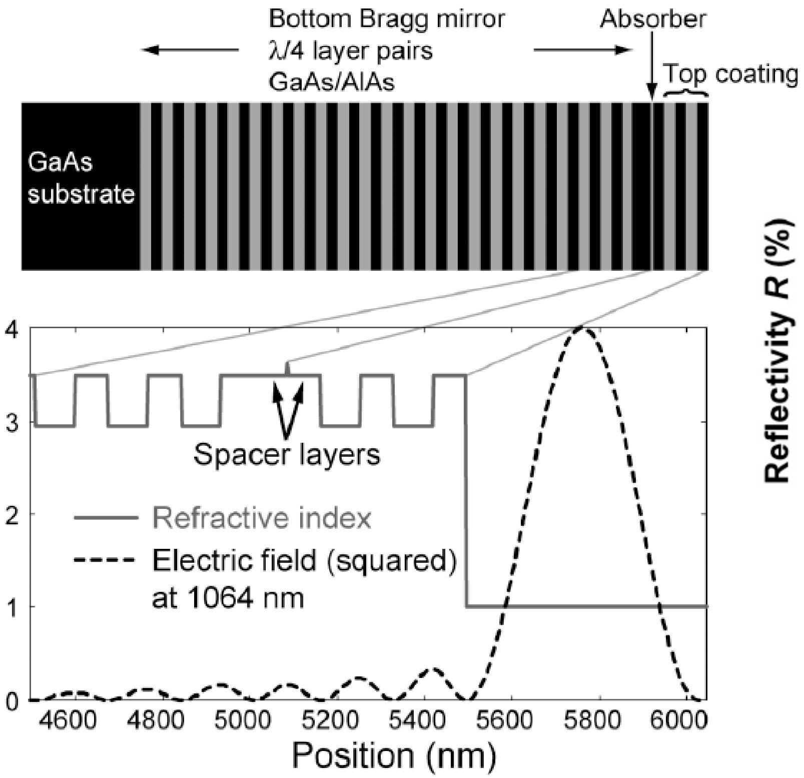
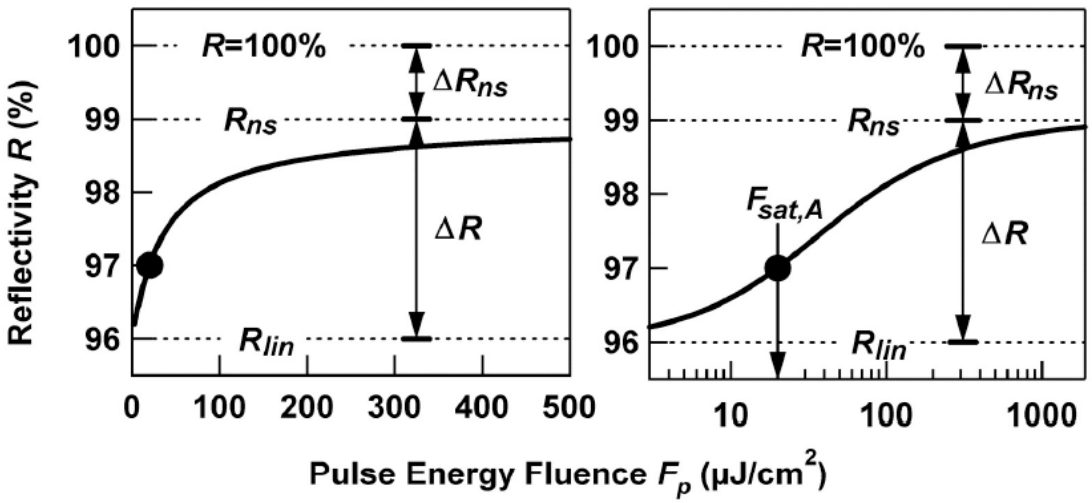


Figure taken from: M.C. Stumpf *et al.* Appl. Phys. B, **99**, 401-408 (2010)

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





- Self-starting
- Robust
- Reproducible mode-locked state

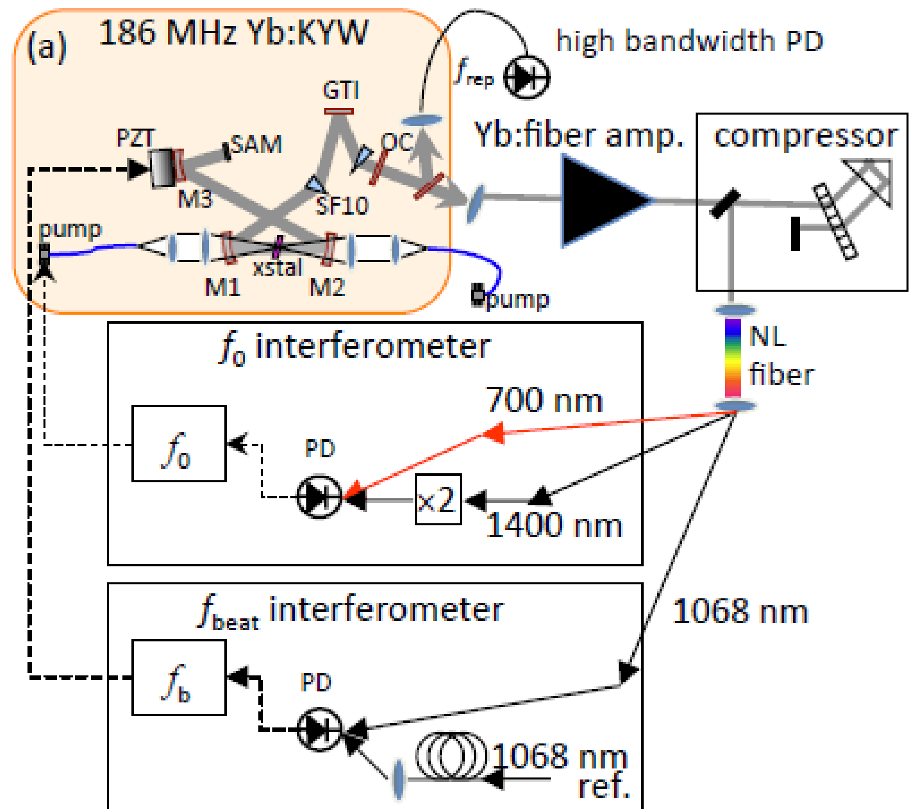
Laser typical overall parameters

Parameter	Value	Remark
Repetition rate	40 – 1000 MHz	Typical 100 MHz
Output power	> 100 mW	Directly out of the oscillator.
Pulse duration	< 200 fs	Soliton
Wavelength	1040 nm & 1560 nm	Yb and Er doped gain media
Size	200 x 300 x 75 mm^3	Typical for 100-MHz rep rate, laser head only
Power consumption	< 10 W	Laser head
Weight	3 kg	Typical for 100-MHz rep rate, laser head only

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

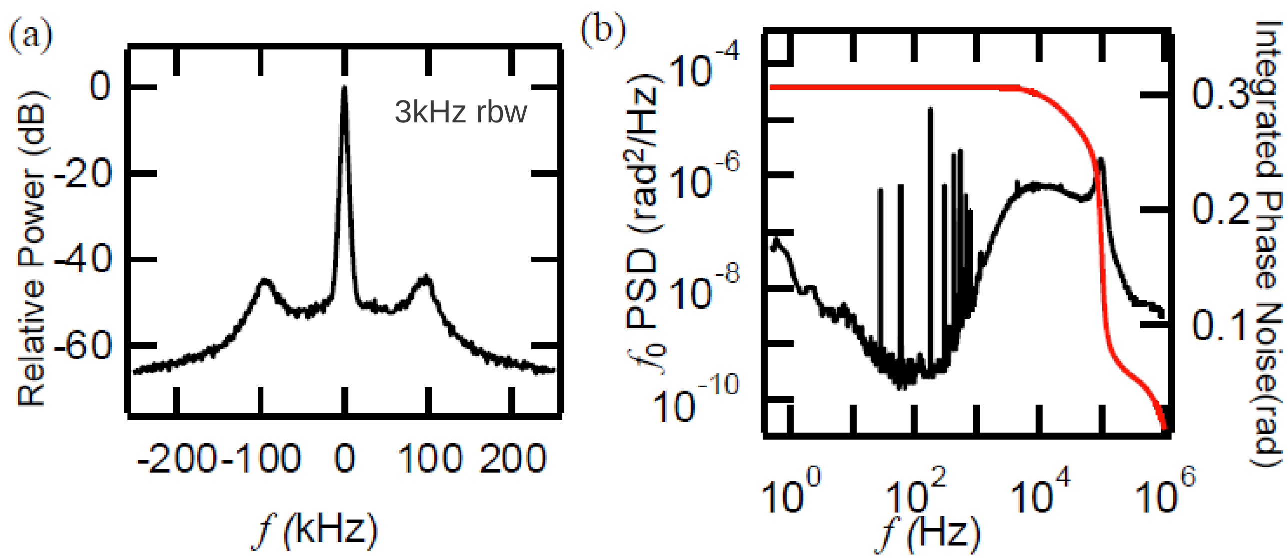


To be published in Appl. Phys. B: S. A. Meyer, T. M. Fortier, S. Lecomte, S.A. Diddams, A frequency-stabilized Yb:KYW femtosecond laser frequency comb and its application to low-phase noise microwave generation

Carrier-envelope offset frequency stabilization

Yb:KYW

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



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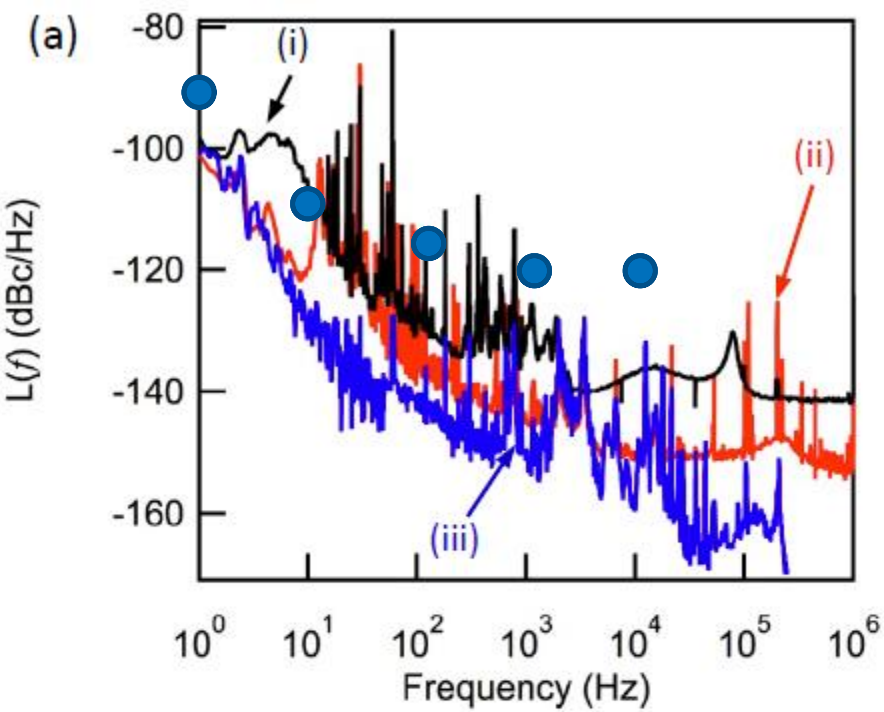
Low phase-noise microwave generation with DPSSL

Yb:KYW laser

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

Frequenz (Hz)	Spektrale Phasenrauschdichte (PSD) ($\mathrm{dBrad}^2/\mathrm{Hz}$)
1	-90
10	-110
100	-115
1000	-120
10000	-120



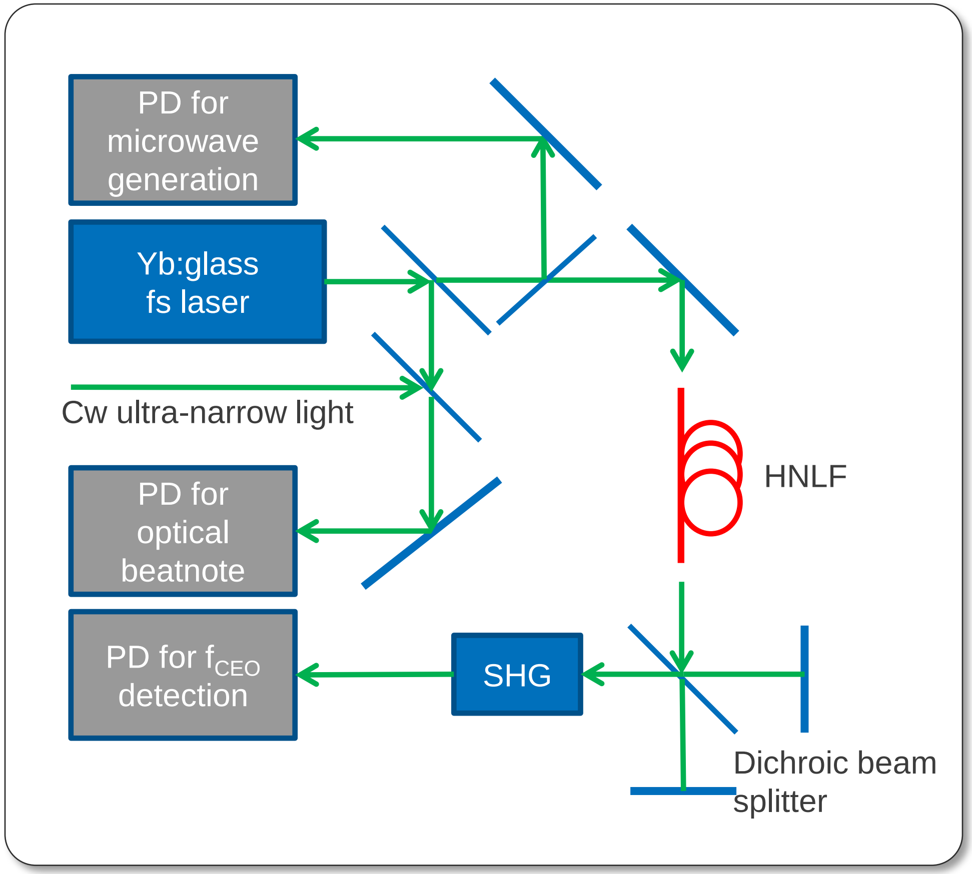
10-GHz carrier frequency

To be published in Appl. Phys. B: S. A. Meyer *et al.*

Carrier-envelope offset frequency stabilization

Yb:glass

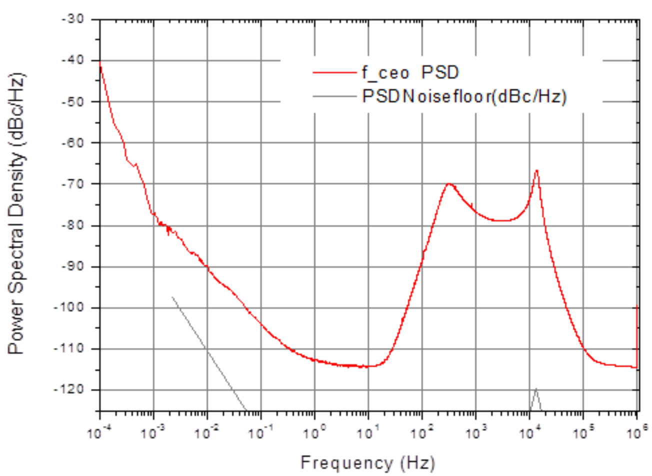
- 200-mW average output power and 110-fs solitons at 1047 nm directly out of the oscillator at a repetition rate of 100 MHz
- f_{CEO} detected with SNR above 40 dB in 100 kHz rbw
- No fiber amplifier required
- Simple and compact system

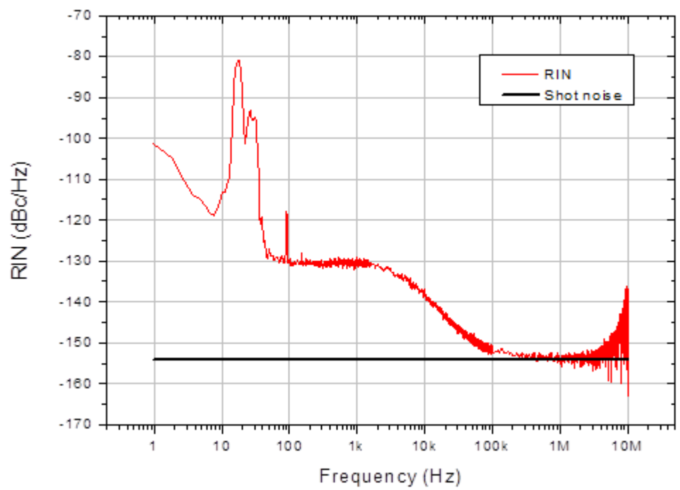


Carrier-envelope offset frequency stabilization

Yb:glass

- f_{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)





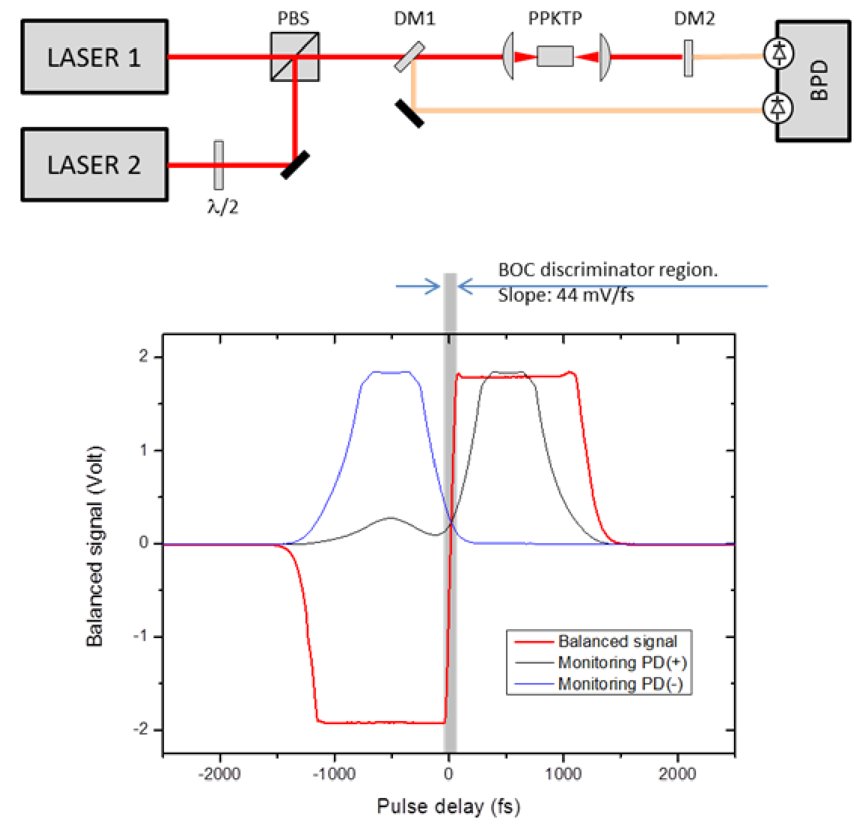
Timing jitter of Er:Yb:glass lasers

Balanced optical cross-correlator measurement

- Er:Yb:glass lasers emits at 1557 nm

BOC provides:

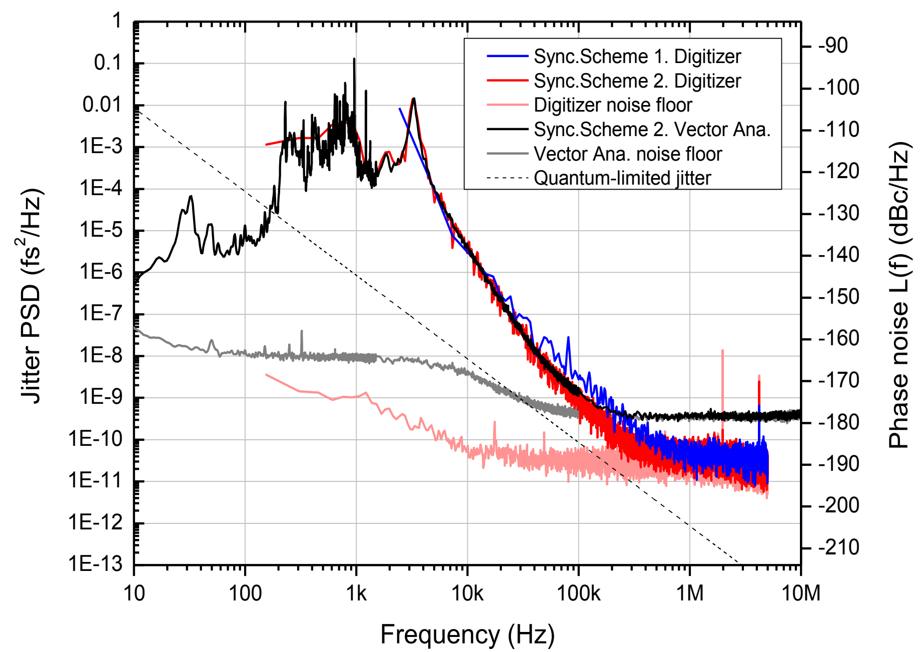
- Immunity to amplitude noise
- High discriminator slope
- No limitation due to photodetection shot noise
- Requires two identical lasers



Timing jitter of Er:Yb:glass lasers

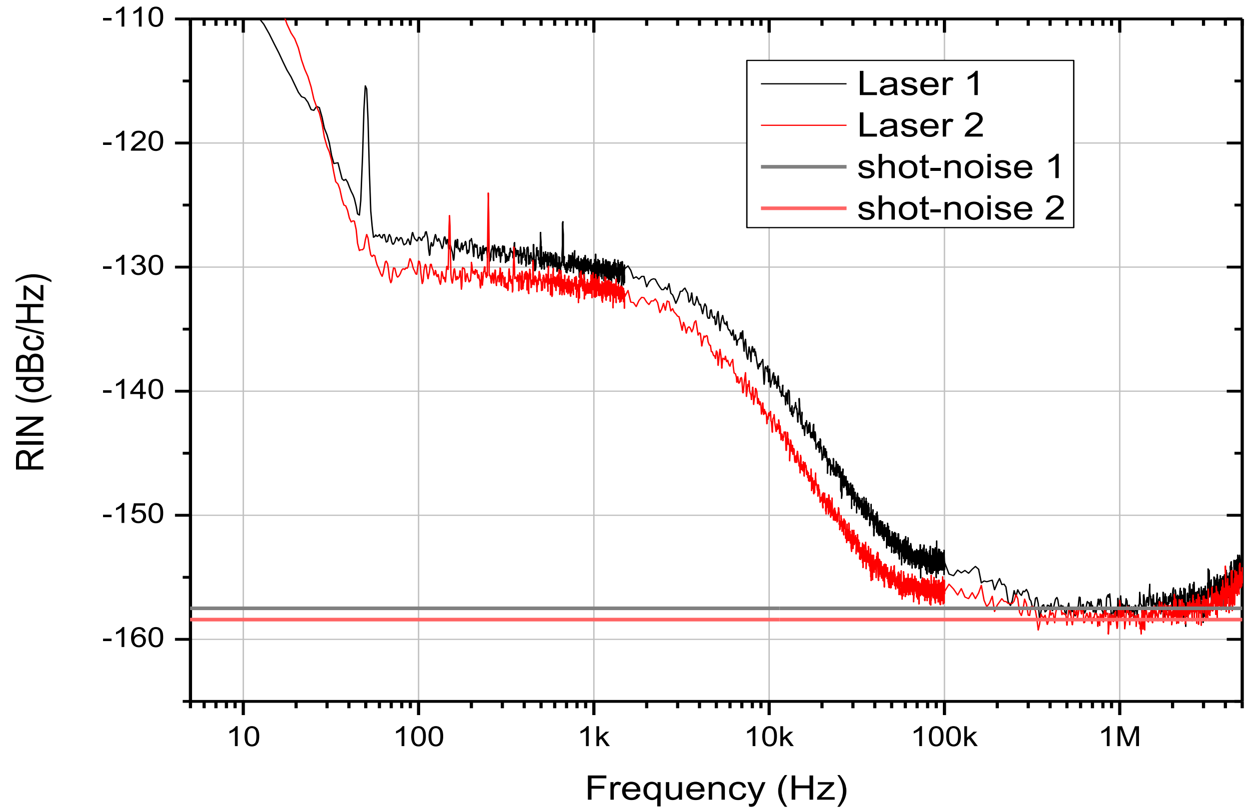
Balanced optical cross-correlator measurement

- 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]



10-GHz carrier frequency

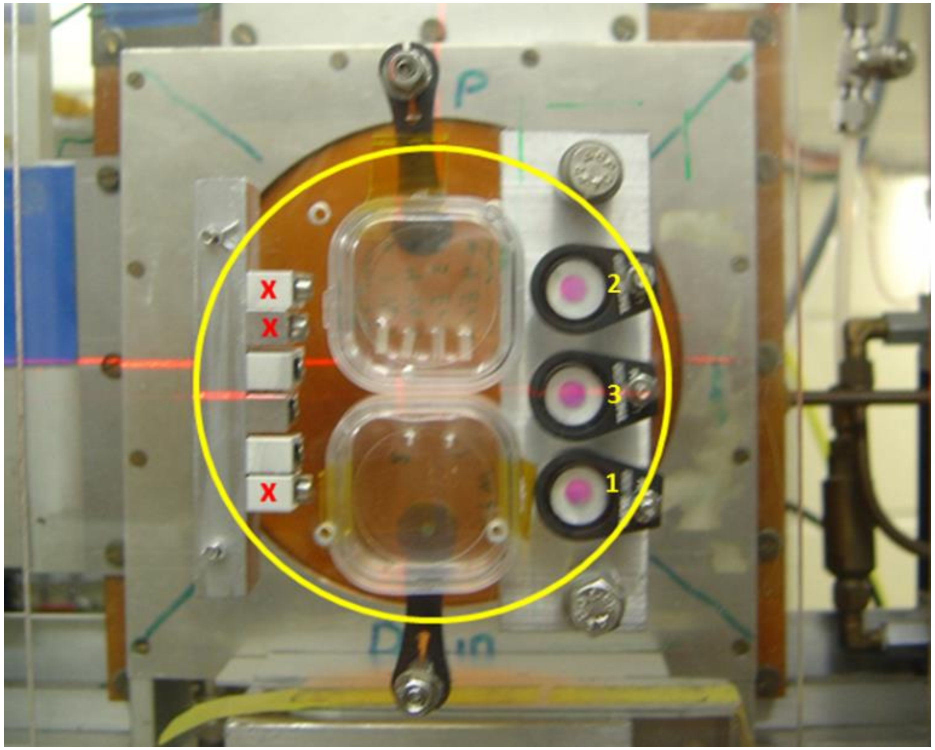
RIN of Er:Yb:glass lasers



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

Engineered laser

- 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-envelop 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 frequenc
  - Ultra-low pulse-to-pulse timing jitter
  - Low phase-noise microwave generatio
  - Turn-key capability
  - High mechanical stabili s
  - Robustness aga be confirmed in a running laser)
- STE-QUEST will allow to
  - In ation hardness of a working laser
  - te the long term carrier-envelope offset frequency stabilization

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

Acknowledgments

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