Recent advances in SESAM-modelocked high-power thin disk lasers

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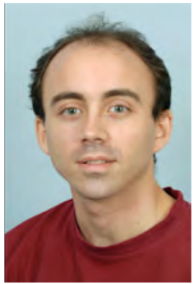
Plenary Talk

Acknowledgments

ETH Zurich


Prof. Dr. Clara Saraceno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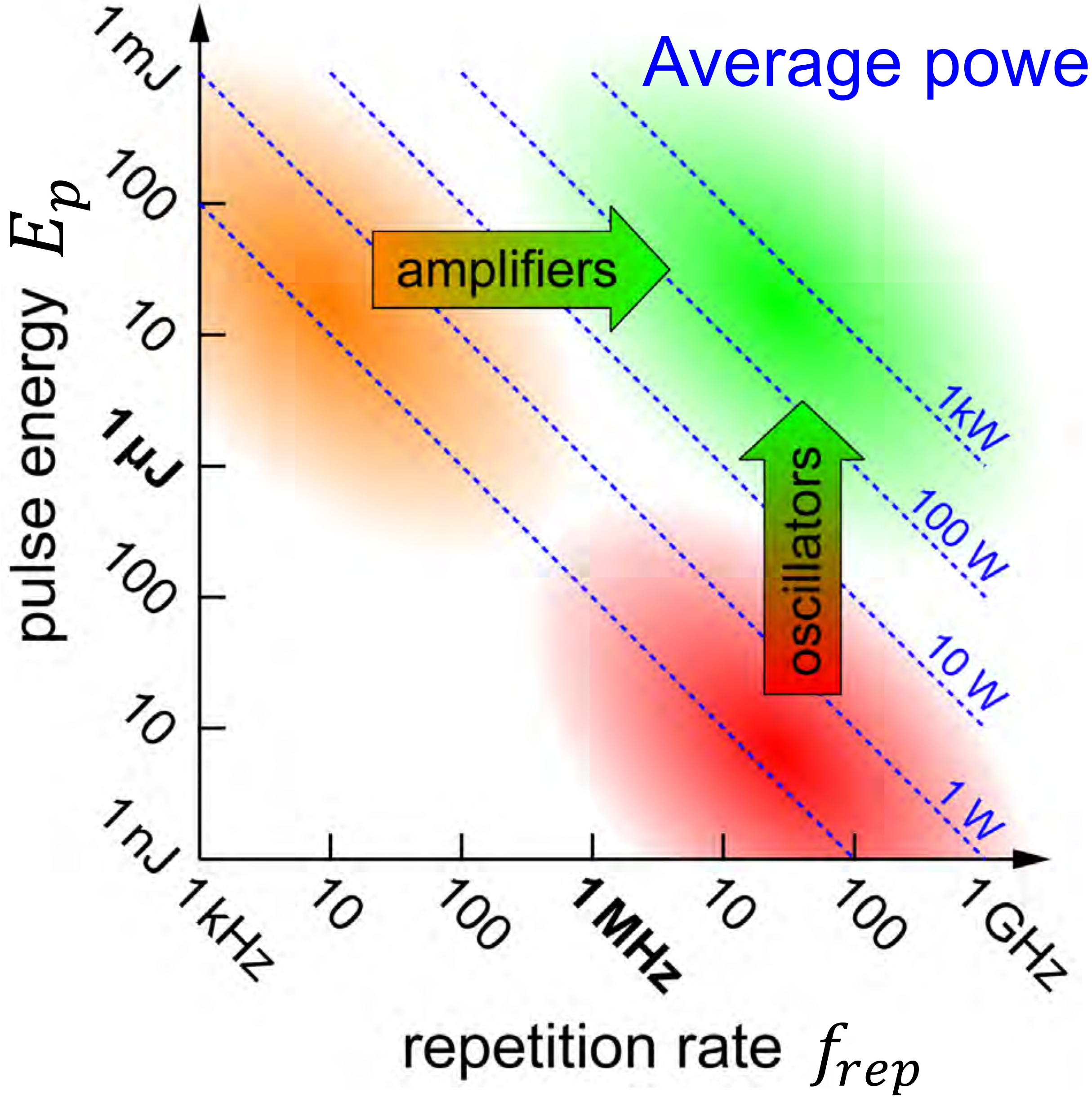
Dr. Garrett Cole

Trumpf Laser GmbH

Dr. Dirk Sutter
Dr. Dominik Bauer
Dr. Tom Metzger

High energy and high (MHz) pulse repetition rates

Average power $P_{av} = E_p \cdot f_{rep}$



Nature Photonics 2, 599, 2008

High energy and high (MHz) pulse repetition rates

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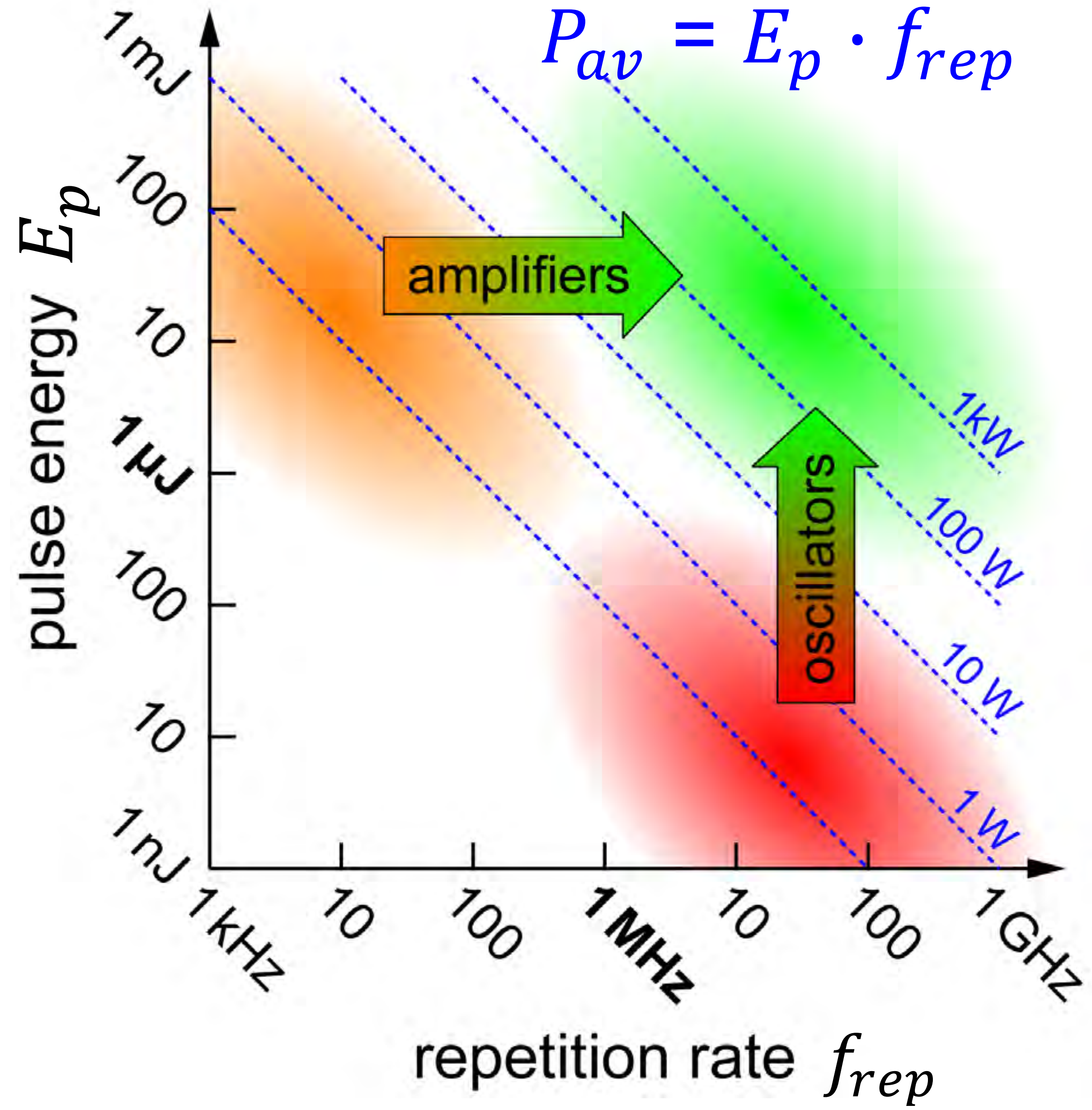
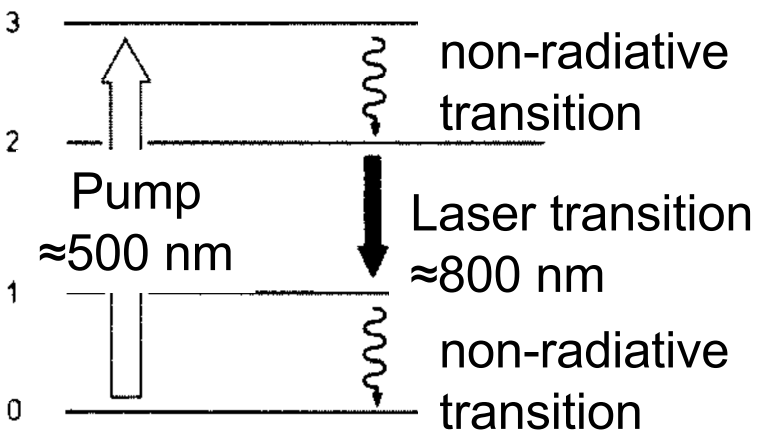


Nature Photonics 2, 599, 2008

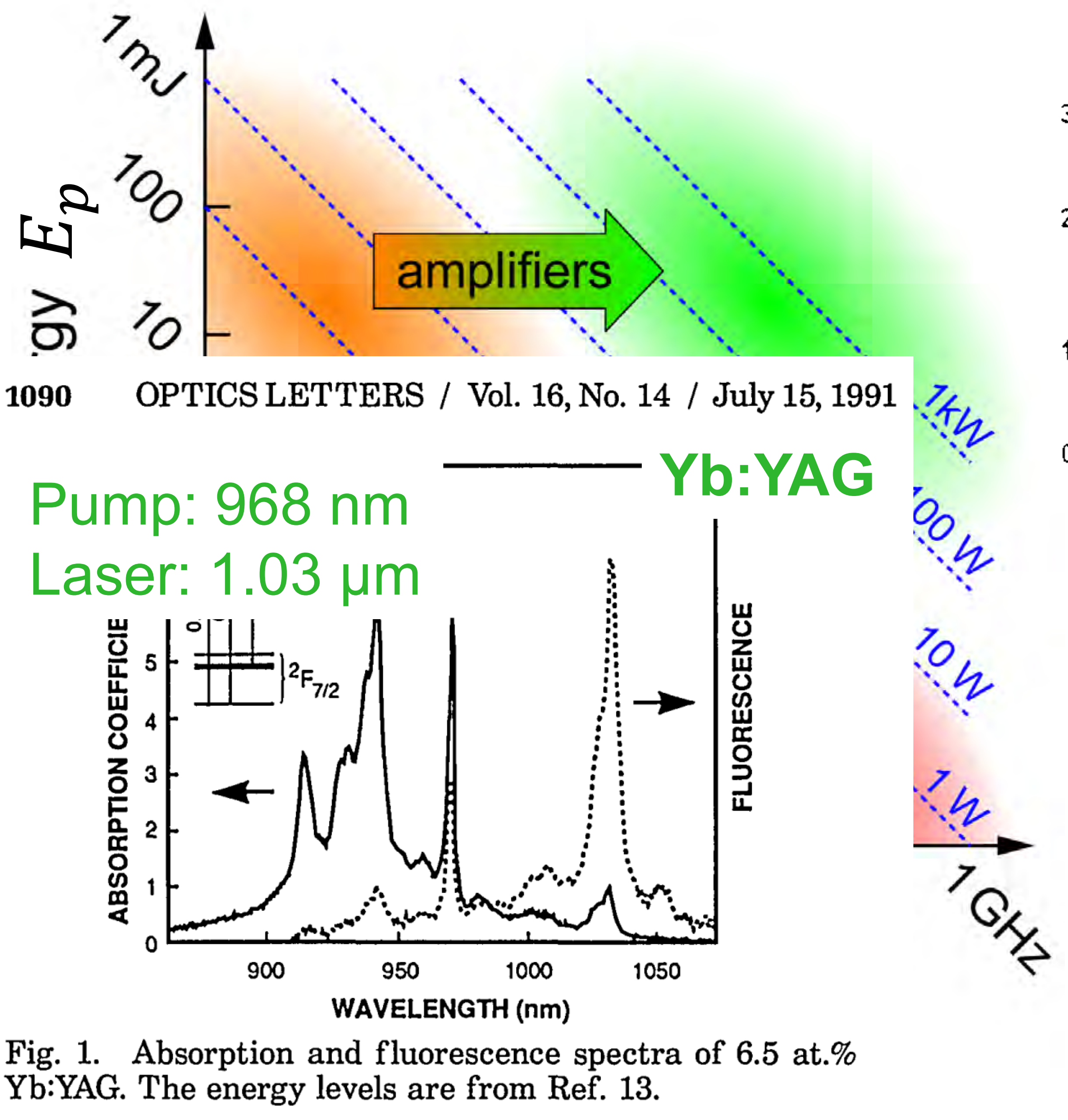
Ti:sapphire laser:



Non-radiative transitions:
Large heat load for kW-level lasers

Solution:
Yb:YAG laser
Opt. Lett. 16, 1089, 1991
T. Y. Fan, MIT Lincoln Lab

High energy and high (MHz) pulse repetition rates



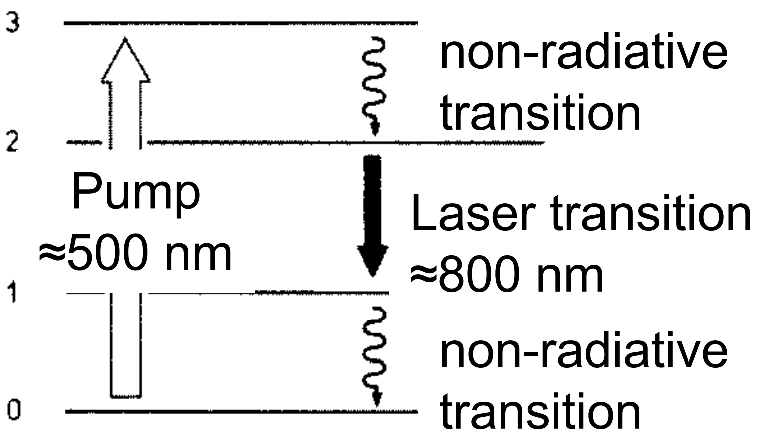
1090 OPTICS LETTERS / Vol. 16, No. 14 / July 15, 1991

Yb:YAG

Pump: 968 nm
Laser: 1.03 µm

Fig. 1. Absorption and fluorescence spectra of 6.5 at.% Yb:YAG. The energy levels are from Ref. 13.

Ti:sapphire laser:



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Ultrafast high-power laser sources

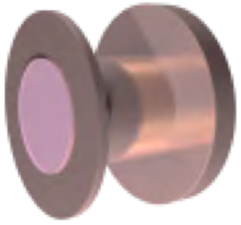
Yb-doped gain crystals

- Good thermal properties
- Availability of low-cost high-power pump diodes
- Emission wavelength around 1 µm

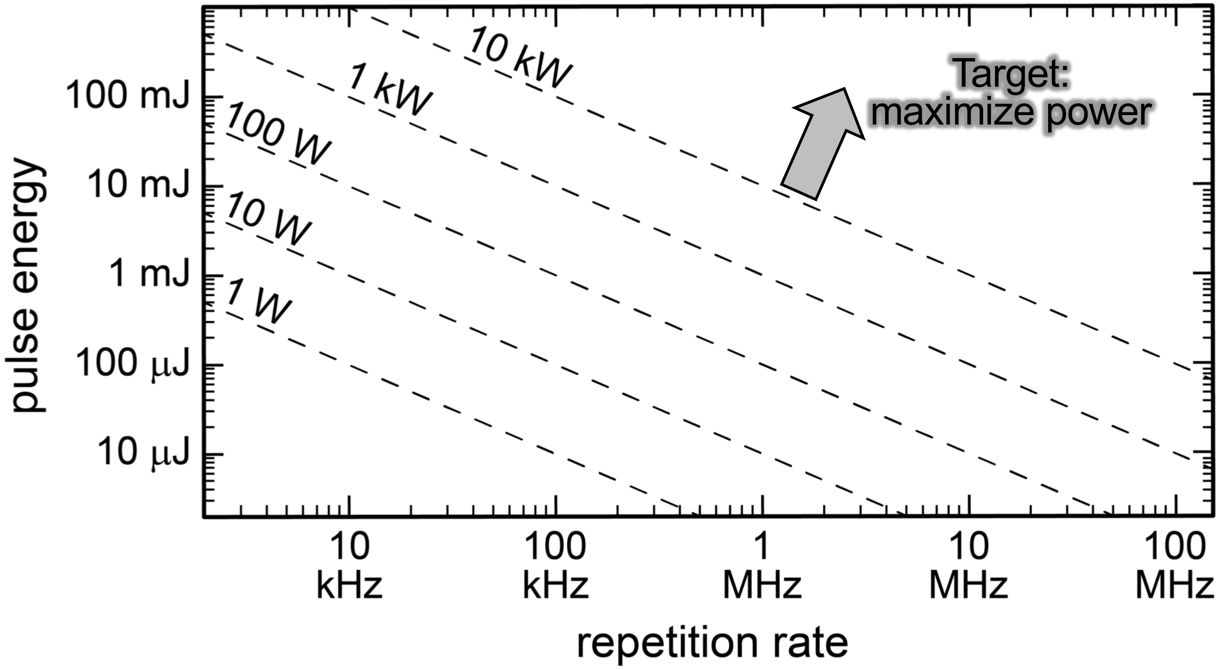
Efficient cooling via maximization of surface/volume ratio of gain crystal

Fiber amplifiers

Slab amplifier

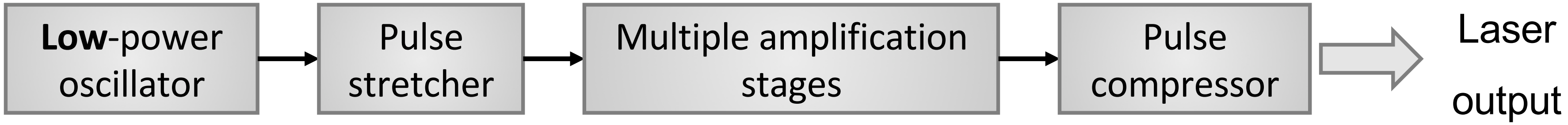


Thin-disk amplifiers and laser oscillators



Ultrafast high-power laser sources

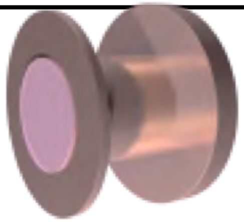
1. Laser amplifier approach



Low-power oscillator → Pulse stretcher → Multiple amplification stages → Pulse compressor ⇒ Laser output

Fiber amplifiers

Slab amplifier



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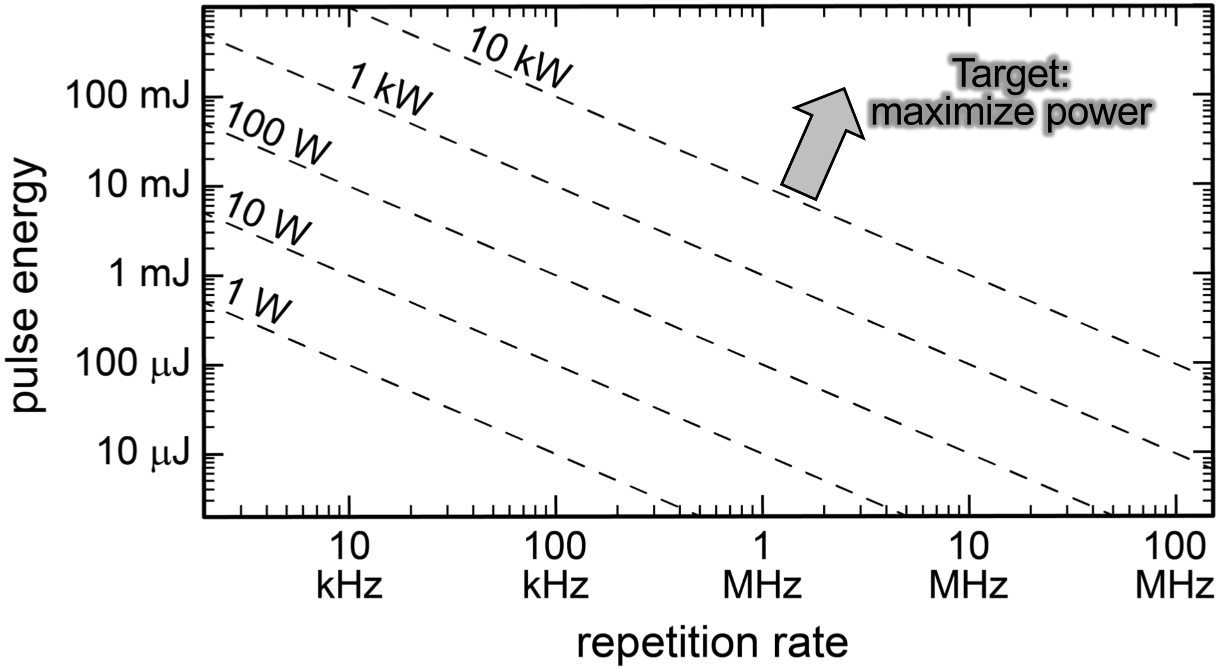

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Technologies: △ Slab amplifiers

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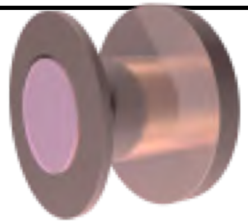

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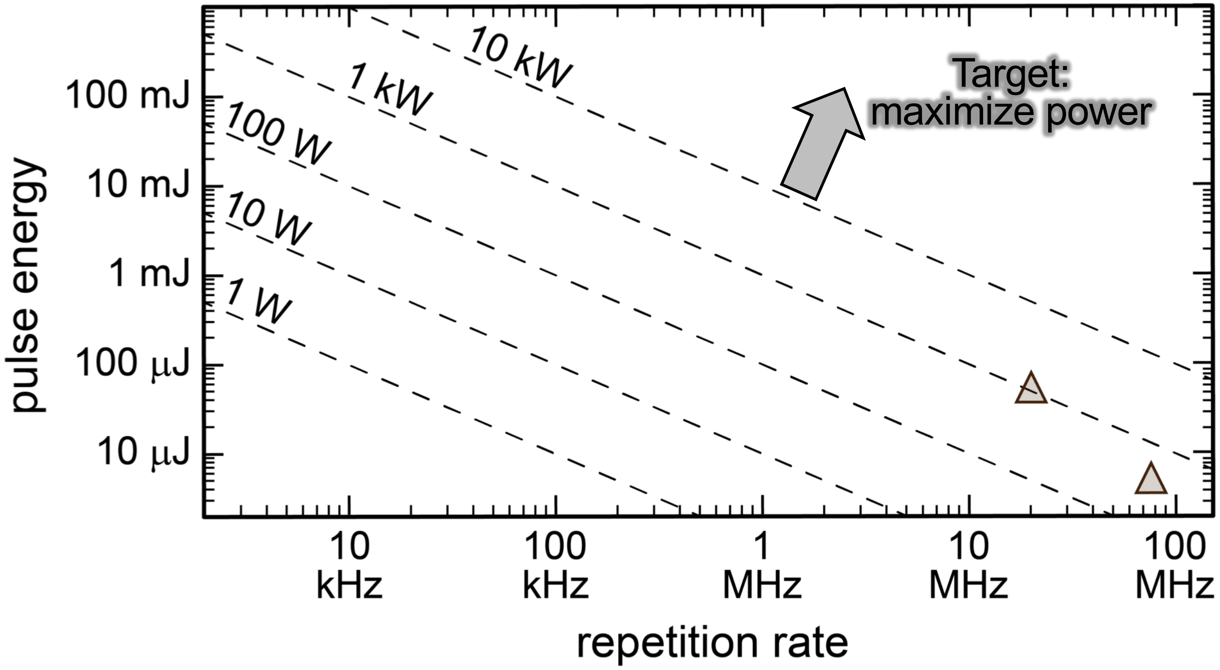

P. Russbueldt, et. al, Opt. Lett. 35, 4169 (2010)

Ultrafast high-power laser sources

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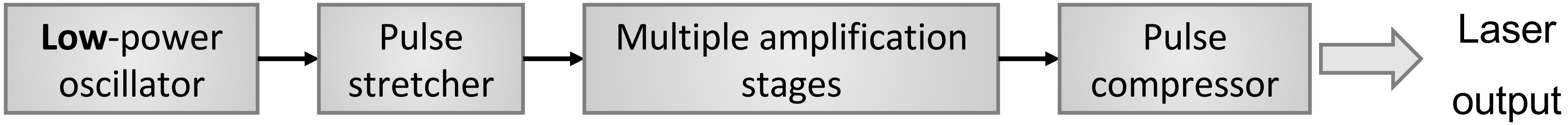
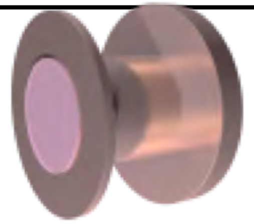


Low-power oscillator → Pulse stretcher → Multiple amplification stages → Pulse compressor ⇒ Laser output

Technologies: △ Slab amplifiers 🔴 Fiber, CPA 🟠 Fiber, coherently combined

Fiber amplifiers

Slab amplifier



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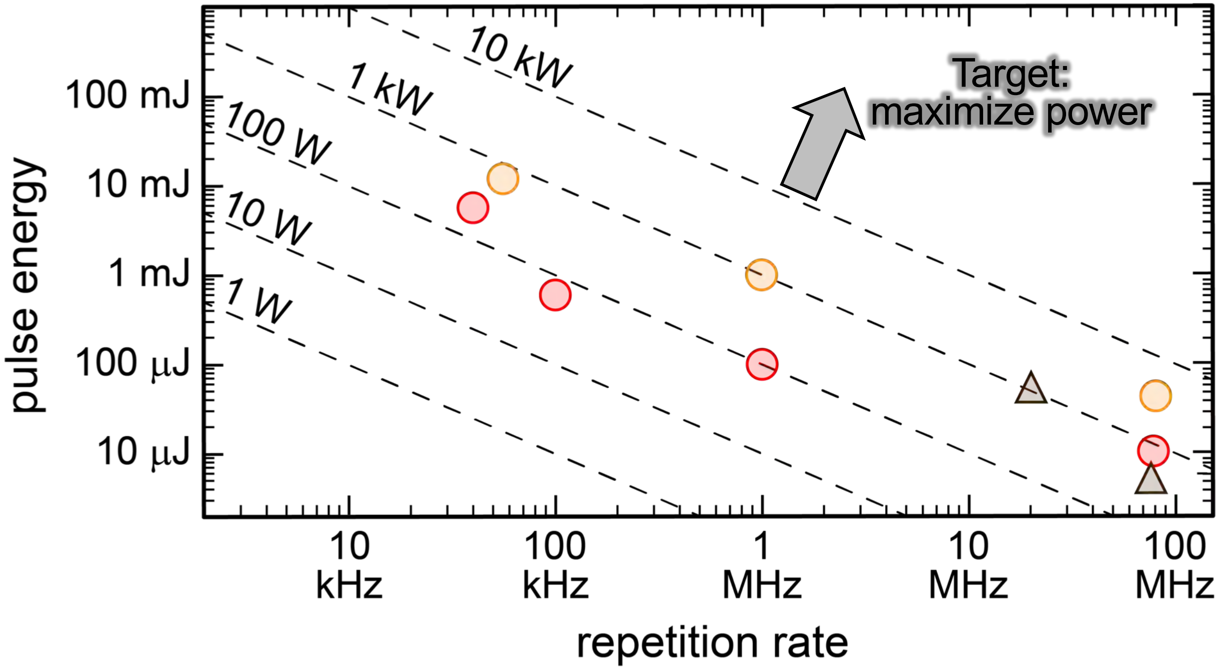

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M. Müller, et. al., Opt. Lett. 43, 6037 (2018)

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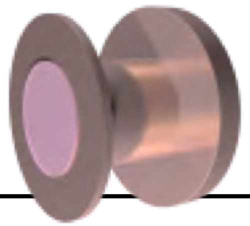
2. Oscillator approach

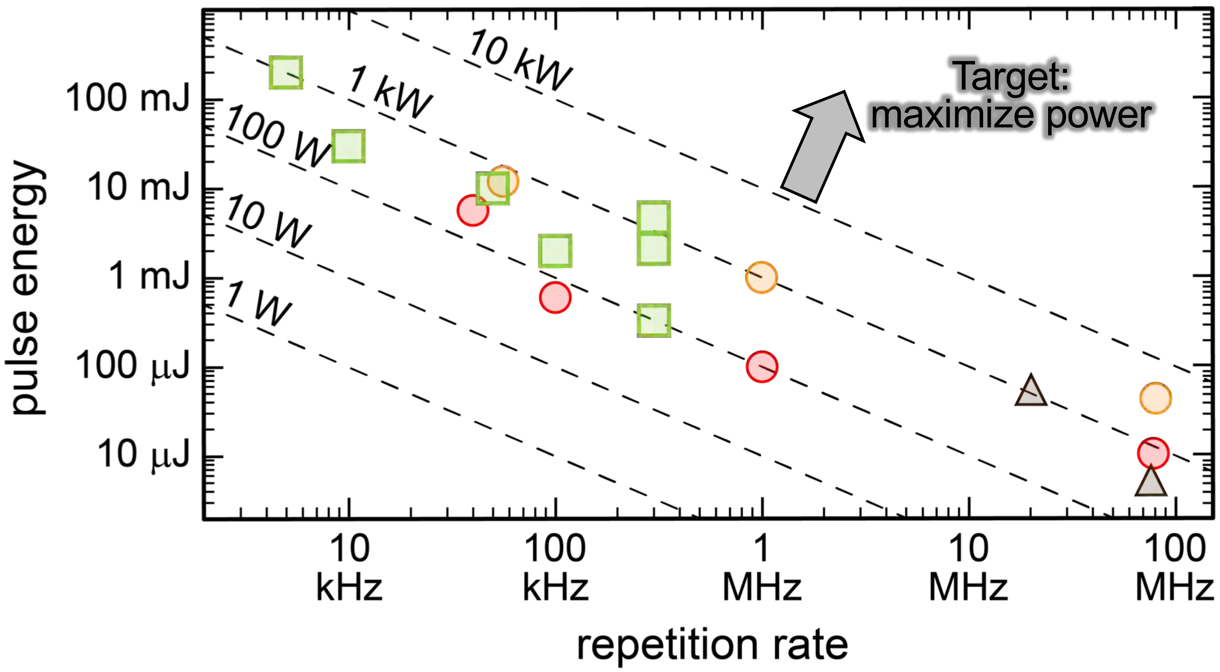
High-power oscillator ⇨ Laser output

Thin-disk amplifiers and laser oscillators



Thin-disk oscillator approach:

- ☐ One-box diode-pumped laser source
- ☐ Excellent beam quality
- ☐ High repetition rate



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M. Müller, et. al., Opt. Lett. 43, 6037 (2018)

J-P Negel, et. al., Opt. Express 23, 21064 (2015)

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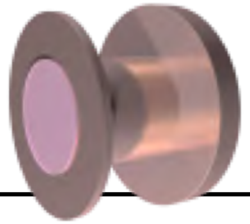

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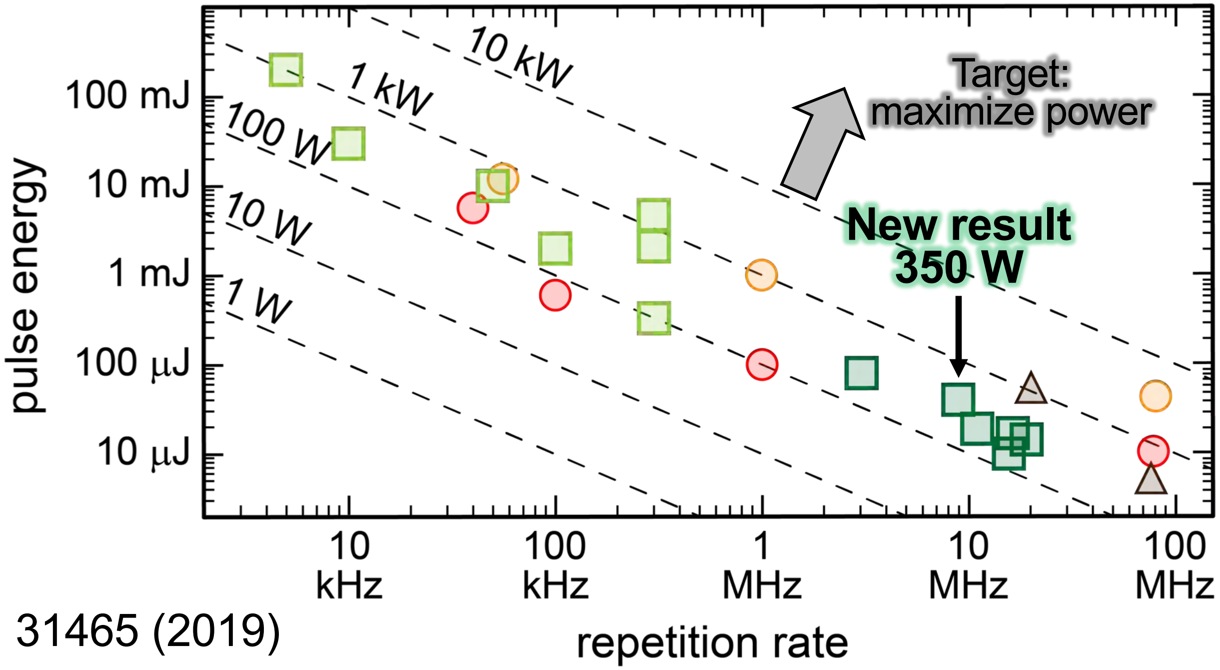
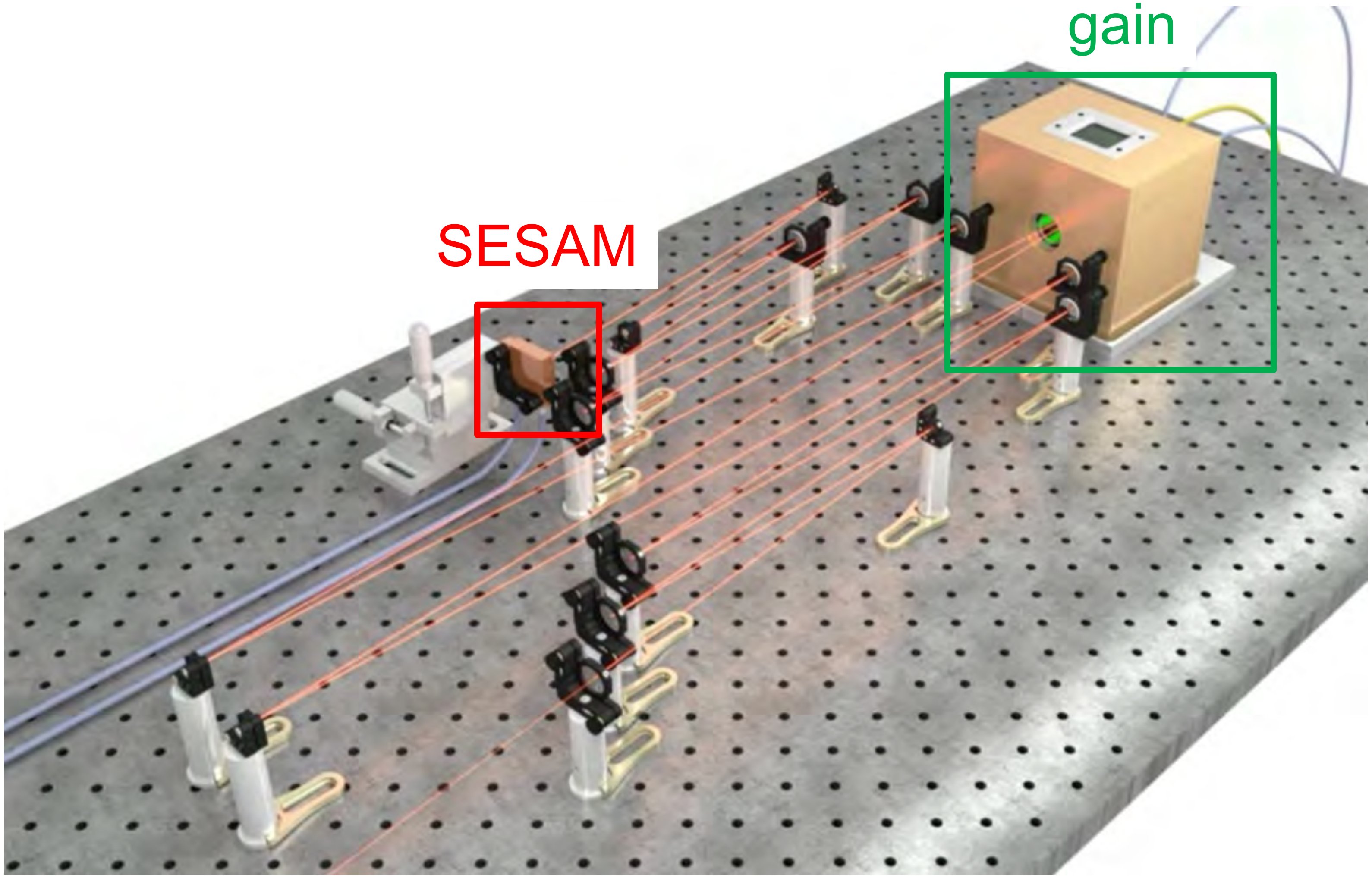


F. Saltarelli et al., *Optics Express* **27**, 31465 (2019)

SESAM-modelocked thin-disk lasers



Graphic by Martin Hoffmann

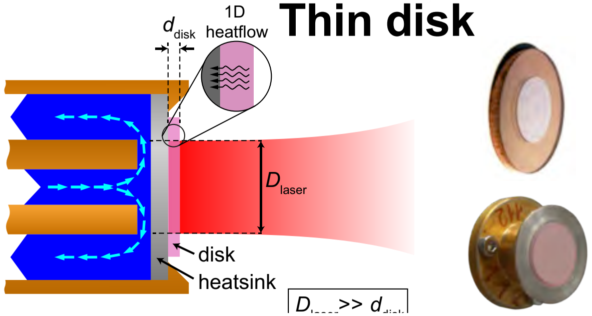
Highest average power (275 W, 16.9 µJ, 0.58 ps, 16 MHz [#1]**) & highest pulse energy (80 µJ,** 242 W, 1 ps, 3 MHz [#2]**) of any ultrafast oscillator technology**

[#1] C. J. Saraceno, et al., *Opt. Express* **20**, 23535 (2012)

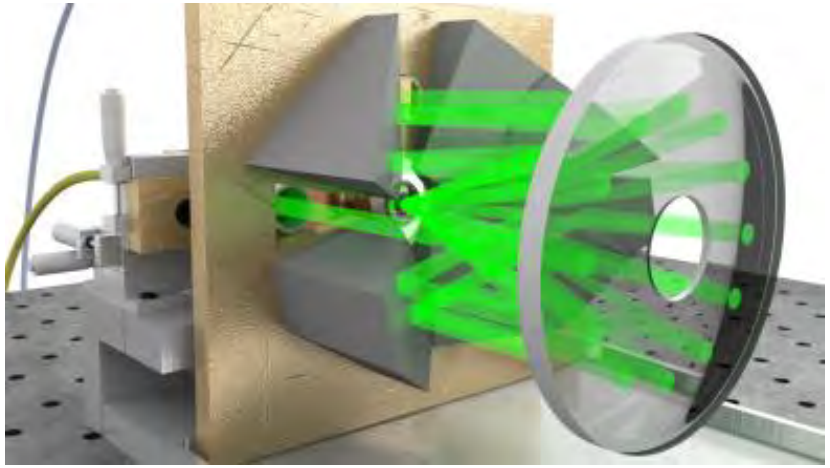
[#2] C. J. Saraceno, et al., *Opt. Lett.* **39**, 9 (2014)

SESAM-modelocked thin-disk lasers

Thin disk



Required: TEM$_{00}$ operation at high average power

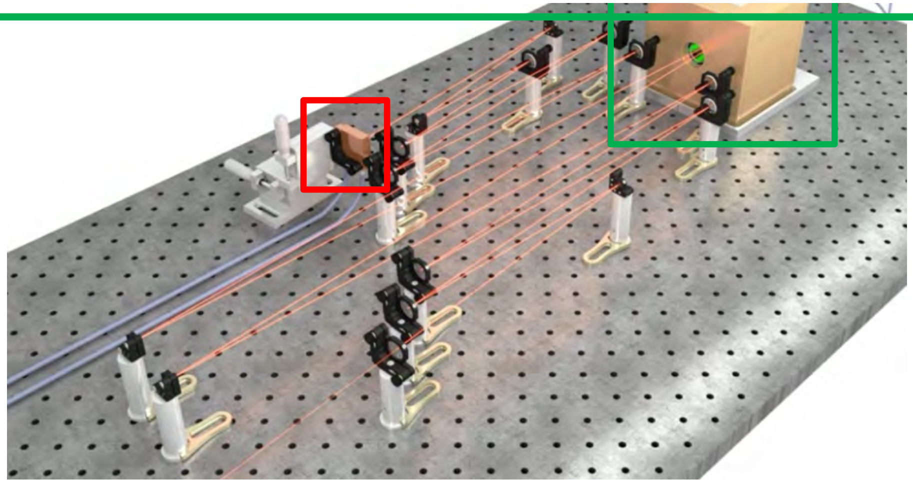


A. Giesen, et al., *Appl. Phys. B* **58**, 365 (1994)

efficient heat removal with thin disk:

→ disk thickness < 100 µm

→ good pump absorption: many passes through gain



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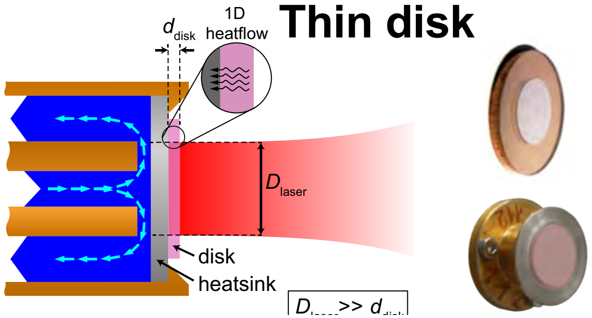

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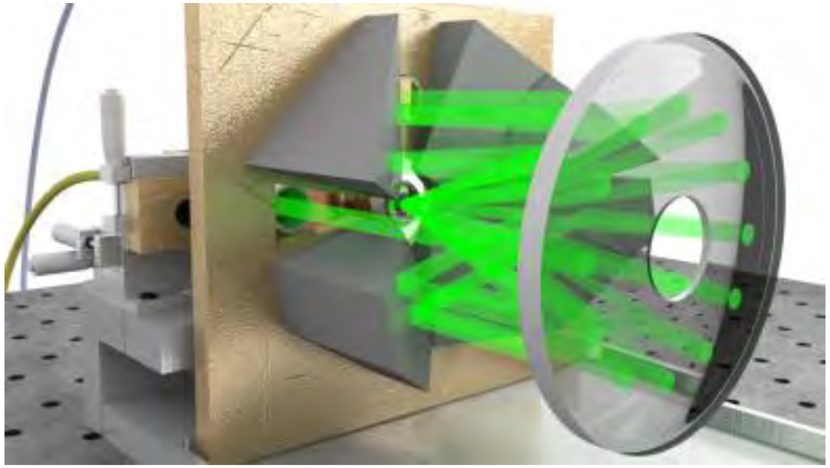

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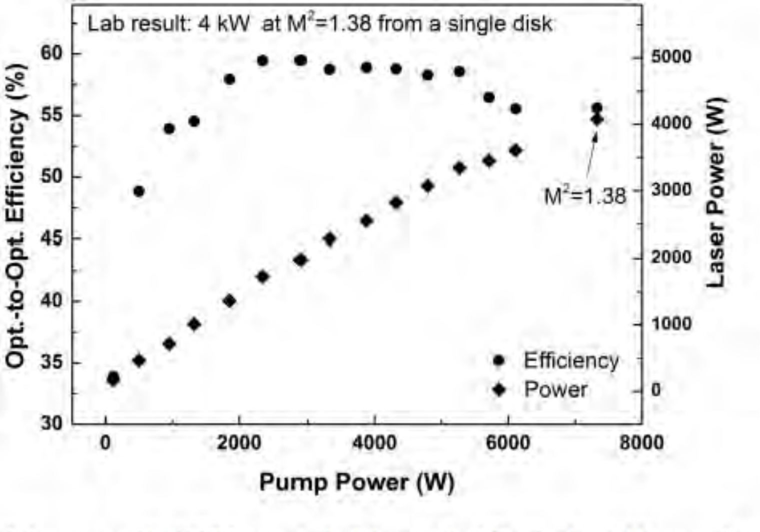
Yb:YAG: the standard thin disk material

- large disks on diamond with excellent quality commercially available
- **4 kW fundamental transverse mode (M^2 <1.4) demonstrated**

→ kilowatt-level modelocked oscillators are in sight

→ goal: pulse energy scaling to the millijoule-level



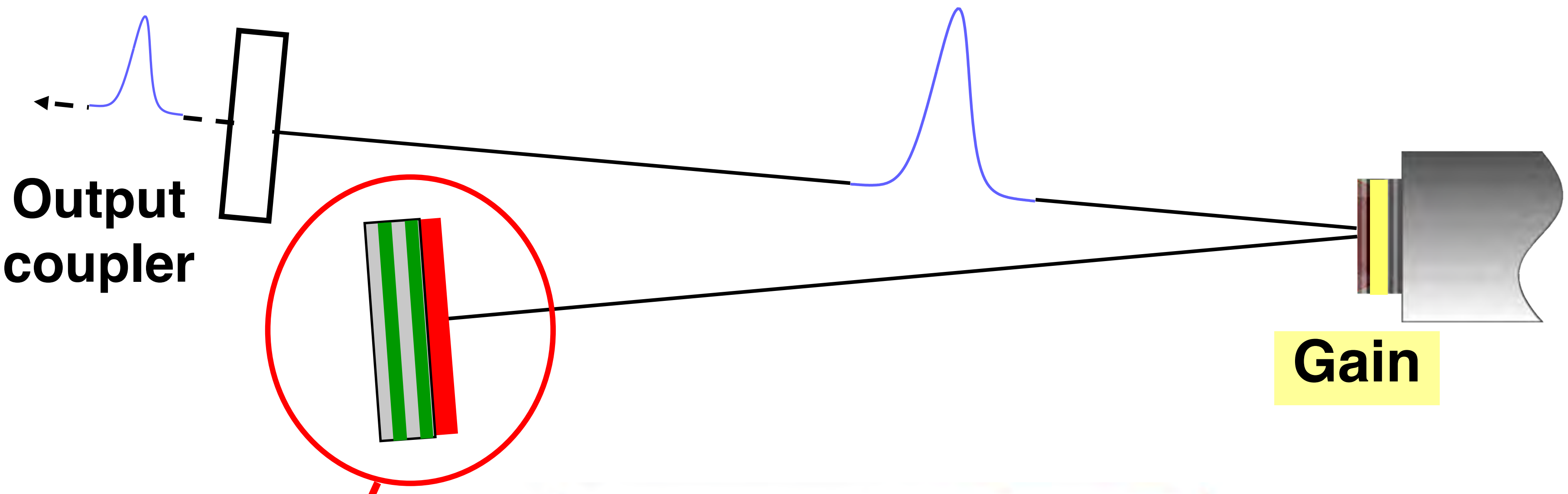
Laboratory result: 4 kW from a single disk at nearly diffraction limited beam quality.

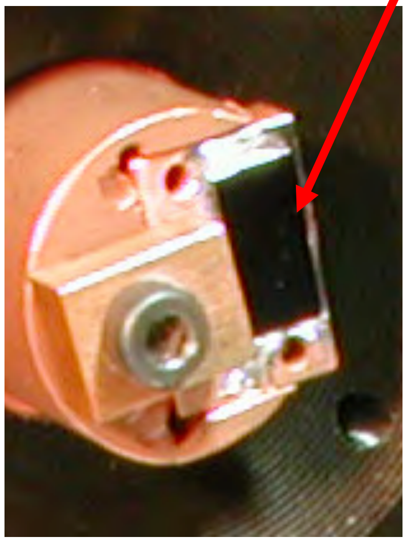
Trumpf: T. Gottwald, et al., *Proc SPIE* **8898** (2014)

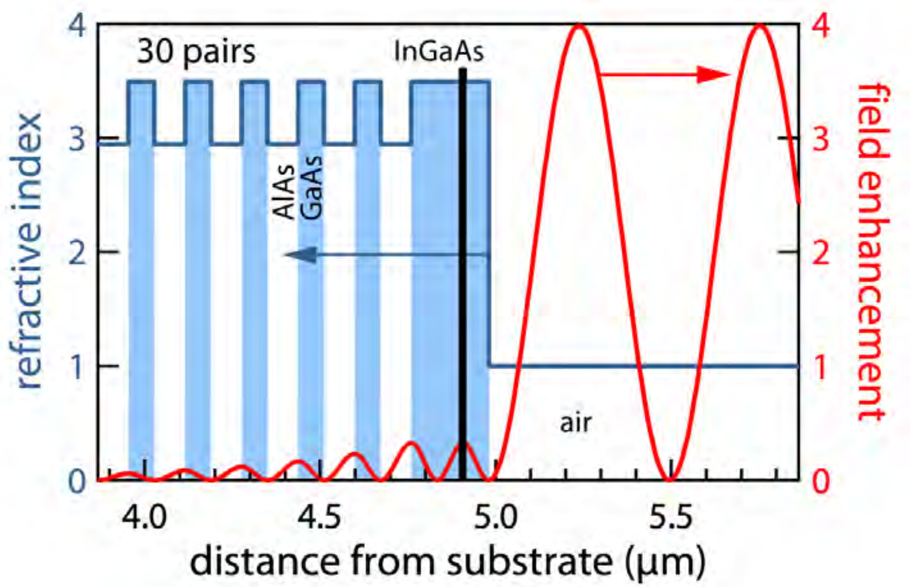
SESAM: designed saturable absorber

SESAM Semiconductor saturable absorber mirror

U. Keller et al., *Optics Lett.* **17**, 505 (1992)
U. Keller et al., *IEEE J. Sel. Top. Quant.* **2**, 435 (1996)







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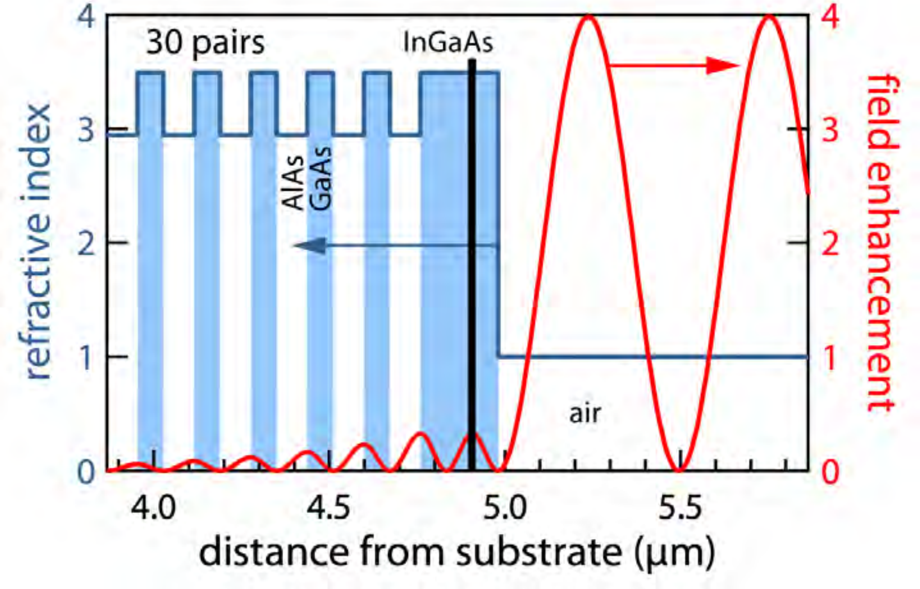
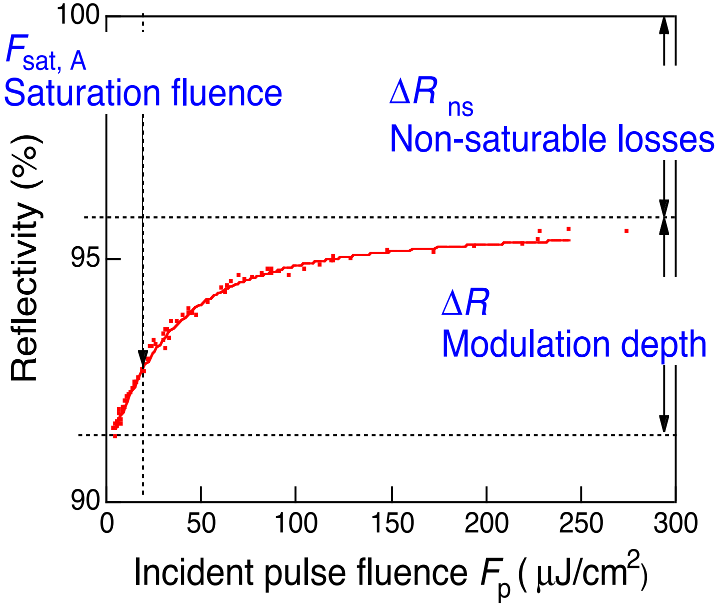
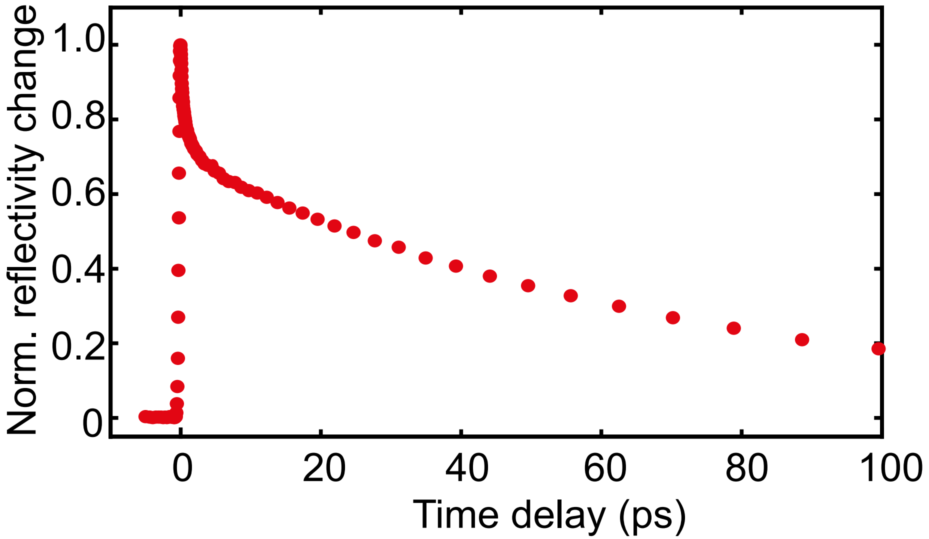


- ✓ Widely tunable absorber parameters (growth conditions, material choice, topsection…) for different types of laser geometries
- ✓ Self-starting, reliable modelocking
- ✓ **Power scalable by increase of mode diameter (constant saturation)**





SESAM

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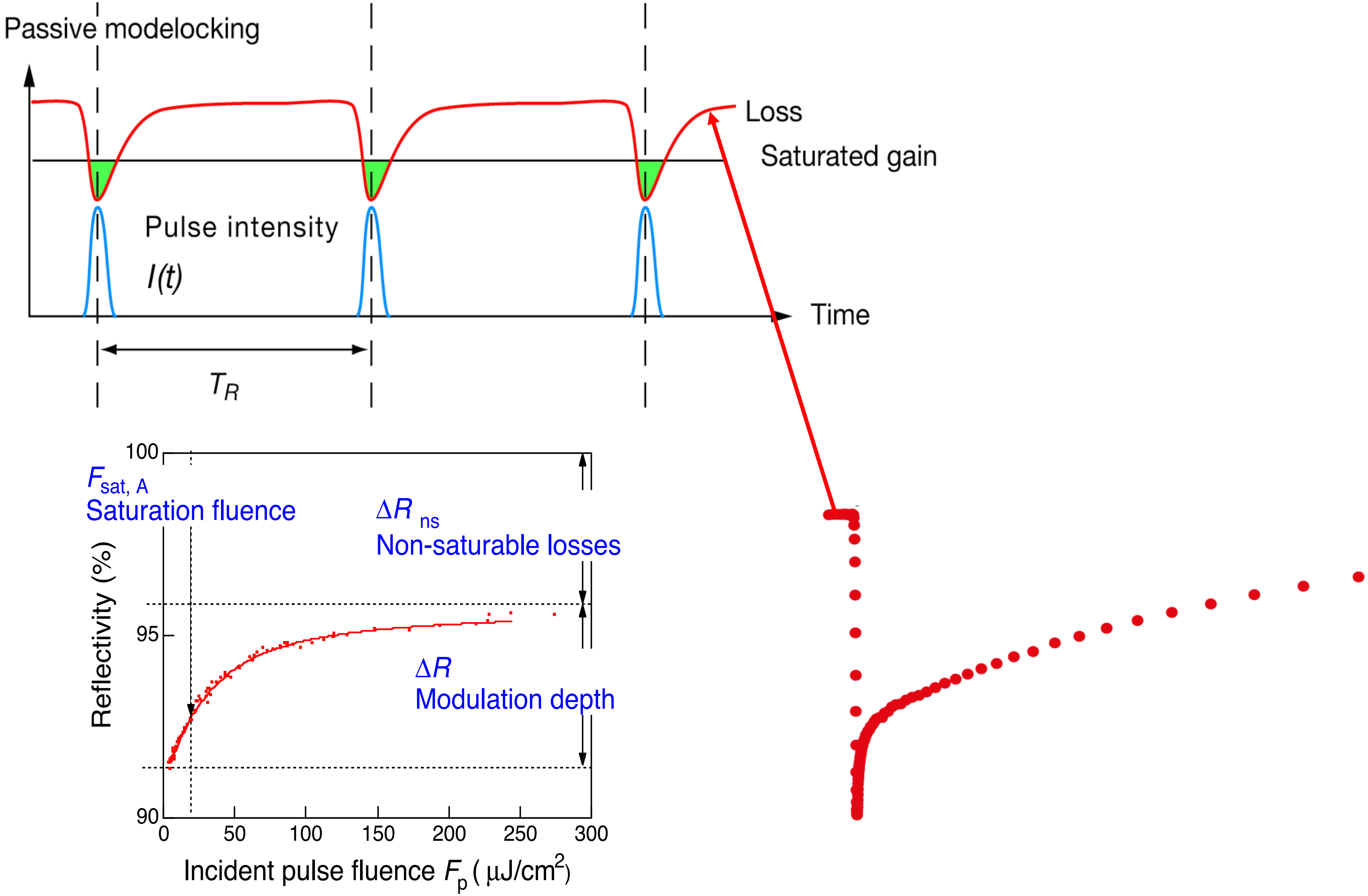
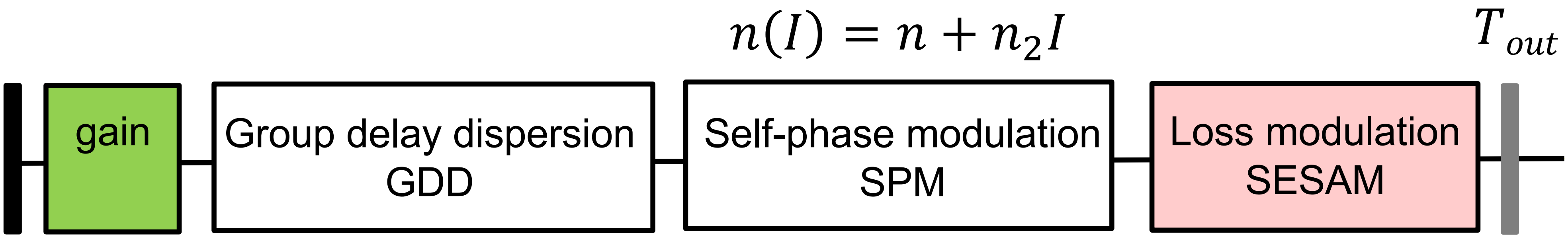


SESAM-modelocked femtosecond solid-state lasers



$n(I) = n + n_2 I$

T_{out}

gain

Group delay dispersion
GDD

Self-phase modulation
SPM

Loss modulation
SESAM

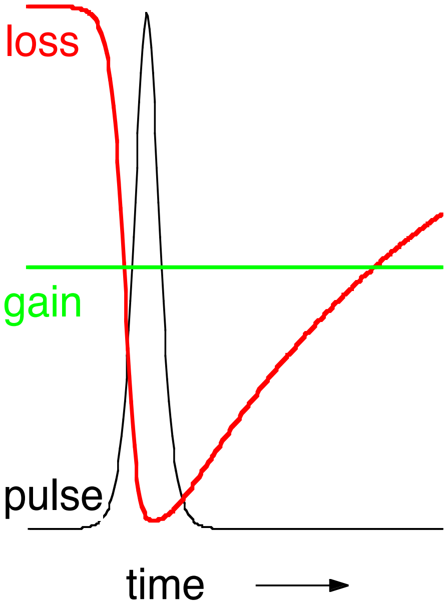
$n_2 > 0$

Given by material
e.g. gain material

Typical soliton modelocking:

GDD < 0

designed with
prism pairs
Gires Tournois Interferometers (GTI)



Solid-state lasers

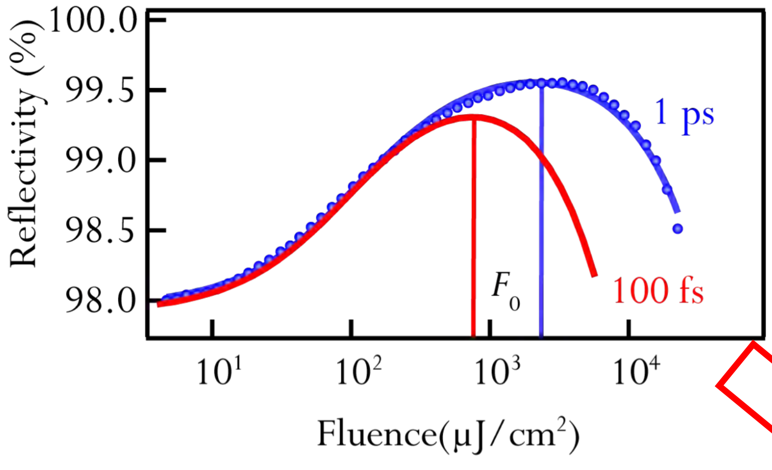
No dynamic gain saturation

Soliton modelocking

F. X. Kärtner, U. Keller,
Opt. Lett. 20, 16, 1995

Challenges for next-generation SESAMs

SESAMs for sub-100-fs TDLs



Fluence $F = E_p / area$

Rollover coefficient $F_2 \propto \tau_p$

Modulation depth ΔR

Operation point $F_0 = \sqrt{F_2 \times F_{sat} \times \Delta R}$

Challenges for sub-100-fs pulses[#1]

→ F_2 decreases

→ F_0 decreases

→ ΔR_{eff} decreases

→ losses increase

[#1] I. J. Graumann, A. Diebold, et al., *Opt. Express* **25** (2017)

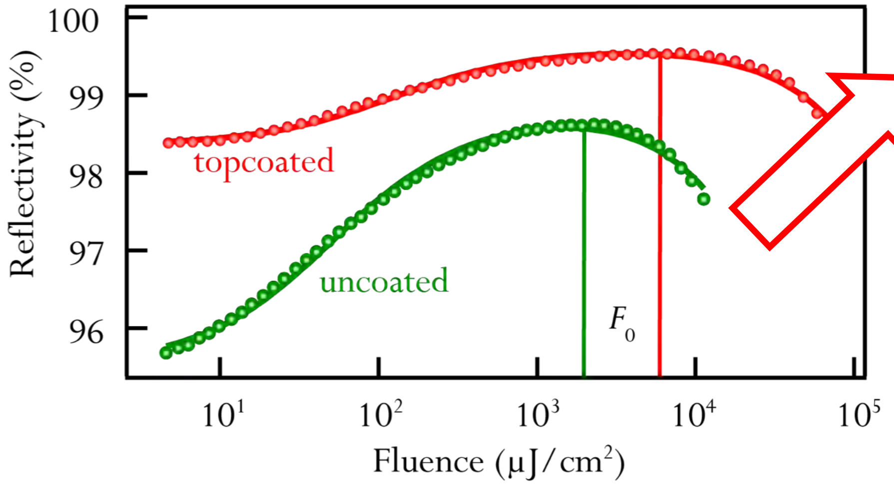
Next-generation SESAMs:

→ adapt growth to increase F_0

→ improve SESAM surface to increase *area*

→ optimize thermal management

SESAMs for kW-class TDLs



ΔR decreased by top coatings[#] to increase F_0

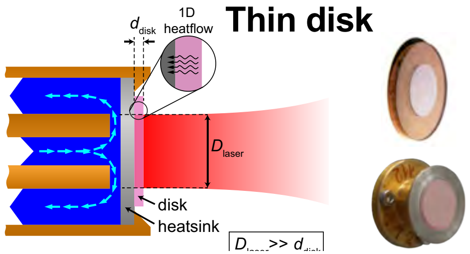
kW-level output powers

→ laser operation limited by F_0

→ heat removal crucial

[#] C.J. Saraceno, et al., *IEEE J. Sel. Top. Quant.* **18** (2012)

SESAM-modelocked thin-disk lasers



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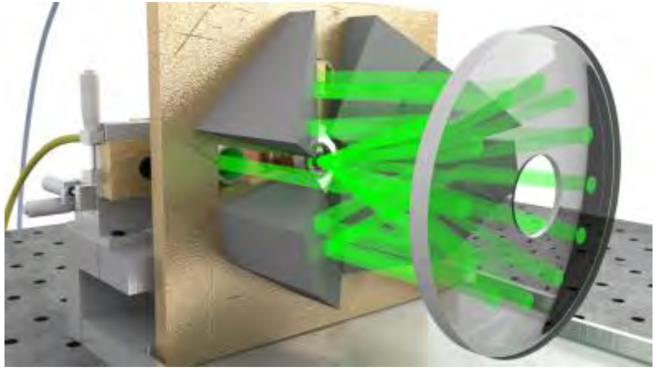
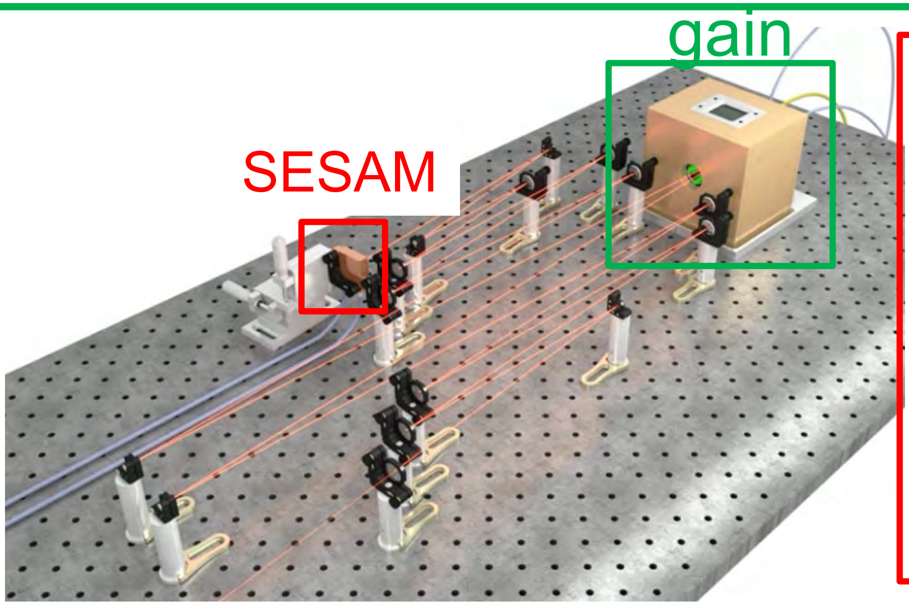
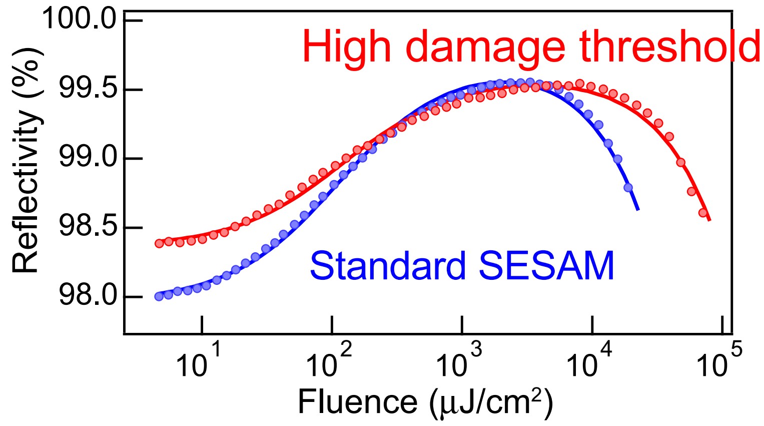


A. Giesen, et al., *Appl. Phys. B* **58**, 365 (1994)



Graphic by Martin Hoffmann



U. Keller, et al., *IEEE J. Sel. Top. Quant.* **2** (1996)
C. J. Saraceno, et al., *IEEE JSTQE* **18**, 29-41(2012)

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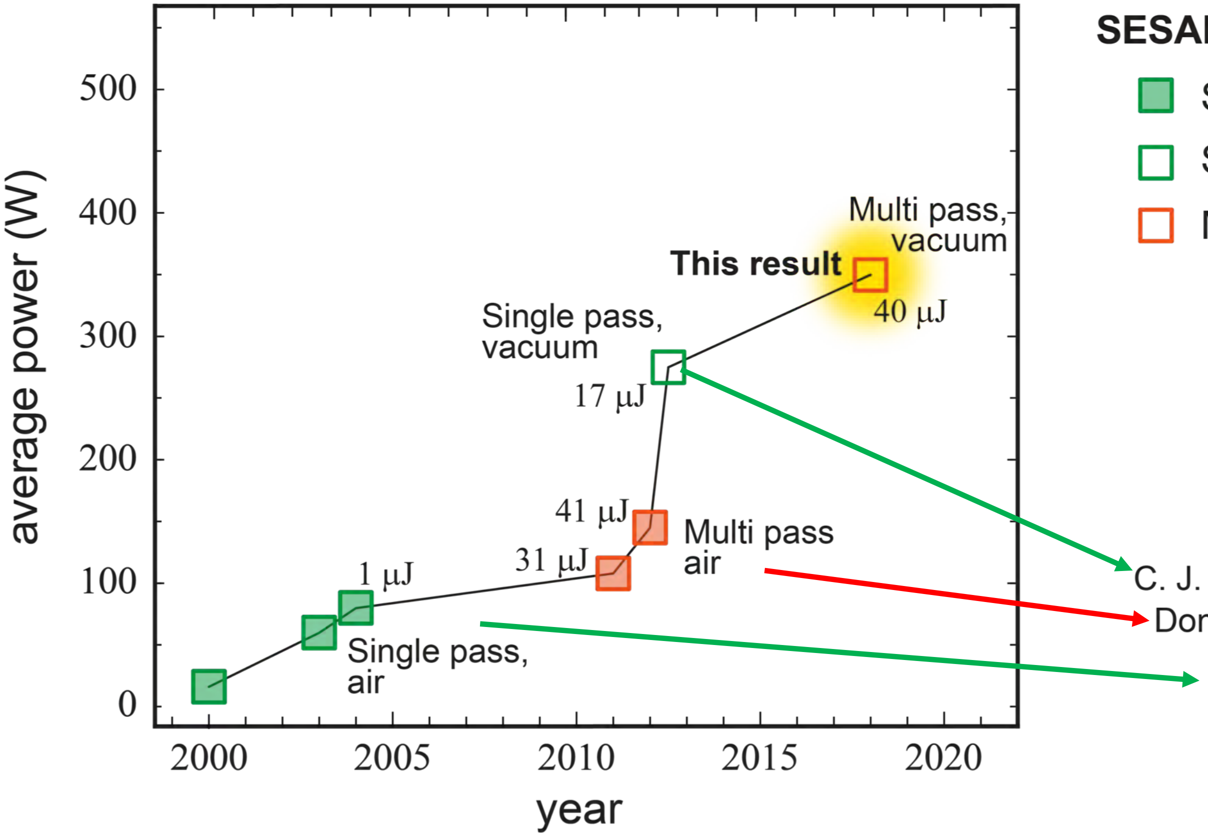
#2 C. J. Saraceno, et al., *Opt. Lett.* **39**, 9 (2014)

This result: 350 W average output power



SESAM modelocked thin-disk lasers:

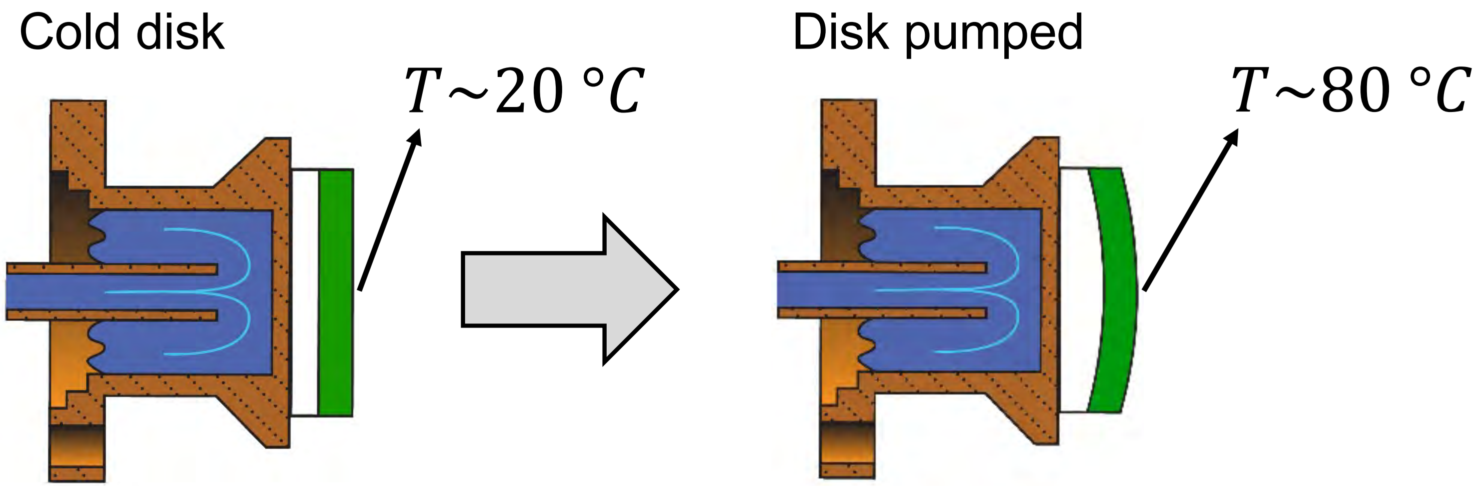
- 🟩 Single-pass cavity, Air
- ☐ Single-pass cavity, Vacuum
- ☐ Multi-pass cavity, Vacuum

C. J. Saraceno, et. al., Opt. Express 20, 23535 (2012)
Dominik Bauer, et. al., Opt. Express 20, 9698 (2012)

F. Brunner, et al., Opt. Letters 29, 1921, (2004)
E. Innerhofer, et al., Opt. Letters 28, 367 (2003)
J. Aus der Au et al., Opt. Letters 25, 859 (2000)

- **350 W –** new record average output power from an ultrafast oscillator
- **Vacuum** operation ➔ mitigates disk's thermal lensing and reduces overall SPM
- **Multi-pass** cavity ➔ minimizes the intracavity power

Further Power Scaling: Thermal lensing



- **Disk-material thermal lensing** is well-known in literature

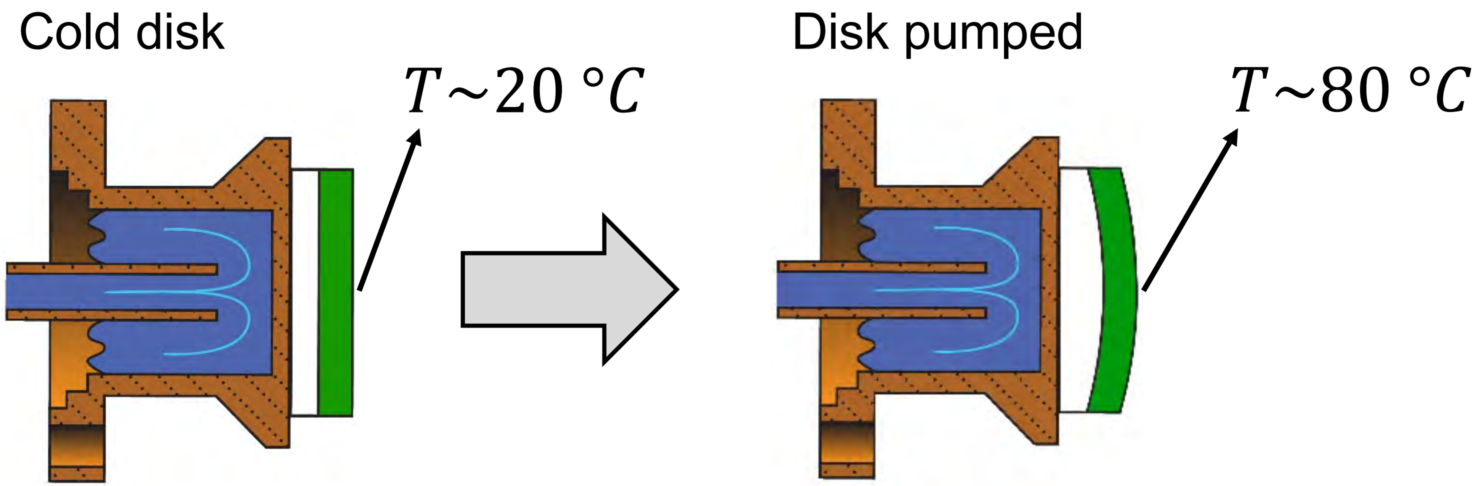
- When the disk heats up it changes its radius of curvature (ROC)

➔ **Diopter change:** $\Delta F_{disk}(T) = \left({}^{2}/_{ROC(T)} - {}^{2}/_{ROC(cold)} \right)$

S. Chenais, F. Balembois, F. Druon, et al., *IEEE J. Quantum Electron.* **40** (9), 1217–1234 (2004)

G. Zhu, X. Zhu, M. Wang, Y. Feng, and C. Zhu, *Appl. Opt.* **53** (29), 6756–6764 (2014)

Further Power Scaling: Thermal lensing



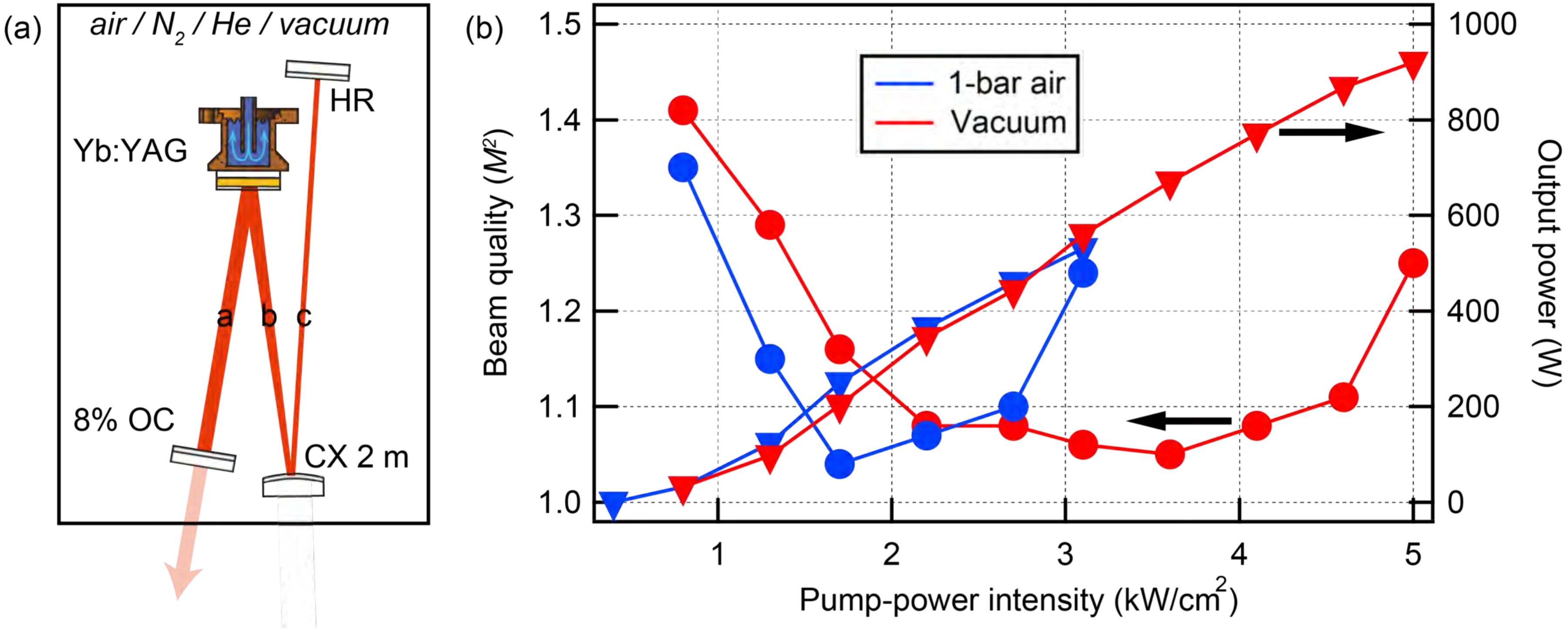
Cold disk

$T\sim 20\,°C$

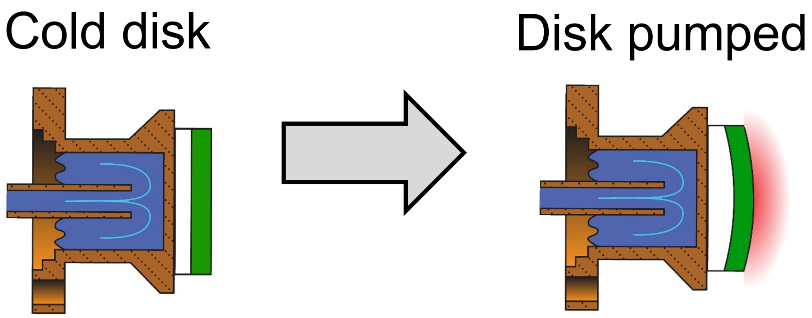
Disk pumped

$T\sim 80\,°C$

A. Diebold et al., *Optics Express* **26** (10), 12648, 2018



Further Power Scaling: Thermal lensing



Total thermal lensing (ΔF_{total}) =

= disk-material lensing + gas lens
~63% ~37%

- ➢ Disk-material lensing is known in literature
- ➢ Gas lens: A. Diebold et al., *Optics Express* **26** (10), 12648, 2018

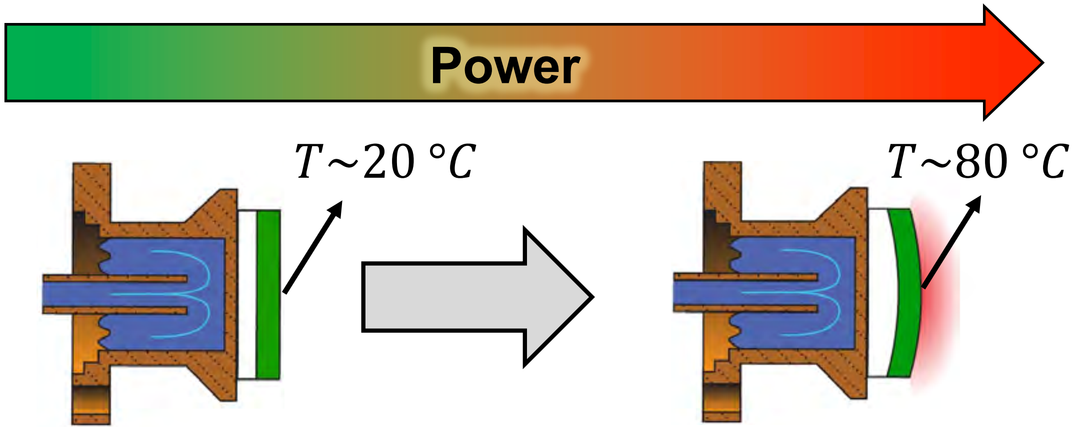
gas in front of the disk heating up ⇨ change in its index of refraction (*n*) ⇨ gas-lens effect

- ➢ What is the difference between **air** and **helium**?

➔ $\left(\frac{dn}{dT}\right)_{helium} \ll \left(\frac{dn}{dT}\right)_{air}$

Challenges for ultrafast TDLs

Step 1: Operate in fundamental spatial mode (gaussian beam, $M^2 < 1.1$)

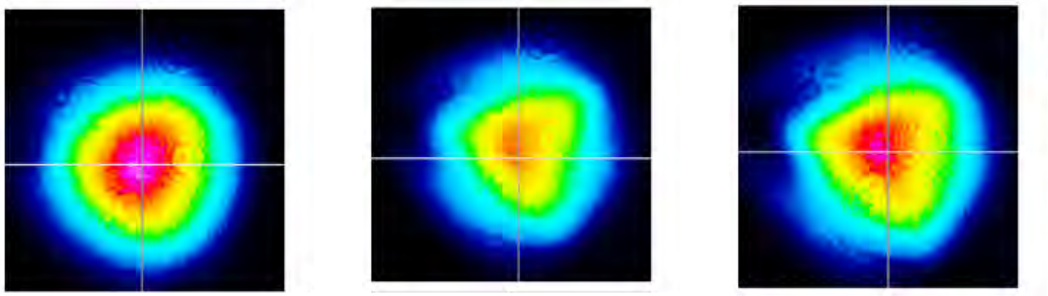


- ☐ Thermal effects from the disk:
  - ☐ Thin disk heating up
  - ☐ Air forming a gas-lens[#]

Challenge:

- ☐ Sensitivity to thermal lensing increases for larger laser spot sizes on the disk

Vittorio Magni, J. Opt. Soc. Am. A, 1962 (1987)



Single spatial mode beam

Distorted beam profile

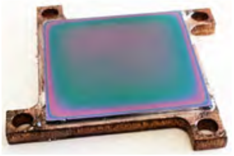
Solution:

- ☐ Operate the laser in vacuum ➔ removes the gas-lens

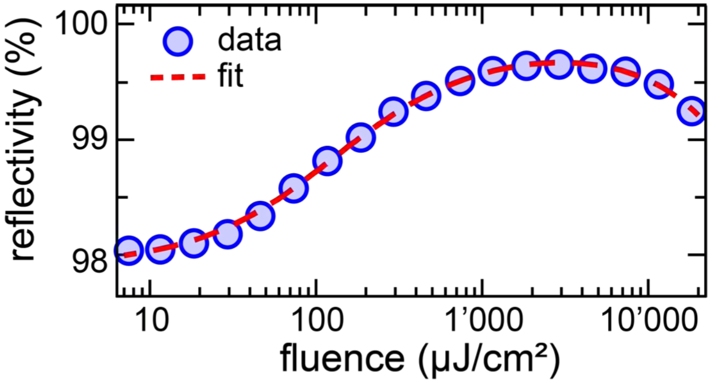
[#] A. Diebold, et al., Opt. Express 26, 12648 (2018)

Challenges for ultrafast TDLs

Step 2: Obtain stable pulse formation



SEmiconductor **S**aturable **A**bsorber **M**irror - SESAM



C. J. Saraceno, et. al., Opt. Express 20, 23535 (2012)

+

Soliton modelocking

- ☐ Requires to balance *dispersion* and *self-phase modulation*

F. X. Kärtner and U. Keller, Opt. Lett. ***20,*** *16 (1995)*

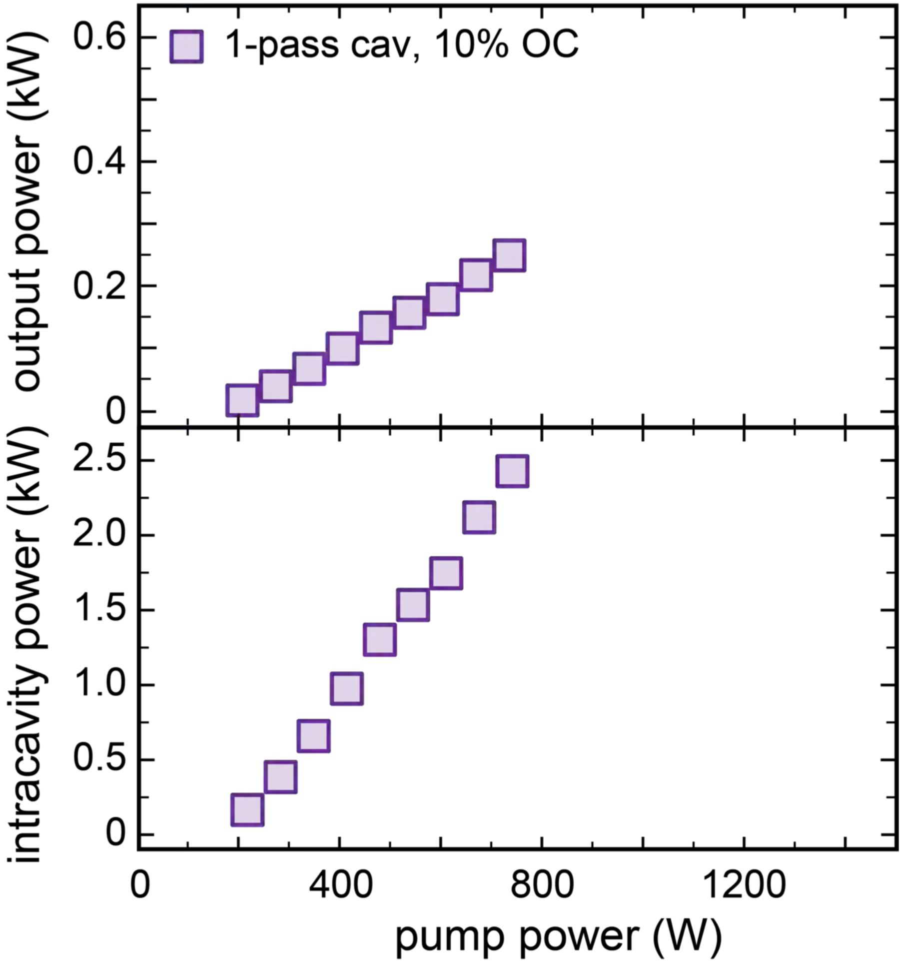
Challenges:

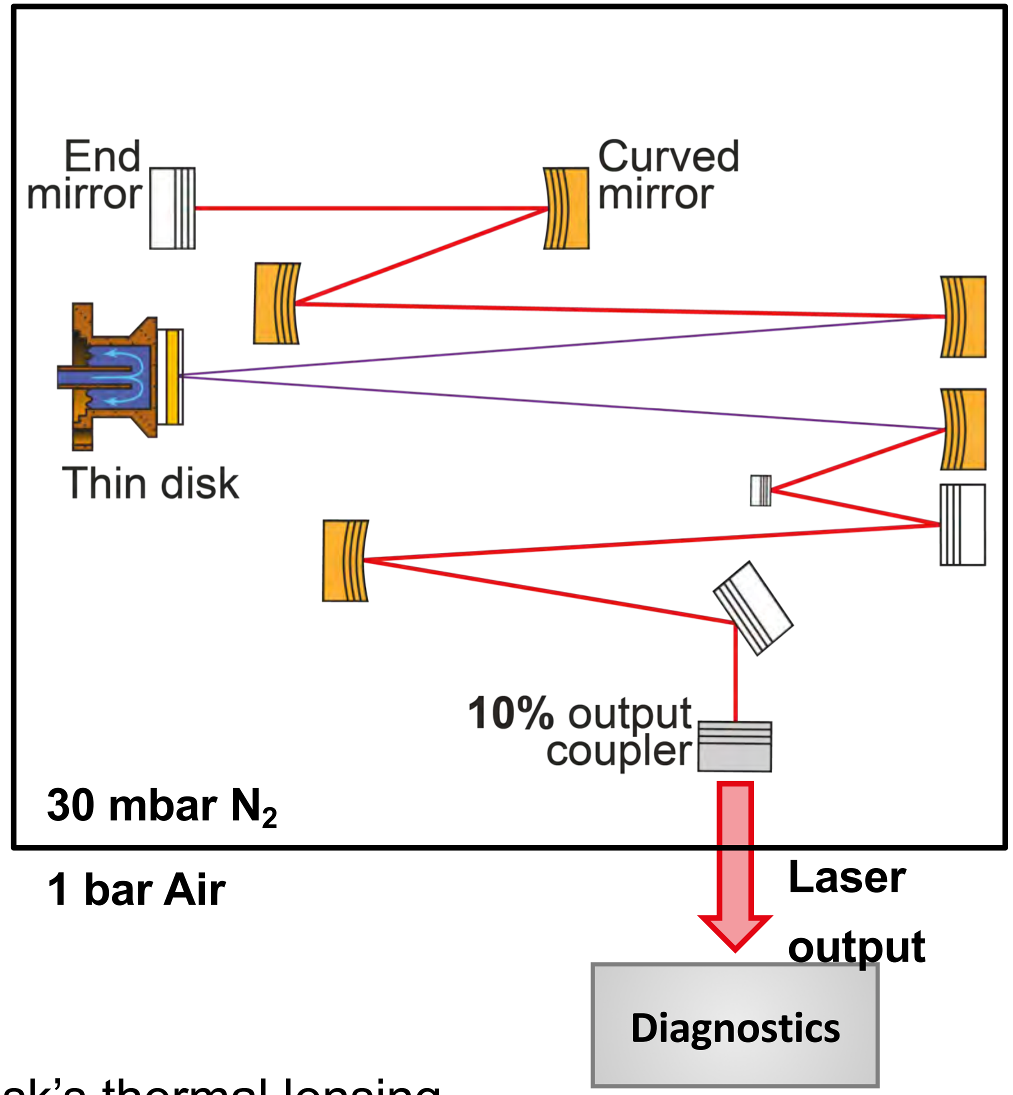
- ☐ Thermal effects from the thin-disk / SESAM / dispersive mirrors
- ☐ The air is a substantial source of SPM at MW level peak power

Possible Solutions:

- ☐ Minimize the intracavity power (i.e. multi-pass gain) ➔ limits the thermal effects
- ☐ Operate the laser in vacuum ➔ limits the amount of SPM and thermal gas lens

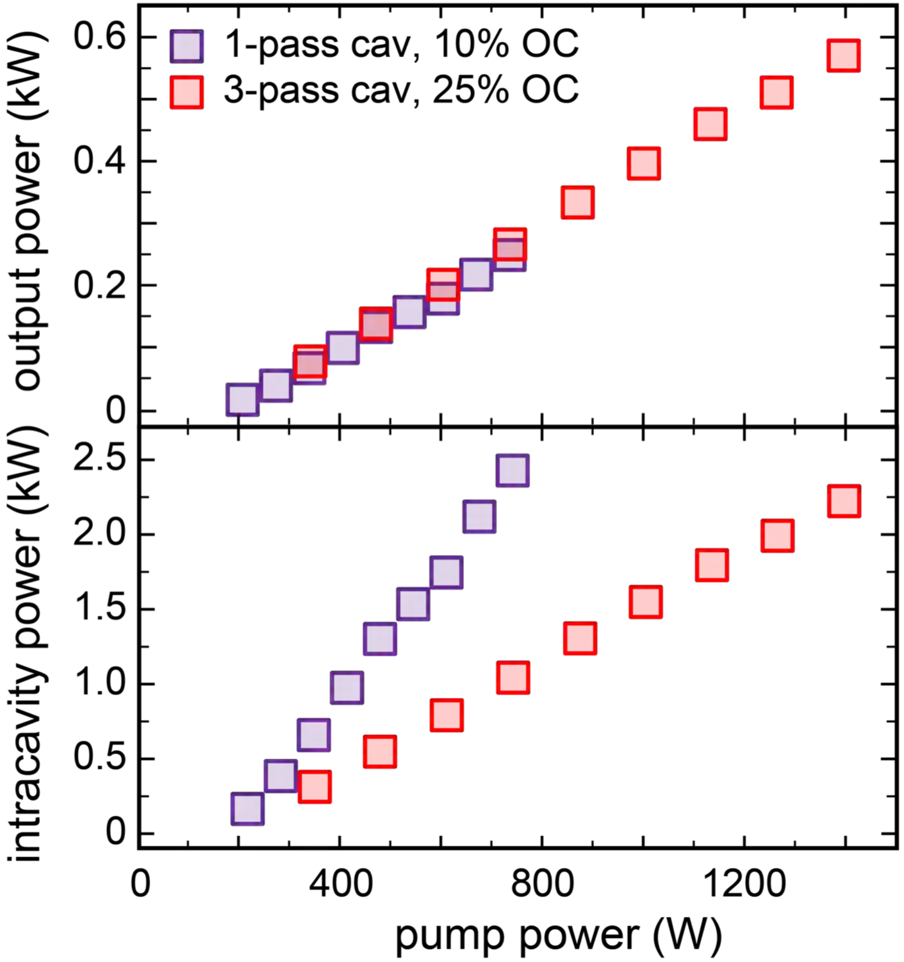
cw single-mode cavity

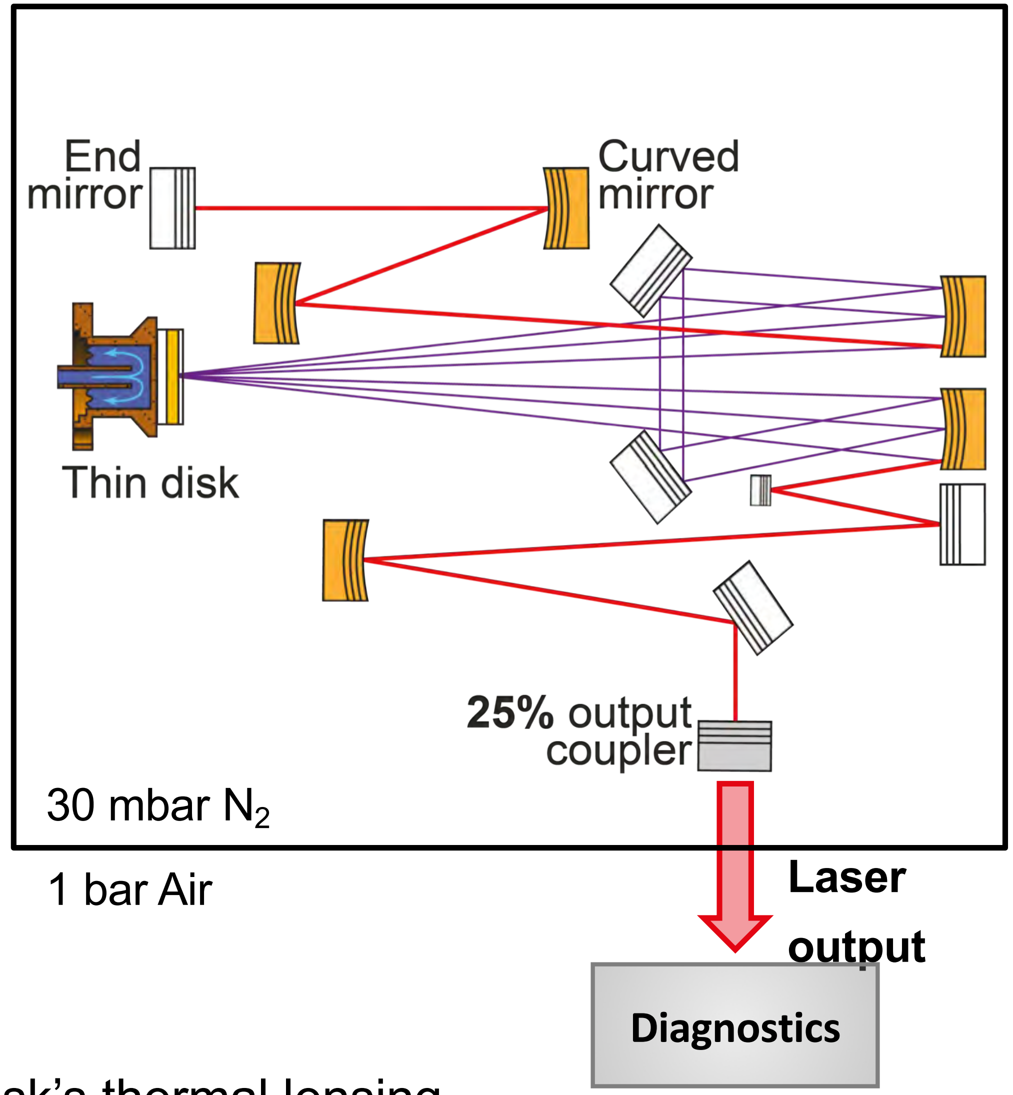




- ☐ Vacuum operation ➔ mitigates disk's thermal lensing

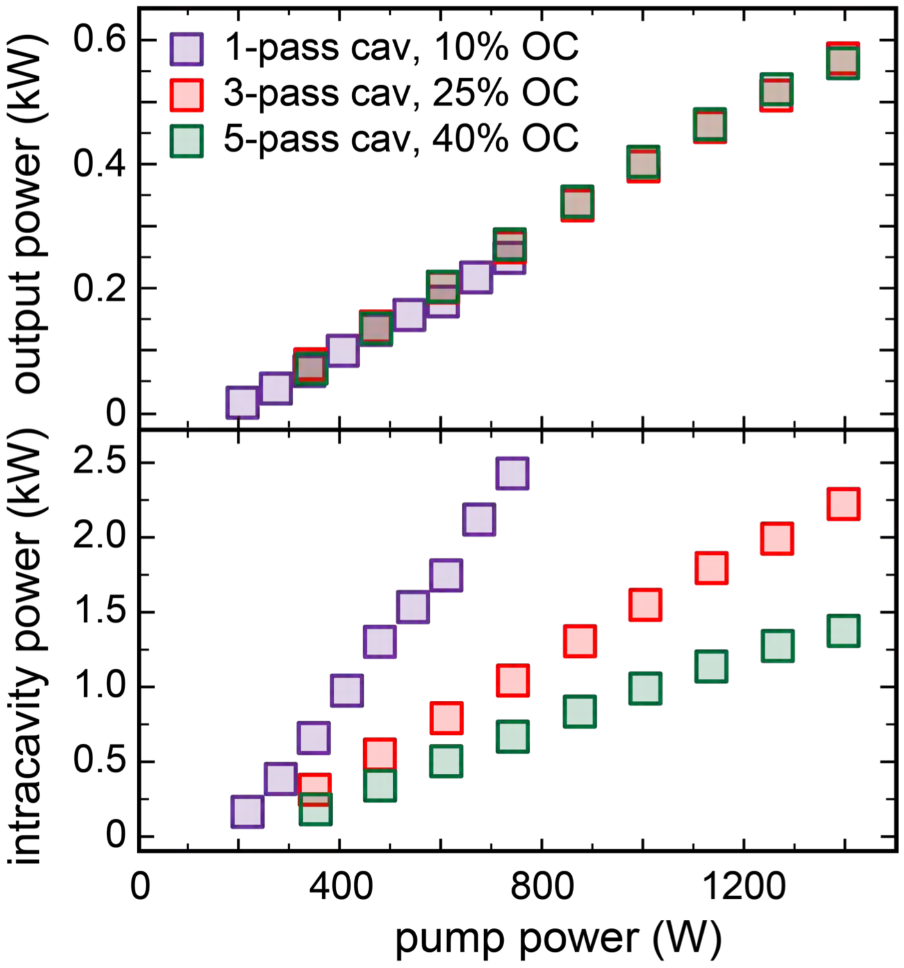
cw single-mode cavity

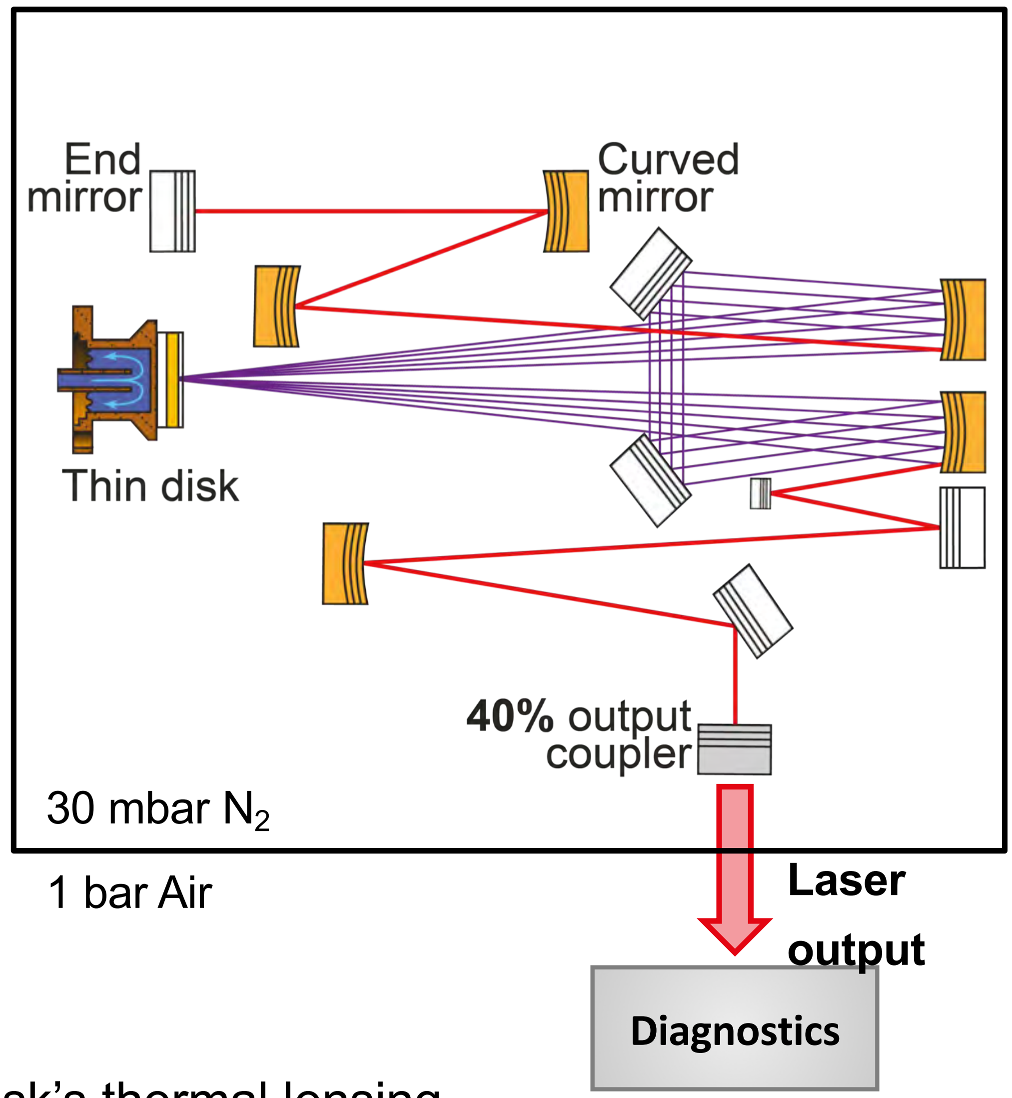




- ☐ Vacuum operation ➔ mitigates disk's thermal lensing
- ☐ Active multi-pass cell ➔ limits the intracavity power

cw single-mode cavity





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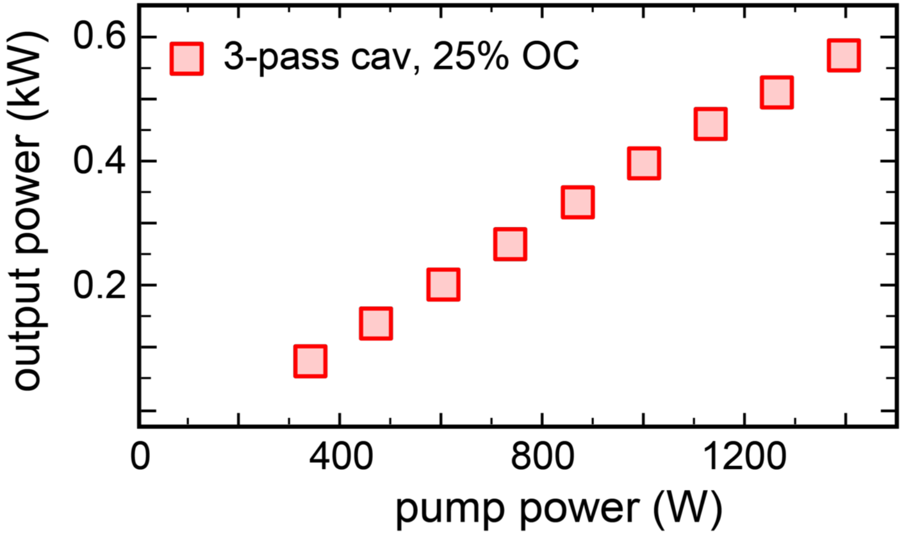
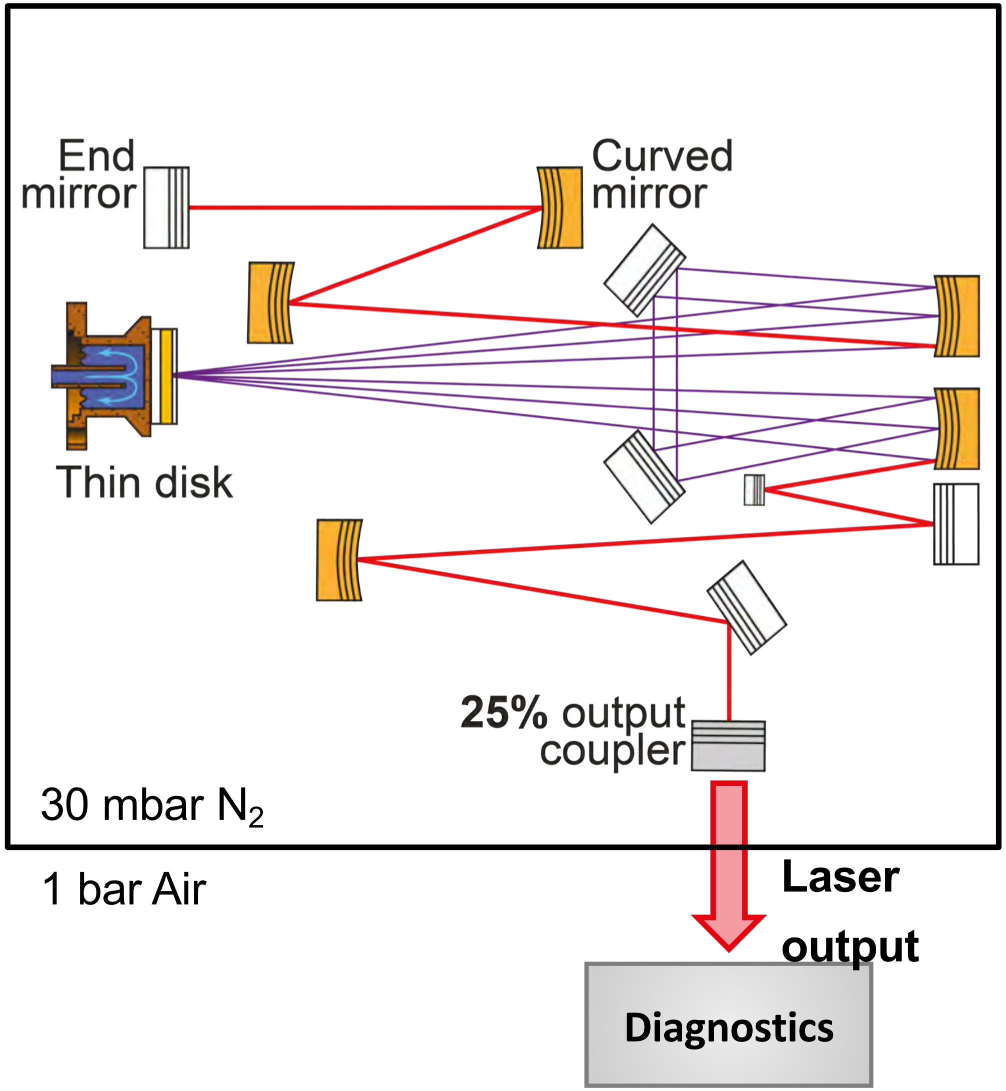
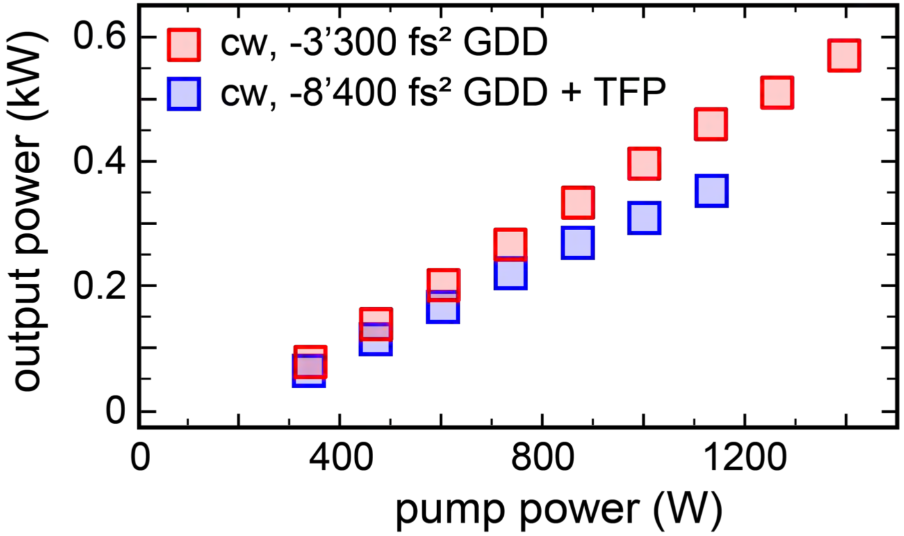
- ❑ Active multi-pass cell ➔ limits the intracavity power

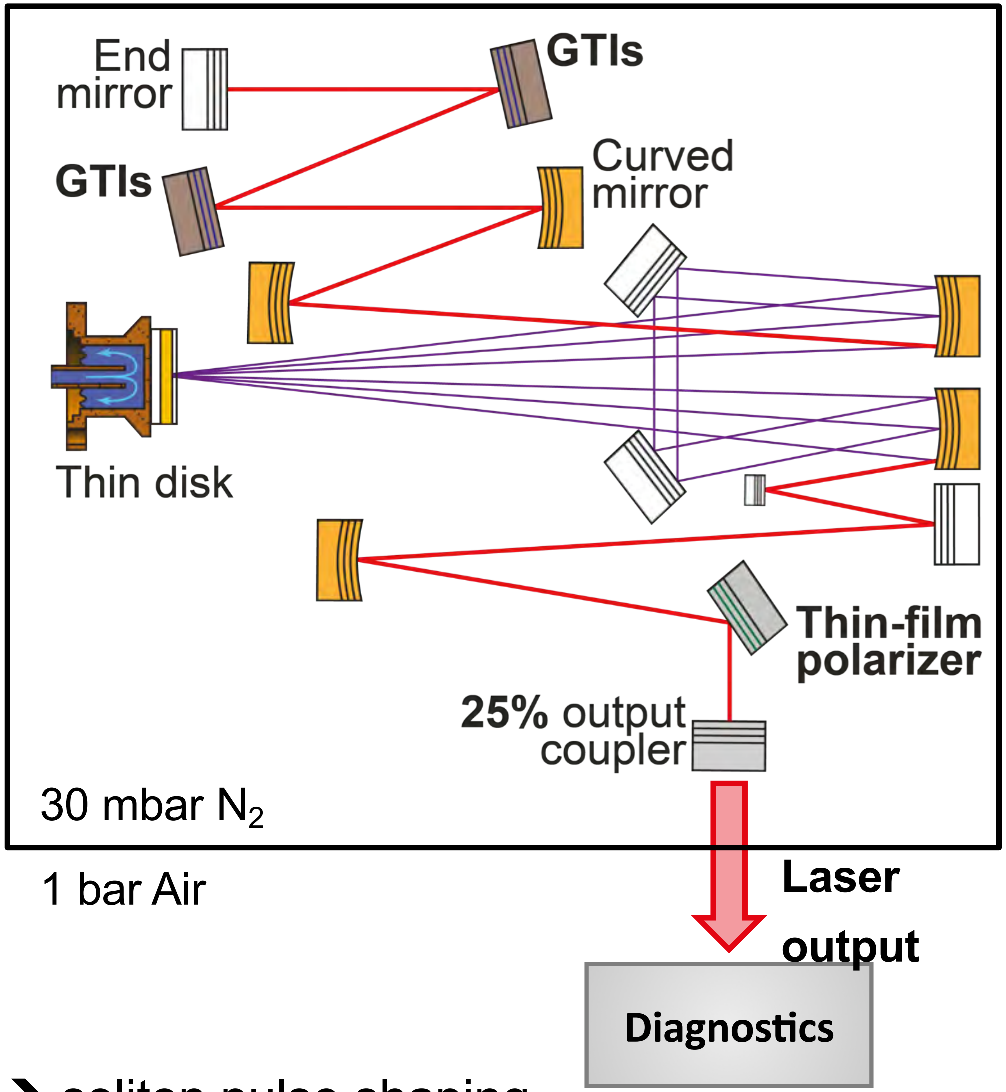
Soliton Modelocking





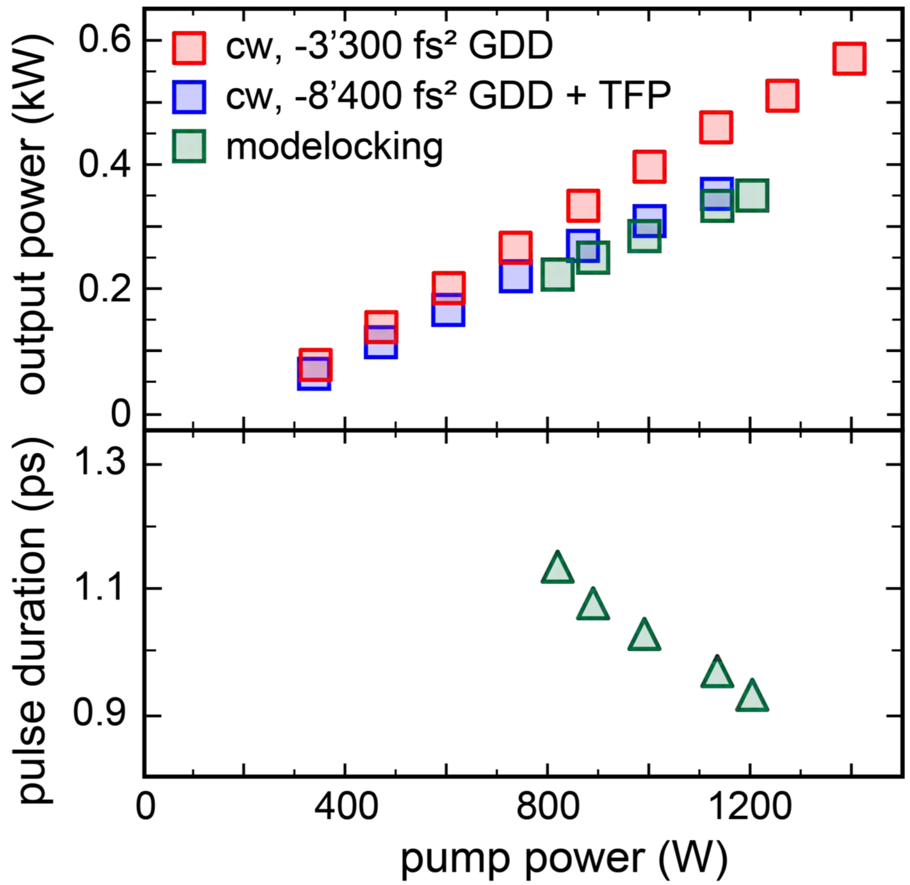
Soliton Modelocking

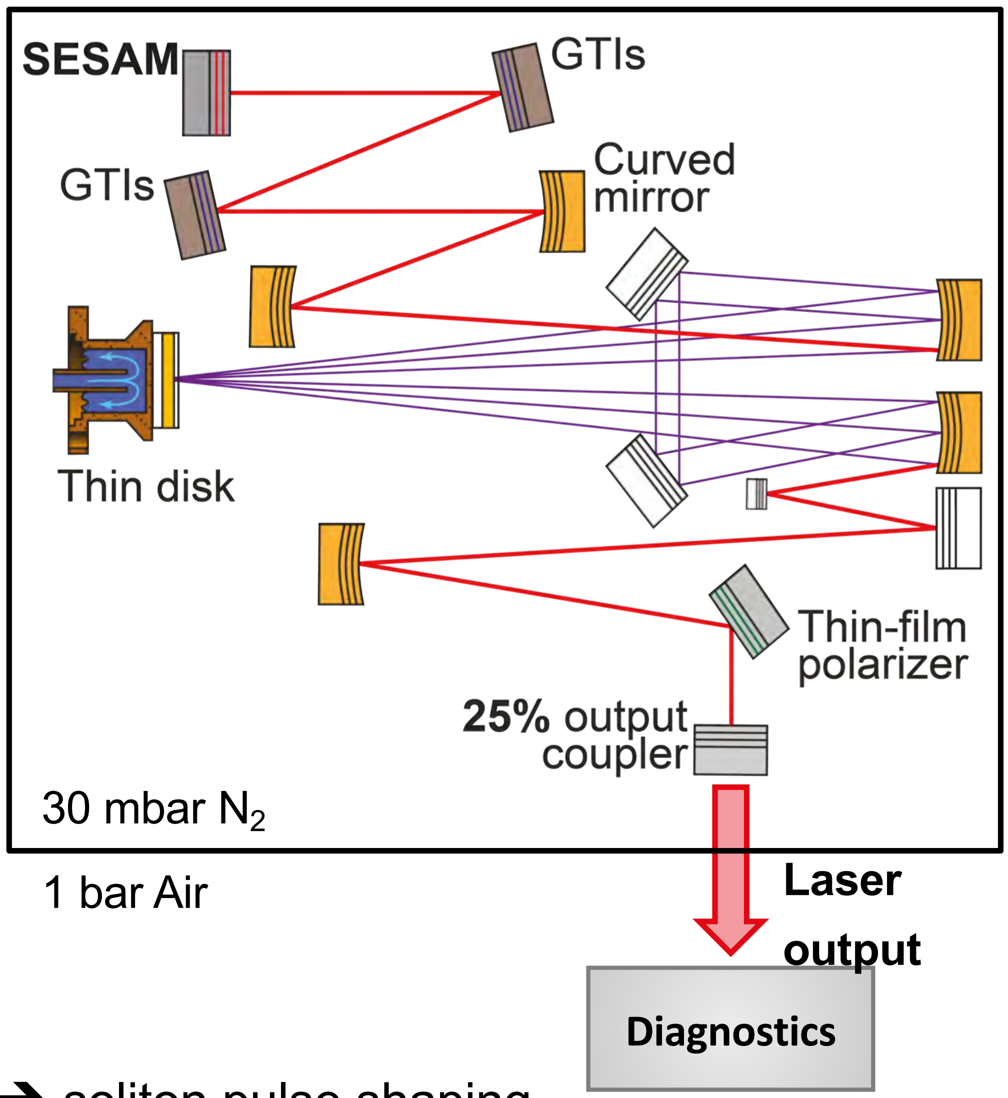




- ❑ Add negative dispersion (GTI mirrors) ➔ soliton pulse shaping

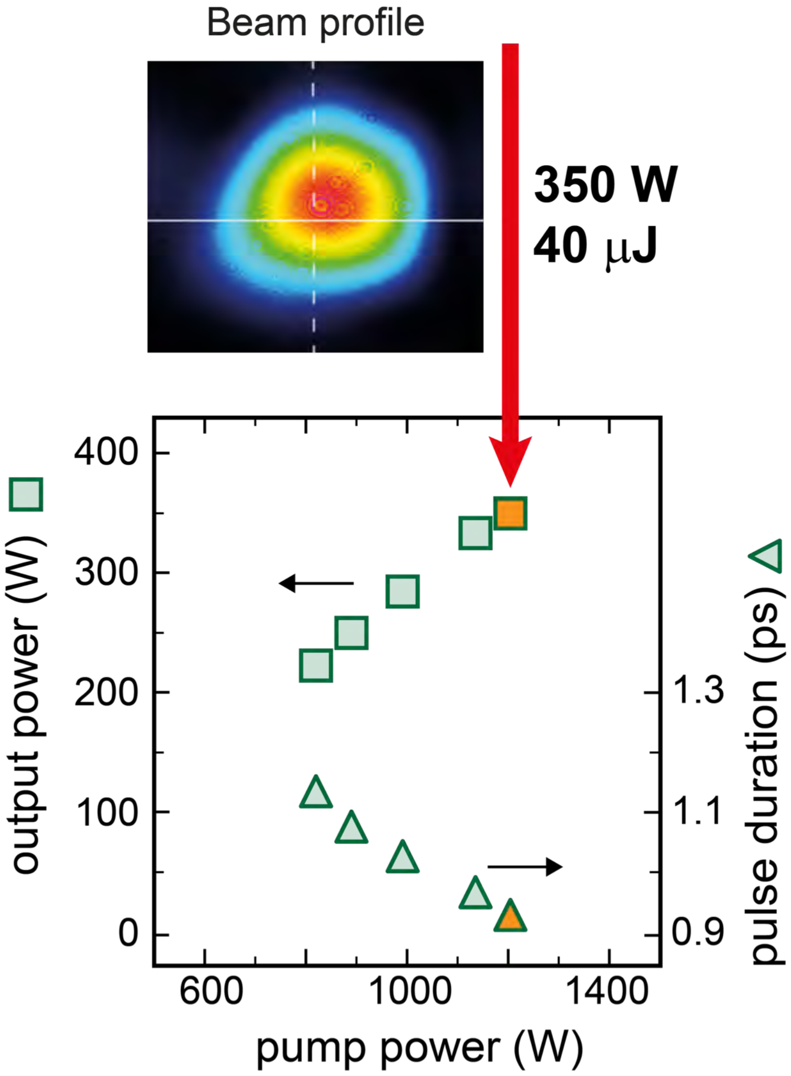
Soliton Modelocking



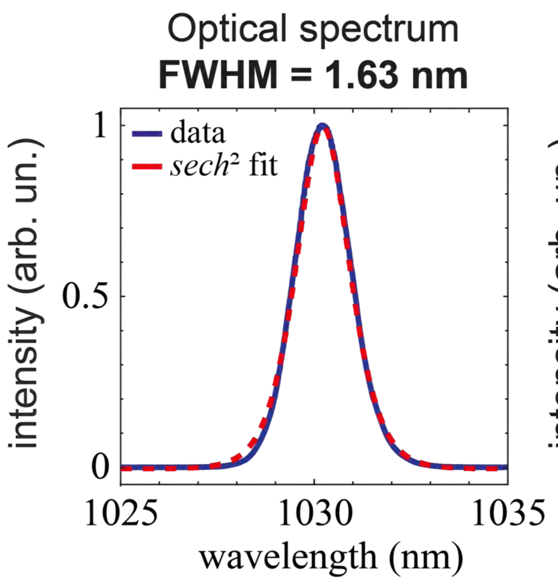


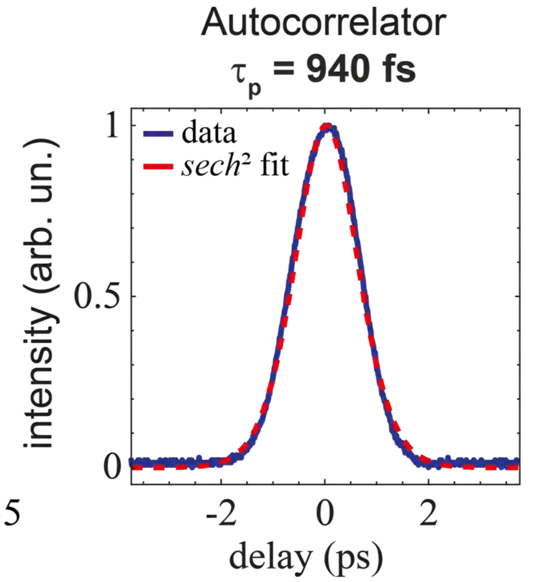
- Add negative dispersion (GTI mirrors) ➔ soliton pulse shaping
- Add the SESAM ➔ start and stabilize soliton modelocking

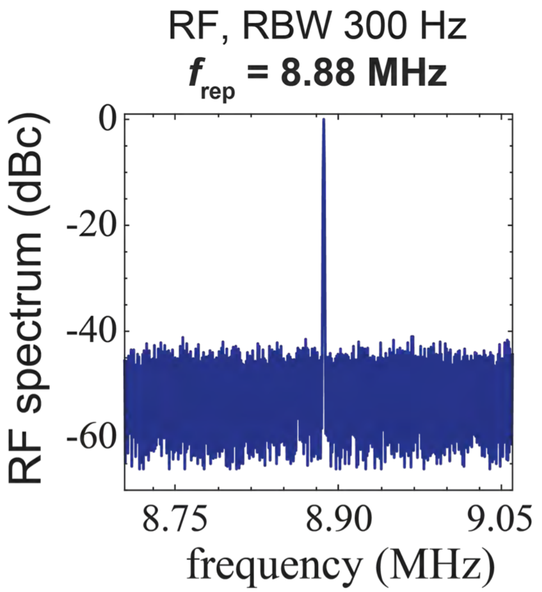
Soliton Modelocking

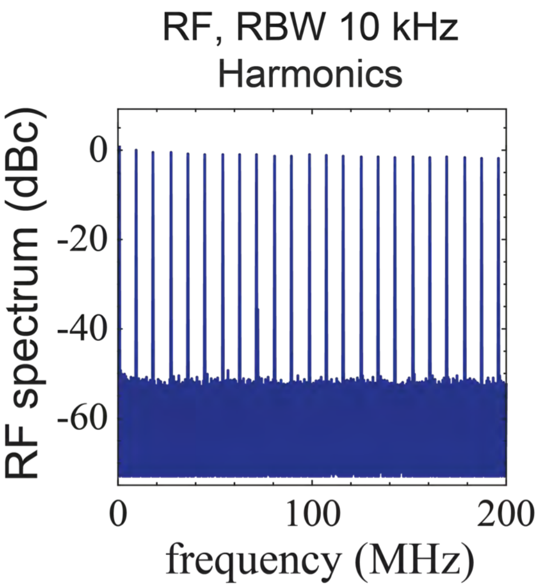

Beam profile

350 W
40 μJ

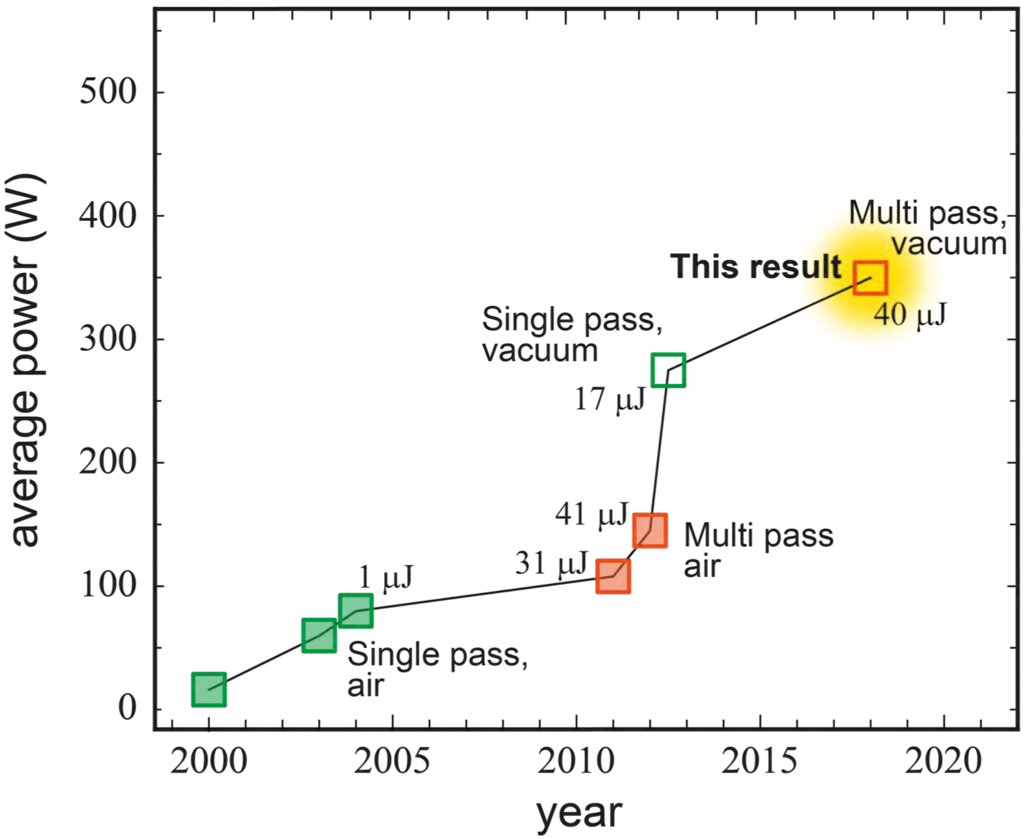

Optical spectrum
FWHM = 1.63 nm


Autocorrelator
τ_p = 940 fs


RF, RBW 300 Hz
f_{rep} = 8.88 MHz


RF, RBW 10 kHz
Harmonics

This result: 350 W average output power



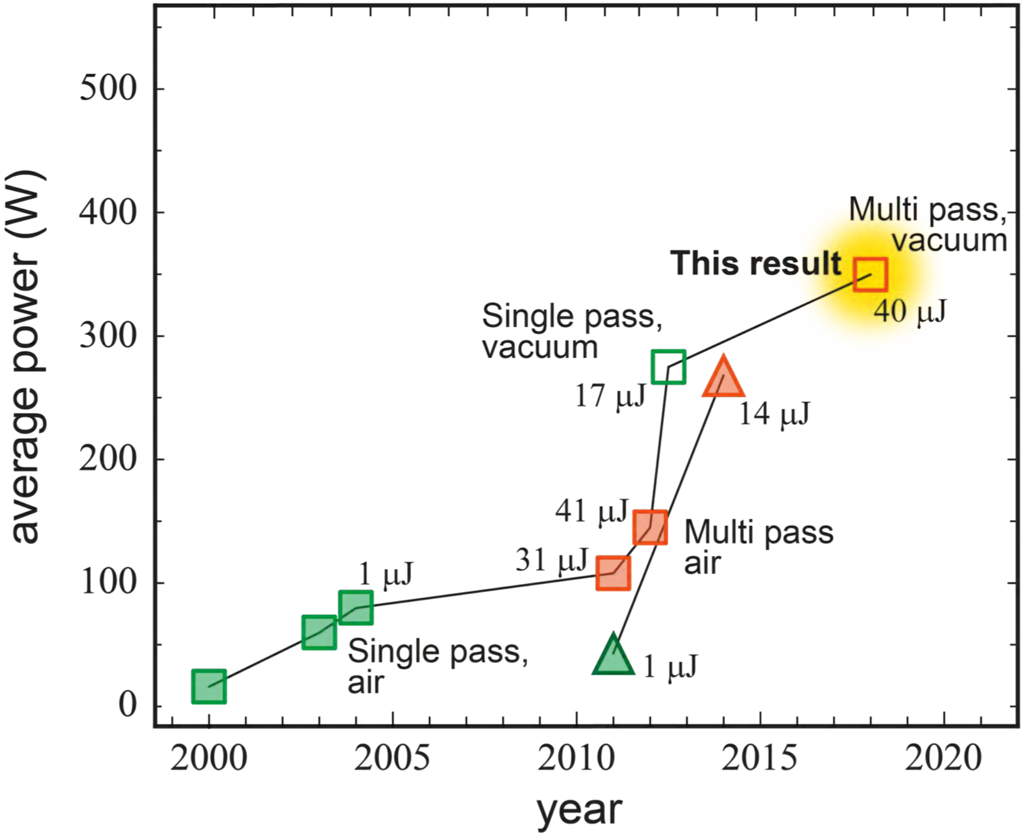
SESAM modelocked thin-disk lasers:

- 🟩 Single-pass cavity, Air
- ☐ Single-pass cavity, Vacuum
- ☐ Multi-pass cavity, Vacuum

C. J. Saraceno, et. al., Opt. Express 20, 23535 (2012)
Dominik Bauer, et. al., Opt. Express 20, 9698 (2012)

- ❑ **350 W –** new record average output power from an ultrafast oscillator
- ❑ **Vacuum** operation ➔ mitigates disk’s thermal lensing and reduces overall SPM
- ❑ **Multi-pass** cavity ➔ minimizes the intracavity power

This result: 350 W average output power



SESAM modelocked thin-disk lasers:

- 🟩 Single-pass cavity, Air
- ☐ Single-pass cavity, Vacuum
- ☐ Multi-pass cavity, Vacuum

Kerr-lens modelocked thin-disk lasers:

- ▲ Single-pass cavity, Air
- ▲ Multi-pass cavity, Air

C. J. Saraceno, et. al., Opt. Express 20, 23535 (2012)
Dominik Bauer, et. al., Opt. Express 20, 9698 (2012)
Pronin et al, Opt. Lett. 36, 4746 (2011)
J. Brons, et. al., Opt. Lett. 39, 6442 (2014)

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Overview ultrafast thin disk lasers

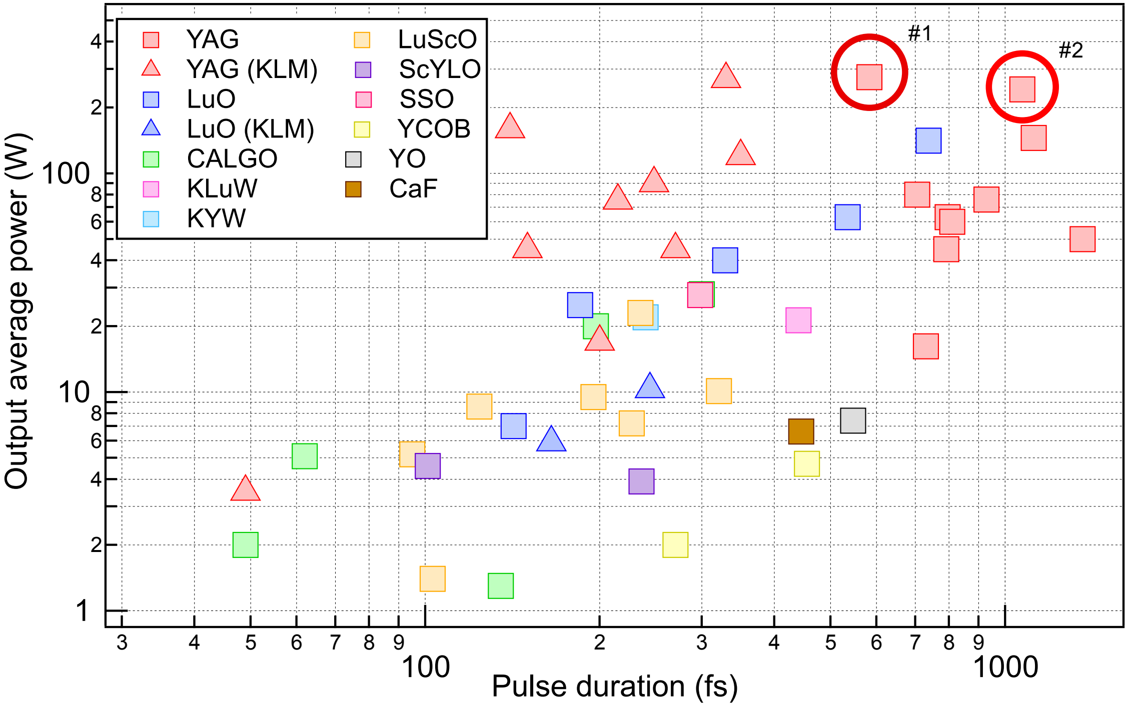
Power and energy scaling

- ✓ **SESAM** modelocked TDLs:
  P_{av} up to 275 W[#1]
  E_p up to 80 μJ[#2]
  P_{pk} up to 66 MW[#2]
  τ_p > 500 fs

[#1] C.J. Saraceno, et al., *Optics Express* ***20*** (2012)
[#2] C.J. Saraceno et al., *Optics Letters* ***39*** (2014)

- ✓ **Kerr-lens** modelocked TDLs:
  P_{av} up to 270 W[#3]
  E_p up to 14 μJ[#3]
  P_{pk} up to 63 MW[#4]
  τ_p > 140 fs

[#3] J. Brons, et al., *Optics Letters* ***39*** (2014)
[#4] J. Brons, et al., *Optics Letters* ***41*** (2016)



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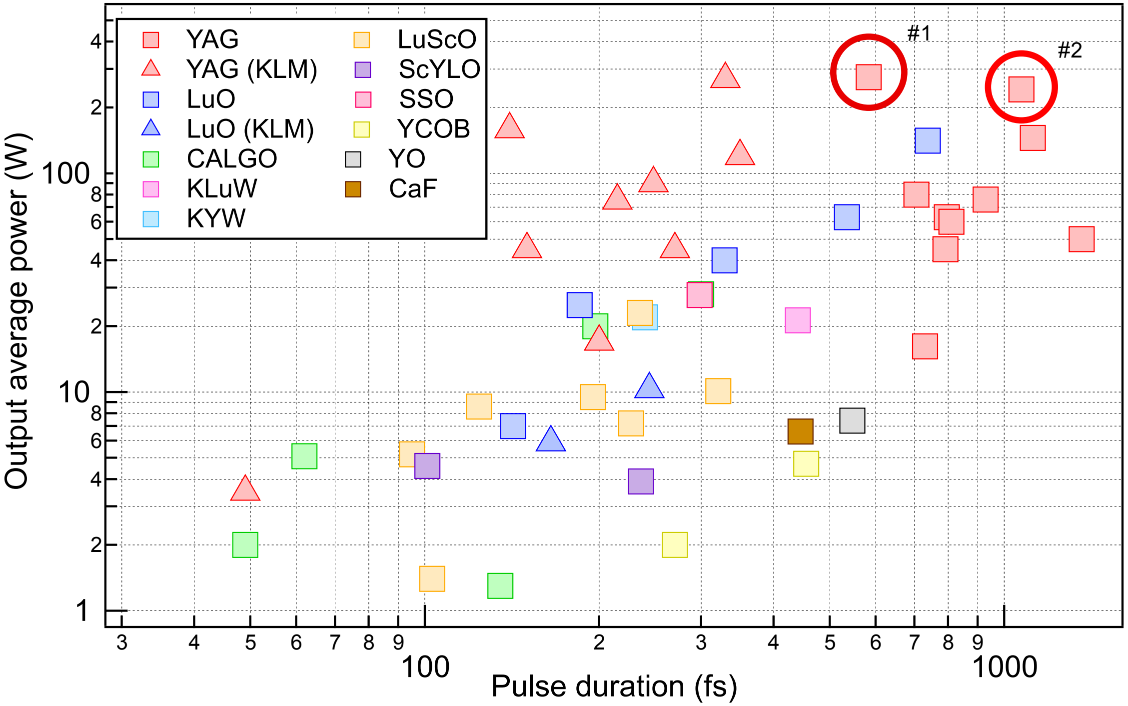
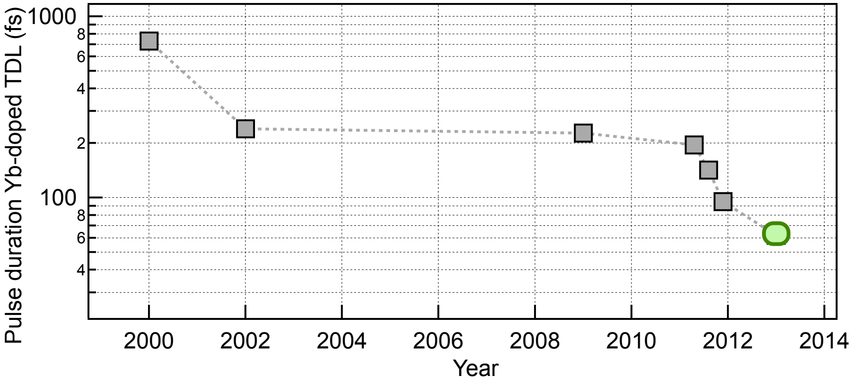


Reaching shorter pulse durations

- ✓ Novel **broadband** gain materials:
  shortest τ_p = 49 fs (Yb:CALGO)[#5]
  low P_{av} < 5 W

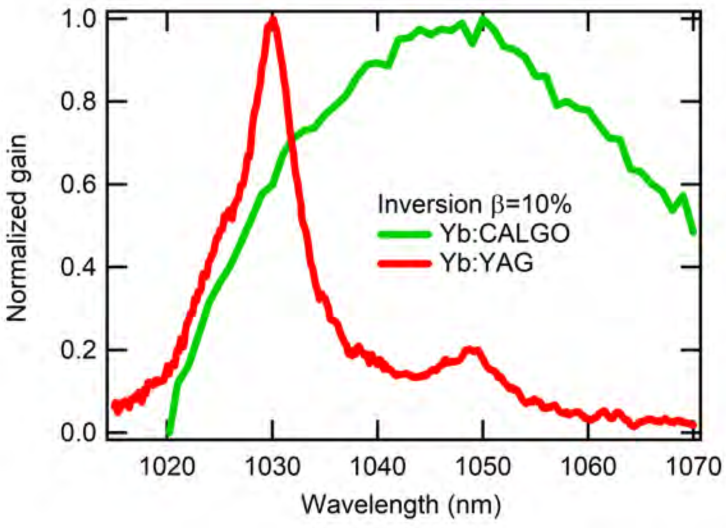
[#5] A. Diebold, et al., *Optics Letters* ***38*** (2013)



Promising material: Yb:CALGO thin-disk laser

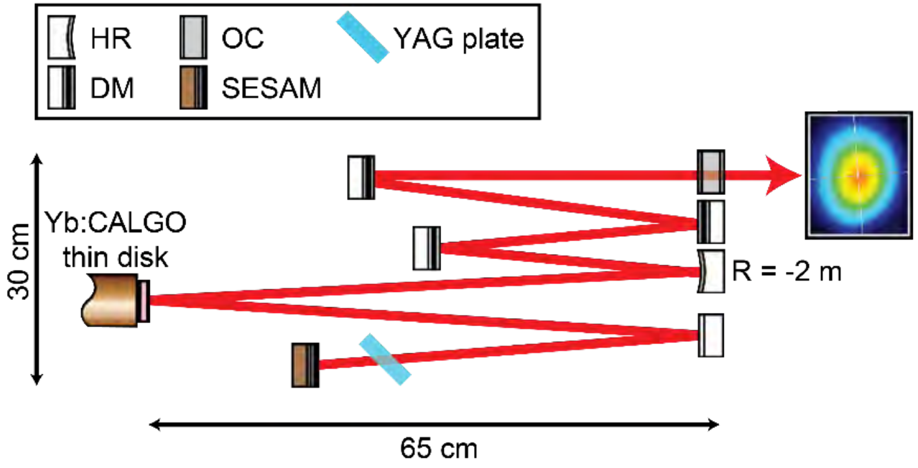
Progress in high-quality crystal growth: & C. Kränkel, et al., *IEEE J. Sel. Top. Quant.* **21** (2015)

→ pulse-duration scaling with Yb:CALGO: J. Petit, P. Goldner, B. Viana, Opt. Lett. **30**, 1345, 2005



	Yb:YAG	Yb:CALGO
Δf_g FWHM (nm)	7.0	35
Thermal conductivity (1 at.%) [W/(m*K)]	8.5	6.3
Crystal growth	+	-

5.1 W, 62 fs: A. Diebold et al., *Opt. Lett.* **38**, 3842 (2013)
C. Schriber et al., ASSL, Paper AF1A.4 (2014)

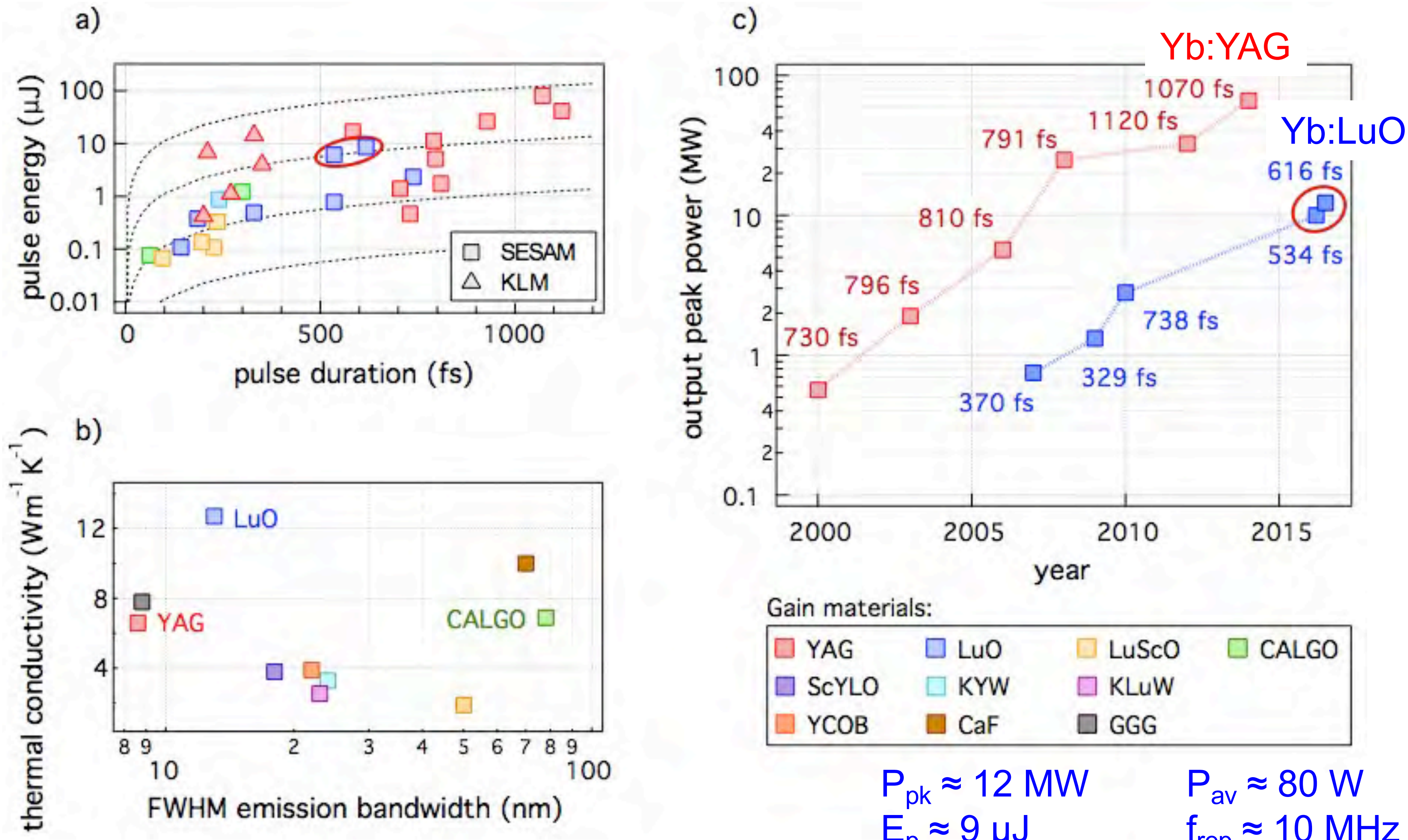


Minimized third-order dispersion by optimizing GTI-type dispersive mirrors

T_{out}	1.6%
f_{rep}	65.0 MHz

P_{av}	**2 W**
τ_p	**49 fs**
$P_{peak, IC}$	35 MW

Promising material: Yb-doped Lu_2O_3 thin-disk laser



$P_{pk} \approx 12$ MW $P_{av} \approx 80$ W
$E_p \approx 9$ µJ $f_{rep} \approx 10$ MHz
$\tau_p = 616$ fs (limited by SESAM)

J. Graumann et al., *Optics Express*, vol. 25, No. 19, 22519, 2017
C. Kränkel, *IEEE J. Sel. Top. Quantum Electron.* ***21*** (2015) – material pioneered by Prof. Huber, Hamburg

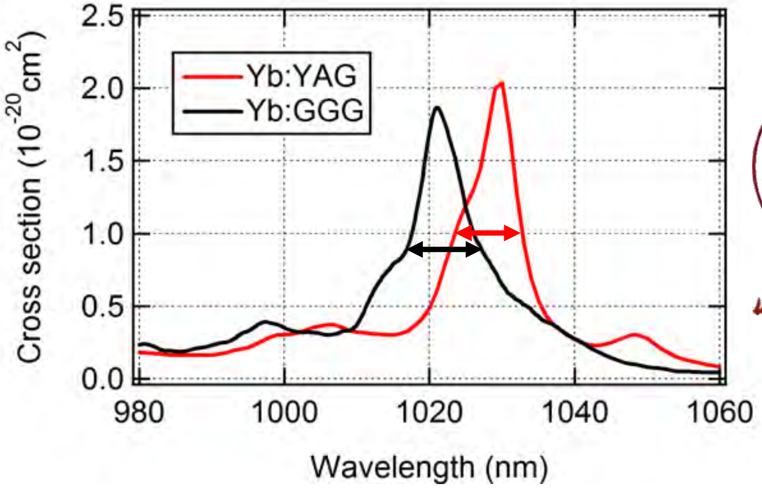
Promising material: Yb:GGG thin-disk laser

	Yb:LuO	Yb:YAG	Yb:GGG
Quantum defect (rel. to YAG)	95%	100%	80%
Thermal conductivity (at 4 at.%) (W/(m*K)	12	8	7.8 (independent of doping)
Melting temperature (°C)	2450	1940	1750
Crystal growth method	HEM	Czochralski	Czochralski

	Yb:YAG	Yb:GGG
FWHM emission spectrum	7 nm	8 nm

Spectrum of **Yb:GGG** should support sub-ps modelocking

Yb:GGG TDL limited by crystal quality so far!

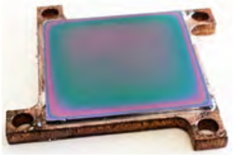


S. Chenais, et al., *Opt. Mat.* **22** 99-106 (2003)
Shandong University, China

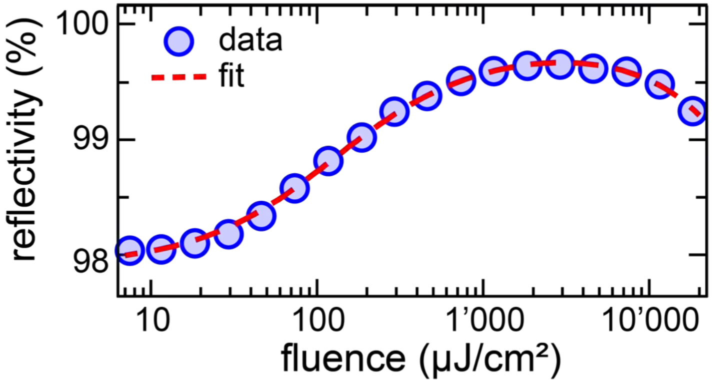
A. Diebold, Z. Jia, I. J. Graumann, Y. Yin, F. Emaury, C. J. Saraceno, X. Tao, U. Keller
“High-power Yb:GGG thin-disk laser oscillator: first demonstration and power scaling prospects“
Optics Express, vol. 25, No. 2, pp. 1452-1462, 2017

Challenges for ultrafast TDLs

Step 2: Obtain stable pulse formation



SEmiconductor **S**aturable **A**bsorber **M**irror - SESAM



C. J. Saraceno, et. al., Opt. Express 20, 23535 (2012)

+

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Possible Solutions:

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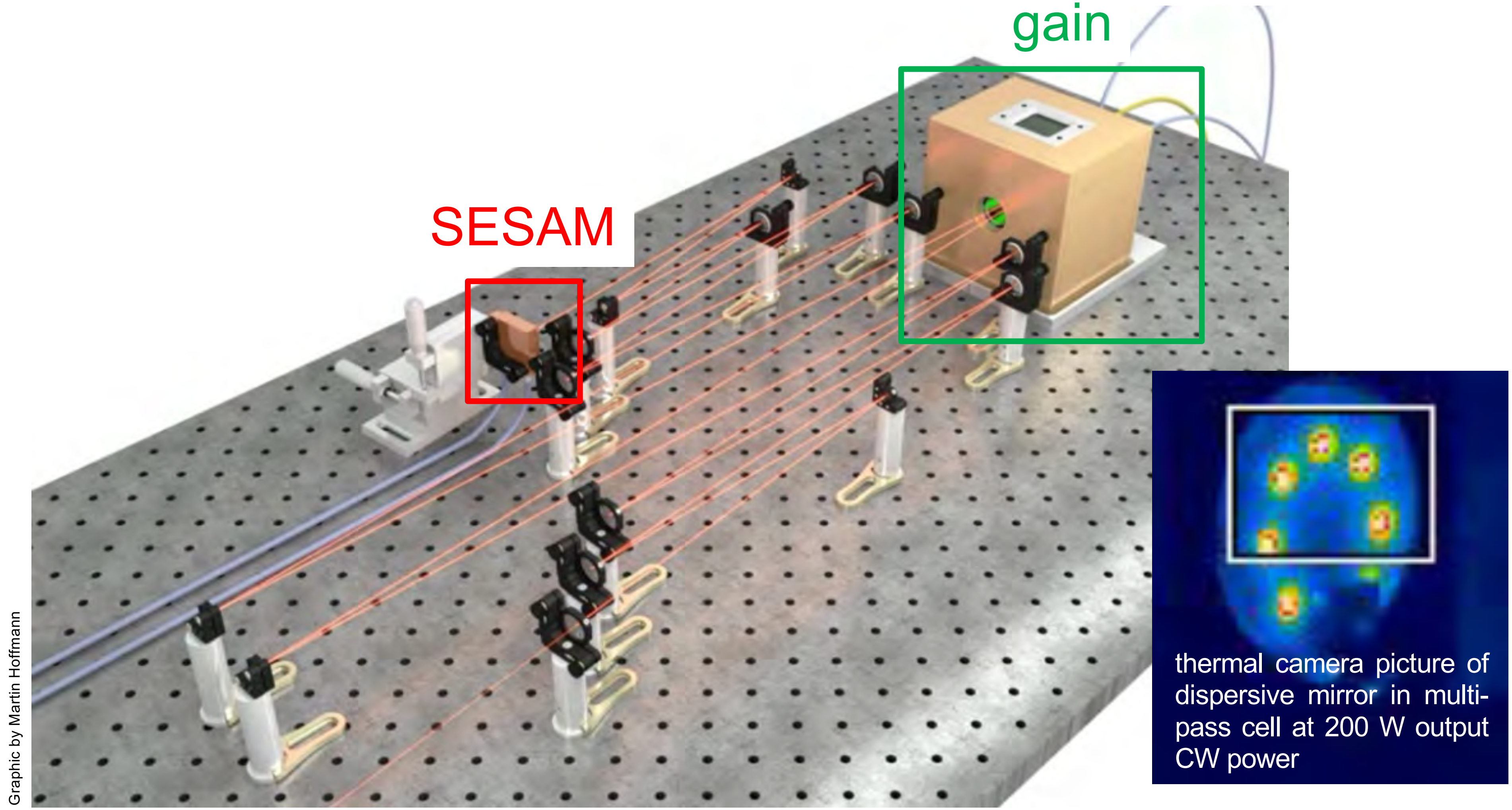
SESAM-modelocked thin-disk lasers



Graphic by Martin Hoffmann

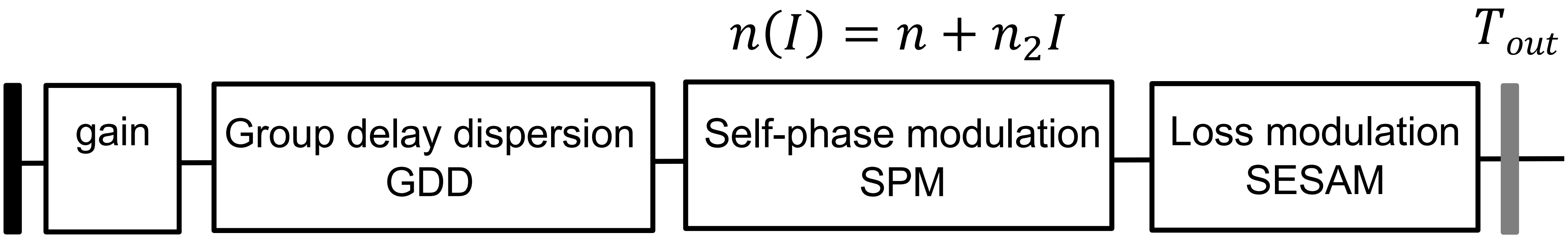
thermal camera picture of dispersive mirror in multi-pass cell at 200 W output CW power

Highest average power (275 W, 16.9 µJ, 0.58 ps, 16 MHz [#1]**) & highest pulse energy (80 µJ,** 242 W, 1 ps, 3 MHz [#2]**) of any ultrafast oscillator technology**

[#1] C. J. Saraceno, et al., *Opt. Express* **20**, 23535 (2012)

[#2] C. J. Saraceno, et al., *Opt. Lett.* **39**, 9 (2014)

Next challenge in high-power thin disk lasers



$$n(I) = n + n_2 I$$

T_{out}

gain

Group delay dispersion
GDD

Self-phase modulation
SPM

Loss modulation
SESAM

SESAM damage
not a problem!

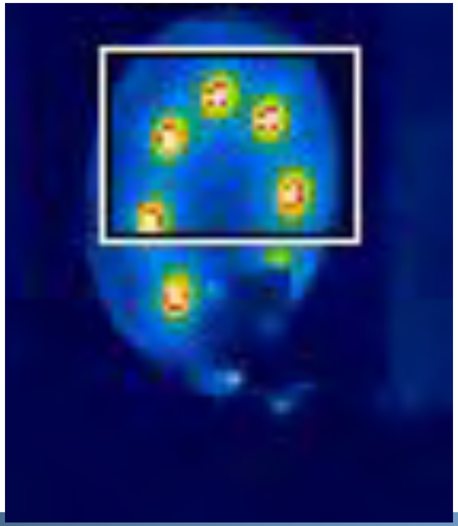
Typical soliton modelocking:

GDD < 0

designed with
prism pairs
Gires Tournois Interferometers (GTI)

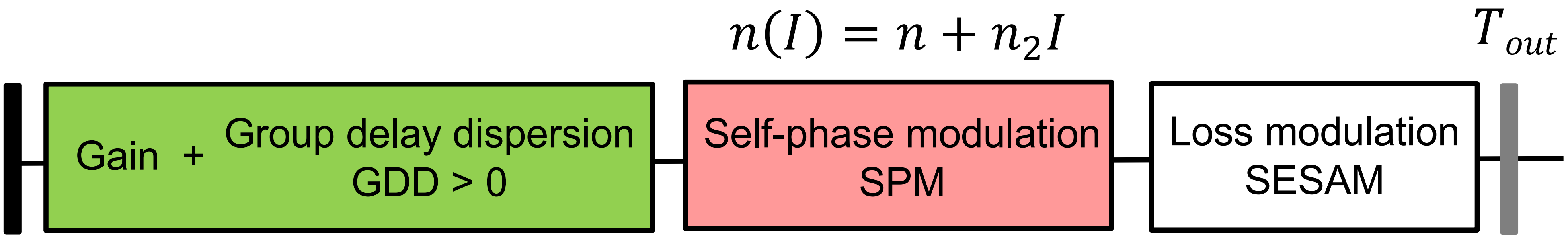
$n_2 > 0$

Given by material
e.g. gain material



Current challenge
Damage of GTI mirrors!

Design nonlinearities



$n(I) = n + n_2 I$

T_{out}

Gain + Group delay dispersion GDD > 0

Self-phase modulation SPM

Loss modulation SESAM

Typical soliton modelocking:

GDD < 0

designed with
prism pairs
Gires Tournois Interferometers (GTI)

$n_2 > 0$

Given by material
e.g. gain material

Designed nonlinearity:

GDD > 0

Given by material
e.g. gain material

$n_2 < 0$

designed ?

$n_2 < 0$ with cascaded quadratic nonlinearities (CQN)

Several publications, e.g.:

- Theoretical investigations [1]
- Kerr lens-modelocking / SESAM modelocking results using LBO[2-4], PPKTP[5,6], PPMgSLT[7]

[1] Review of early work: G. I. Stegeman, D. J. Hagan, and L. Torner, *Opt. and Quant. Electron.* **28,** 1691 (**1996**)

[2] G. Cerullo, S. De Silvestri, A. Monguzzi, D. Segala, and V. Magni, *Opt. Lett.* **20**, 746 (1995)

[3] L.J. Qian, X. Liu, and F. W. Wise, *Opt. Lett.* ***24***,166, (**1999**)

[4] A.Agnesi, L.Carrà, F.Pirzio, G.Reali, *Opt. Express* ***16***, 9549 (**2008)**

[5] C. R. Phillips, A. S. Mayer, A. Klenner, and U. Keller, *Opt. Express.* ***22***, 6060 (**2014**)

[6] H. Iliev, D. Chuchumishev, I. Buchvarov, and V. Petrov, *Opt. Express* ***18***, 5754 (**2010**)

[7] S. J. Holmgren, V. Pasiskevicius, and F. Laurell, *Opt. Express* ***13***, 5270 (**2005**)

[8] H. Iliev, I. Buchvarov, S. Kurimura, and V. Petrov, *Opt. Lett.* ***35***, 1016 (**2010**)

n_2: nonlinear index

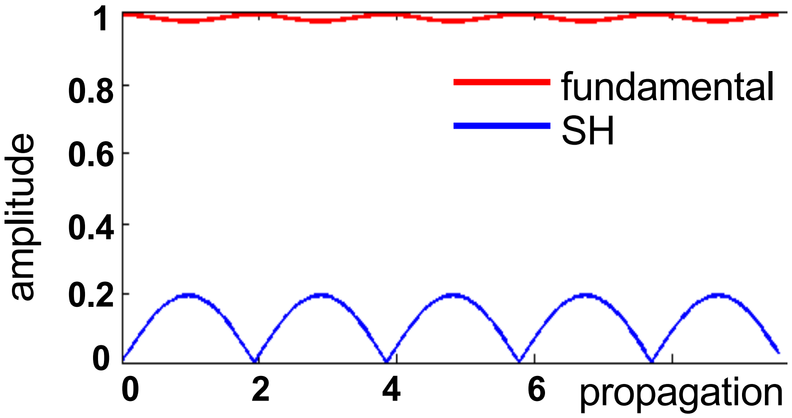
negative

Case 2: Δk large

“Cascading Regime“

→ Large phase mismatch

→ SHG very weak



weak periodic modulation of the fundamental, but no depletion

$n_2 < 0$ with cascaded quadratic nonlinearities (CQN)

Result:

An effective nonlinear index n_2^{casc} that can be **negative in sign**

Intrinsic n_2

$$n_2 = \frac{3}{4}\frac{\chi^{(3)}}{n_F^2 c\varepsilon_0}$$

Cascaded with CQN n_2^{casc}

$$n_2^{\mathrm{casc}} = \frac{3}{4}\frac{\chi^{(3)}_{\mathrm{casc}}}{n_F^2 c\varepsilon_0}$$

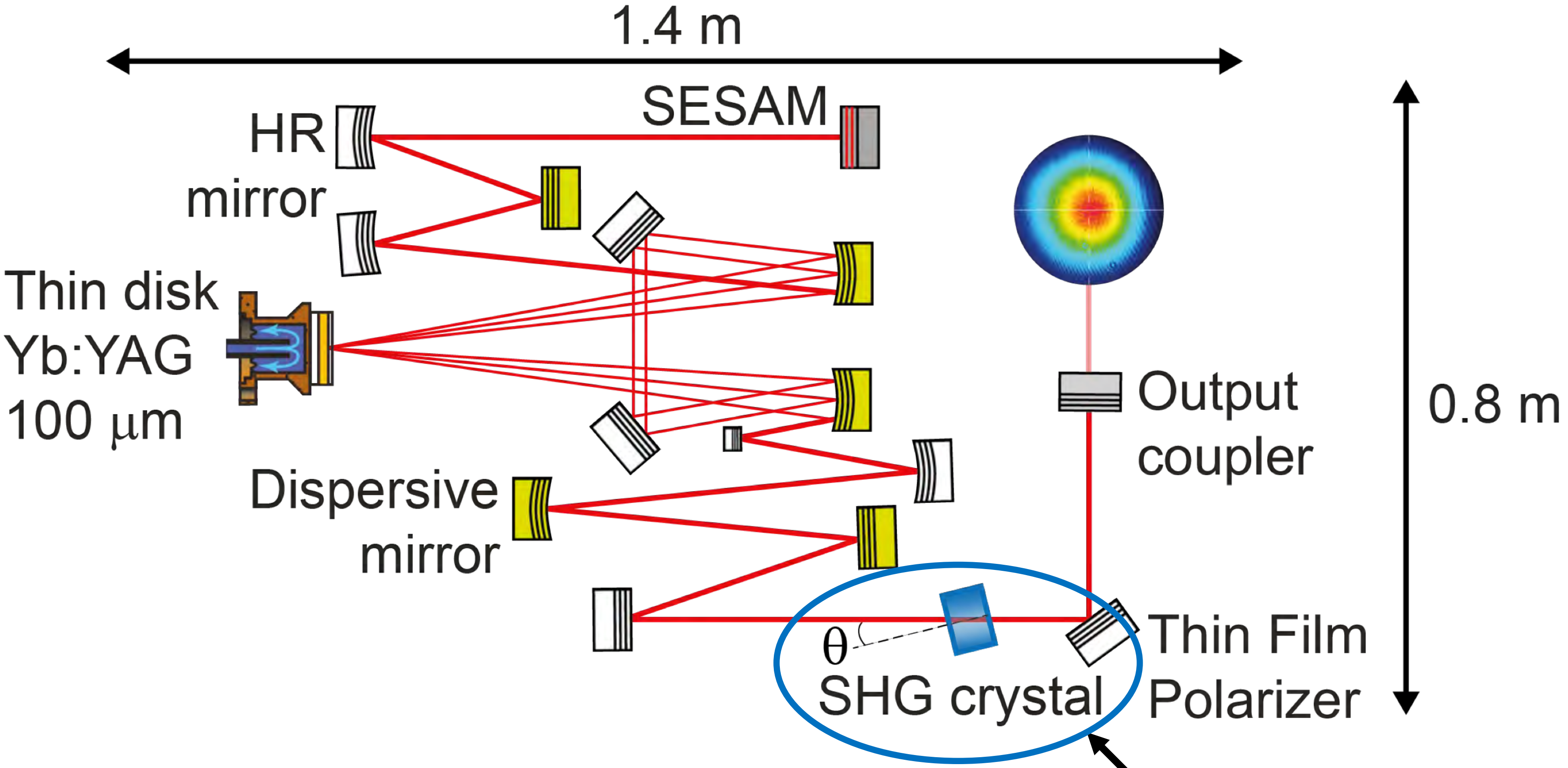
$$n_2^{\mathrm{casc}} = -\frac{1}{\boxed{\Delta k}}\frac{\omega_F}{2n_F^2 n_{SH} c^2 \varepsilon_0}\boxed{(\chi^{(2)})^2}$$

Depends on phase mismatch and second order nonlinearity

SPM coefficient:

$$\gamma = k n_2 \mathrm{L}$$

Laser design



Our approach to SPM mitigation:

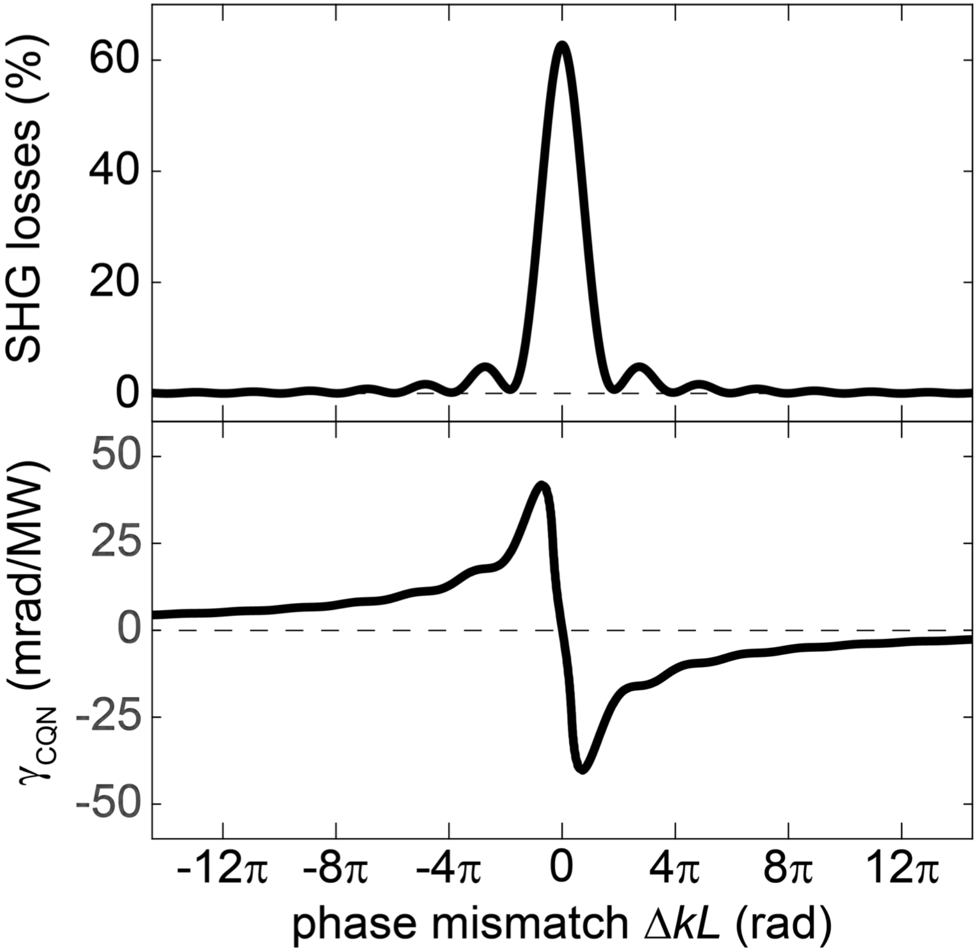
Large output-coupling ratio (40%) to lower the intracavity power

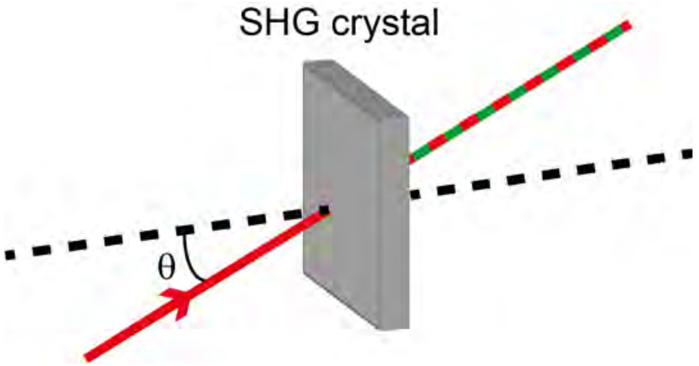
+

5-mm LBO crystal for Cascaded $\chi^{(2)}$ SPM cancellation

Cascaded $\chi^{(2)}$ processes

What happens when you put a SHG crystal as an intracavity component?





- **Second harmonic generation** acting as a loss

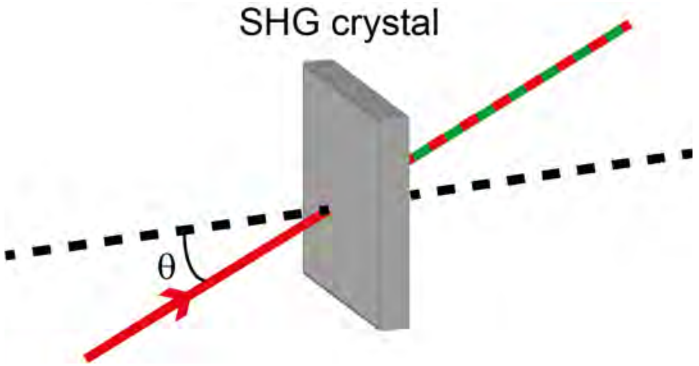
- **SPM coefficient:**

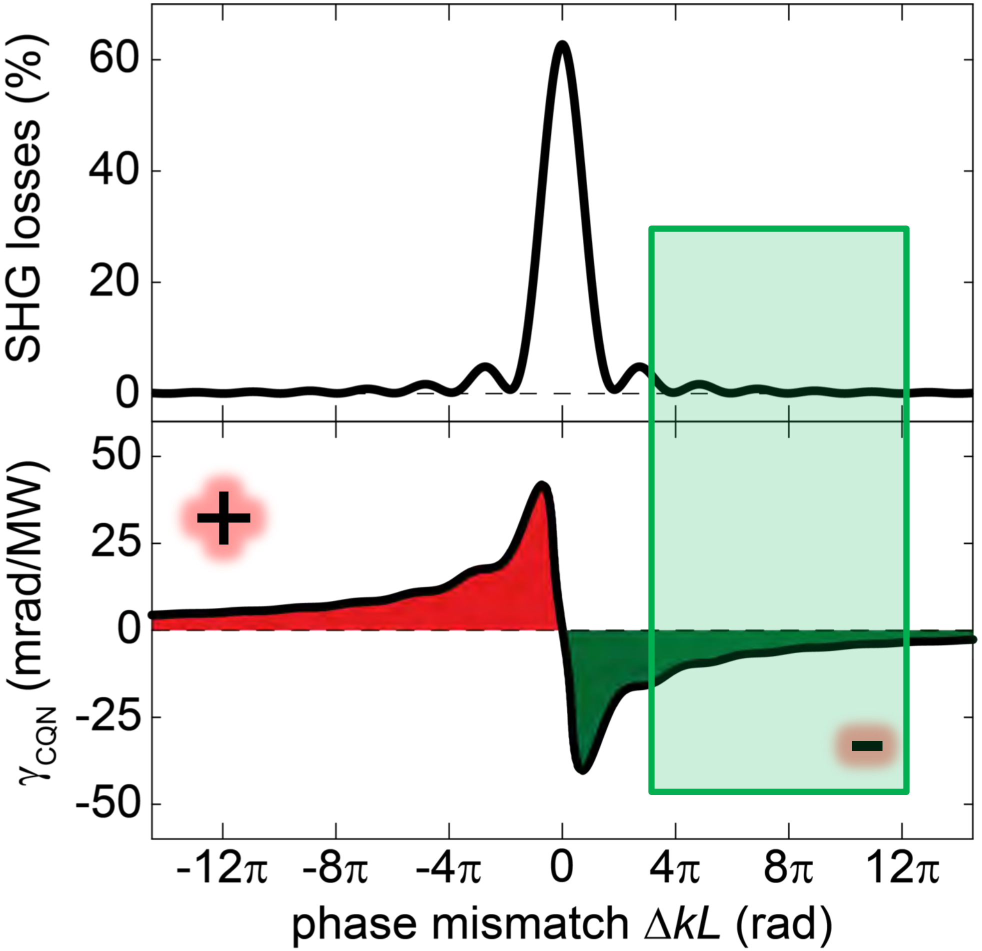
$$\gamma_{CQN} = k n_2^{CQN} L$$

W. Frank, et al., Journal of Nonlinear Optical Physics ***11****, 317-338 (2002)*

Cascaded $\chi^{(2)}$ processes

What happens when you put a SHG crystal as an intracavity component?





- **Second harmonic generation** acting as a loss

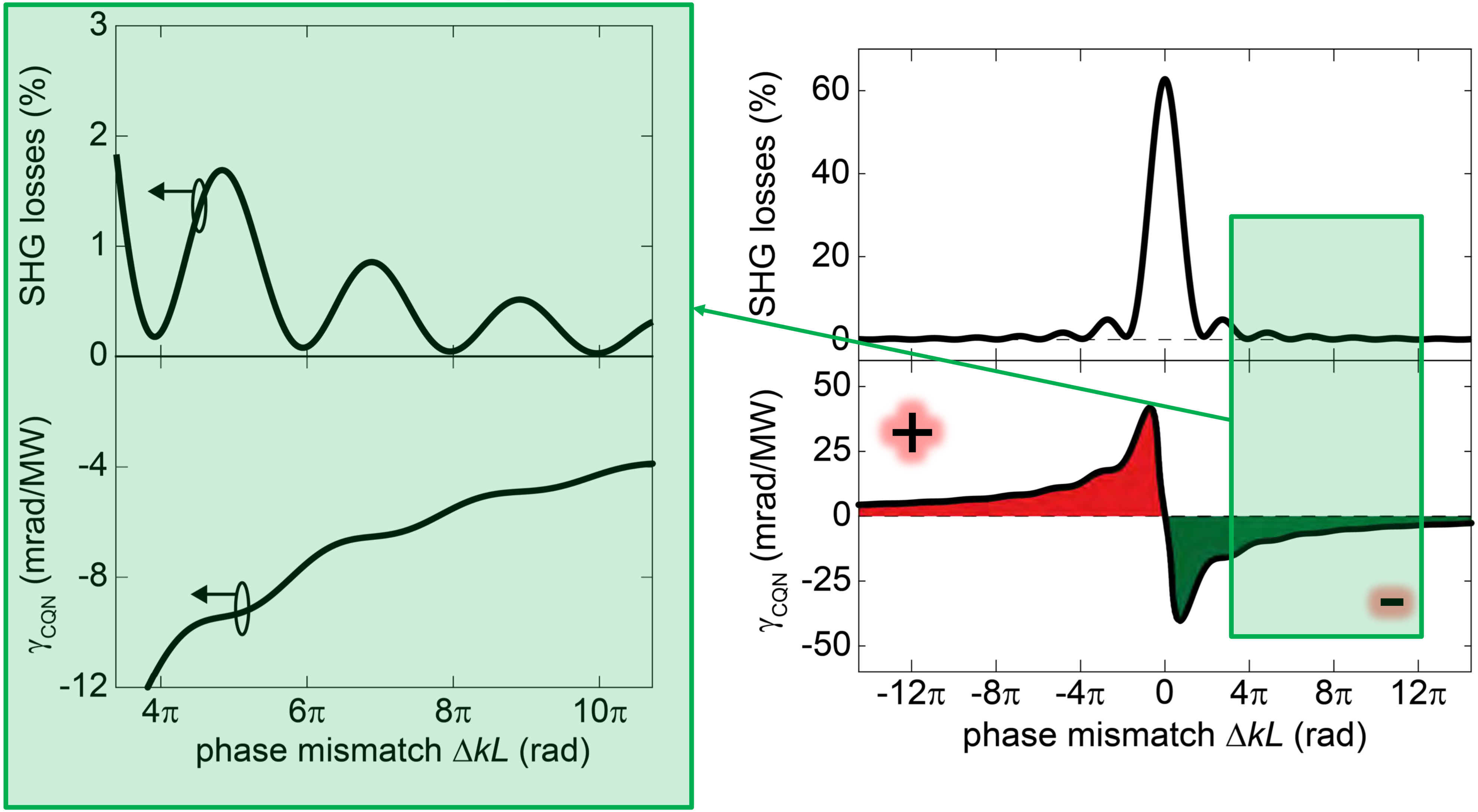
- **SPM coefficient:**

$$\gamma_{CQN} = k n_2^{CQN} L$$

positive or negative!

W. Frank, et al., Journal of Nonlinear Optical Physics ***11****, 317-338 (2002)*

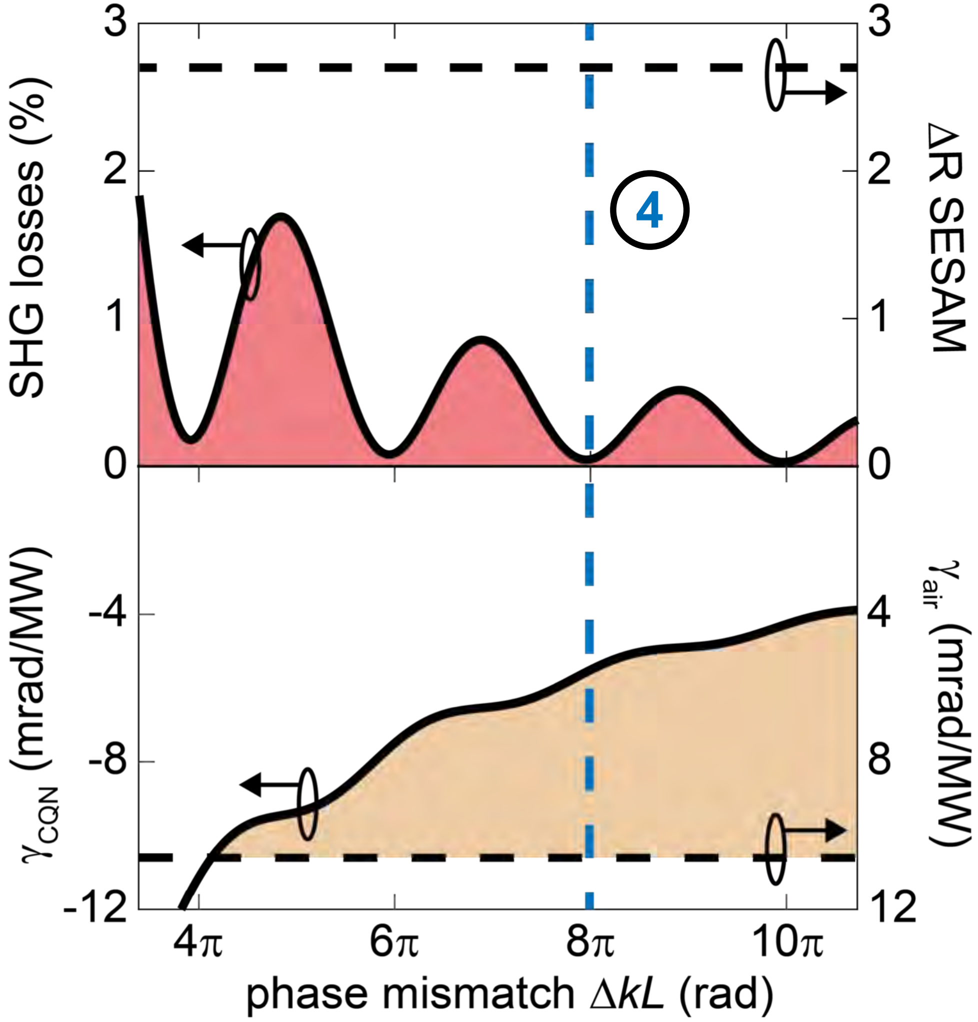
Cascaded $\chi^{(2)}$ – SPM on demand

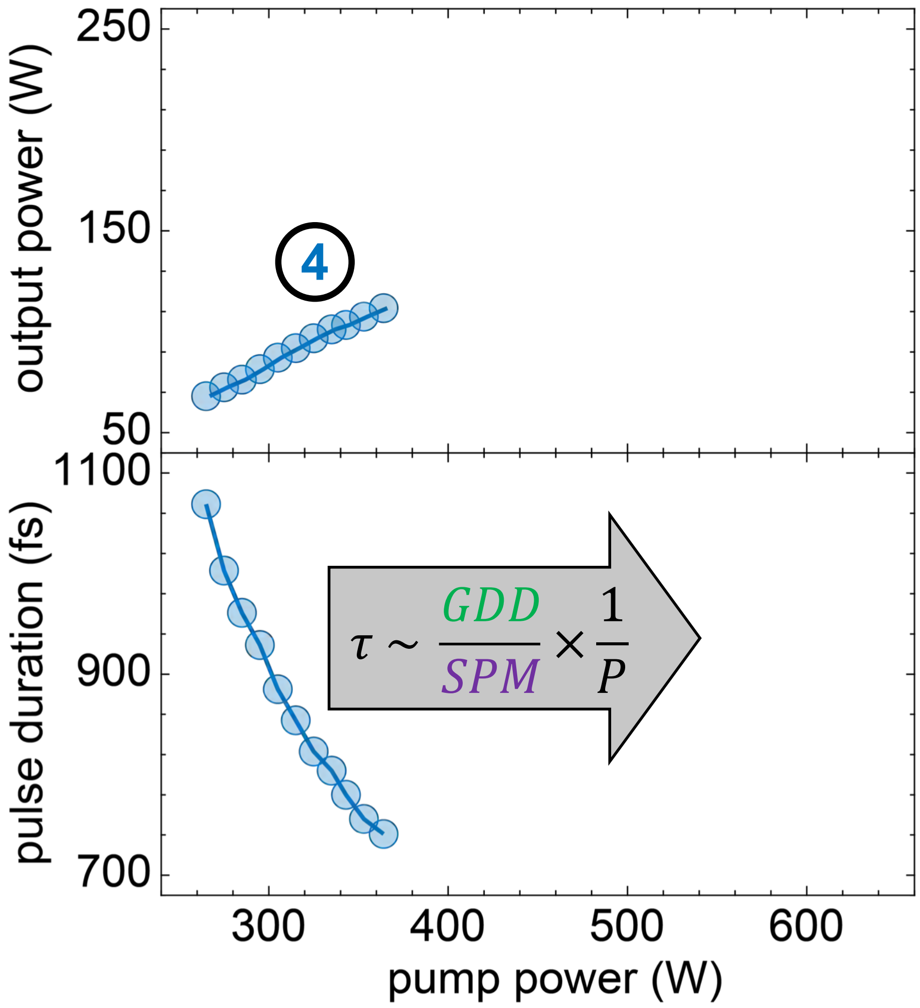


SPM coefficient:

$$\gamma_{CQN} = k n_2^{CQN} L$$

Cascaded $\chi^{(2)}$ – SPM on demand



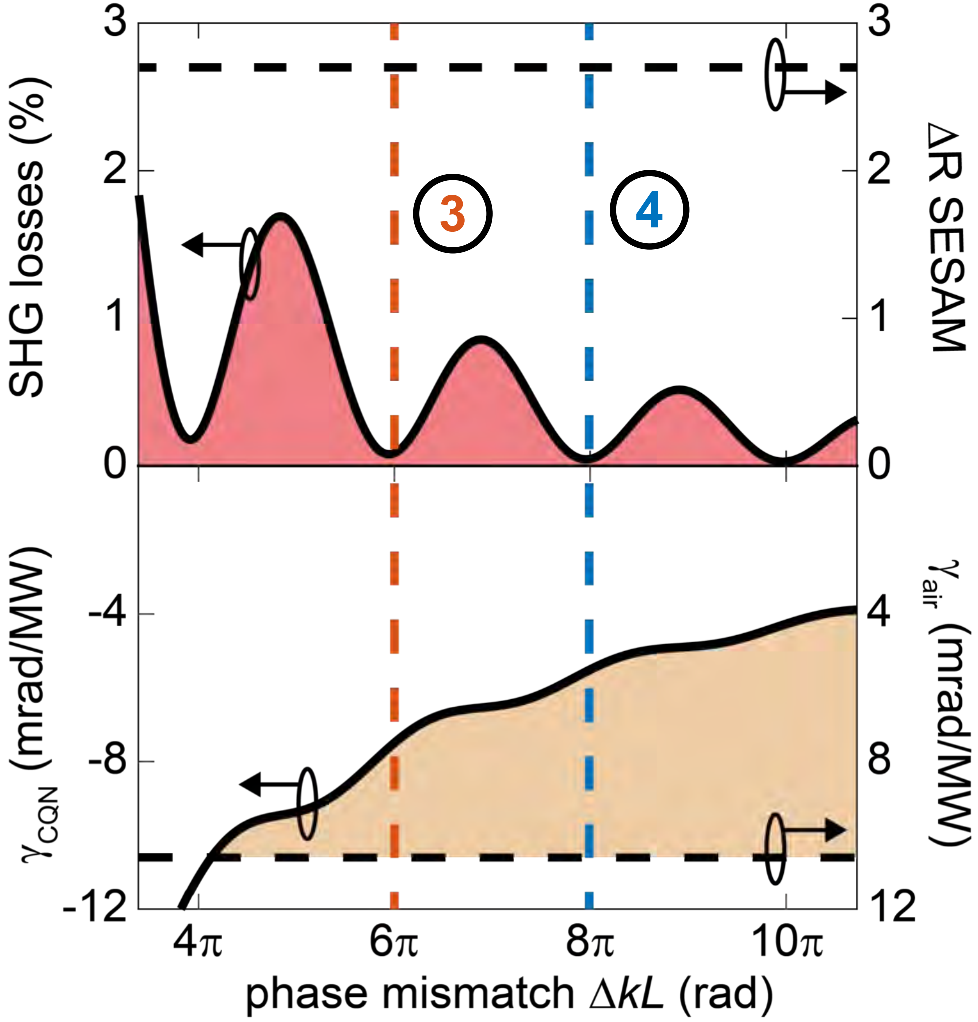


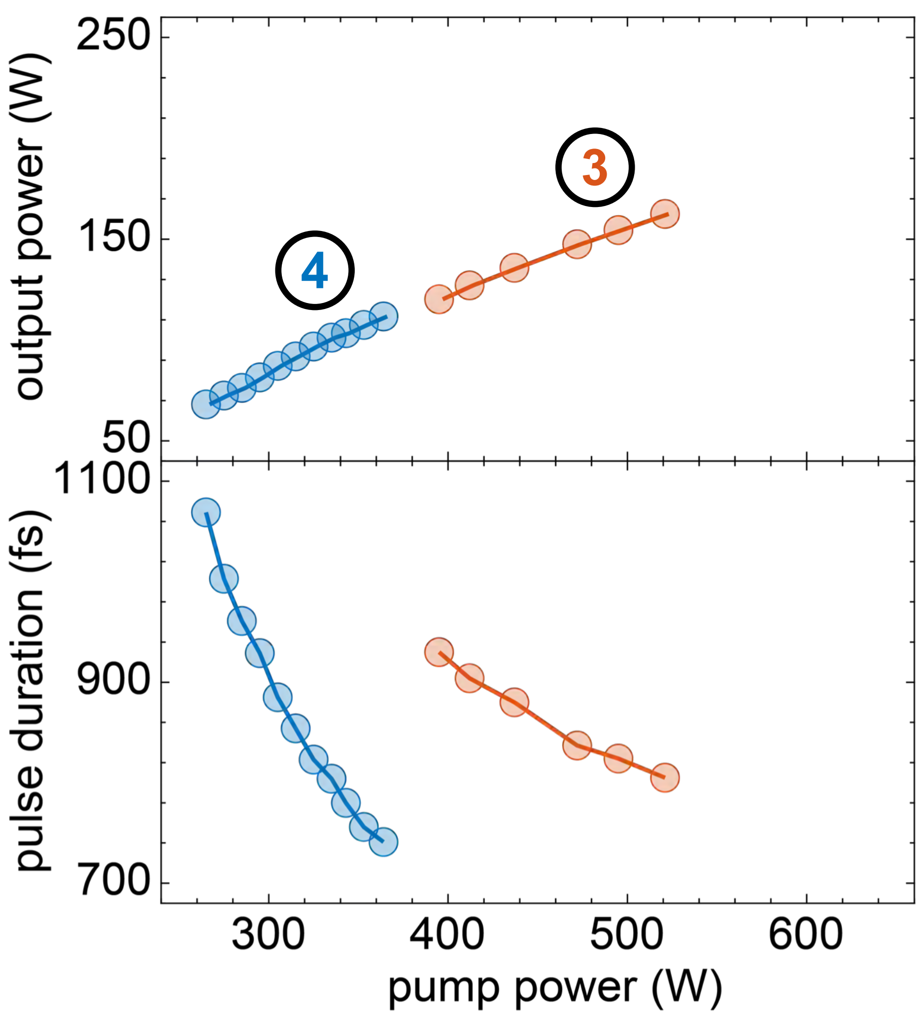
$$\tau \sim \frac{GDD}{SPM} \times \frac{1}{P}$$

- SPM from air cancelled:

④ ≈ 60%

Cascaded $\chi^{(2)}$ – SPM on demand

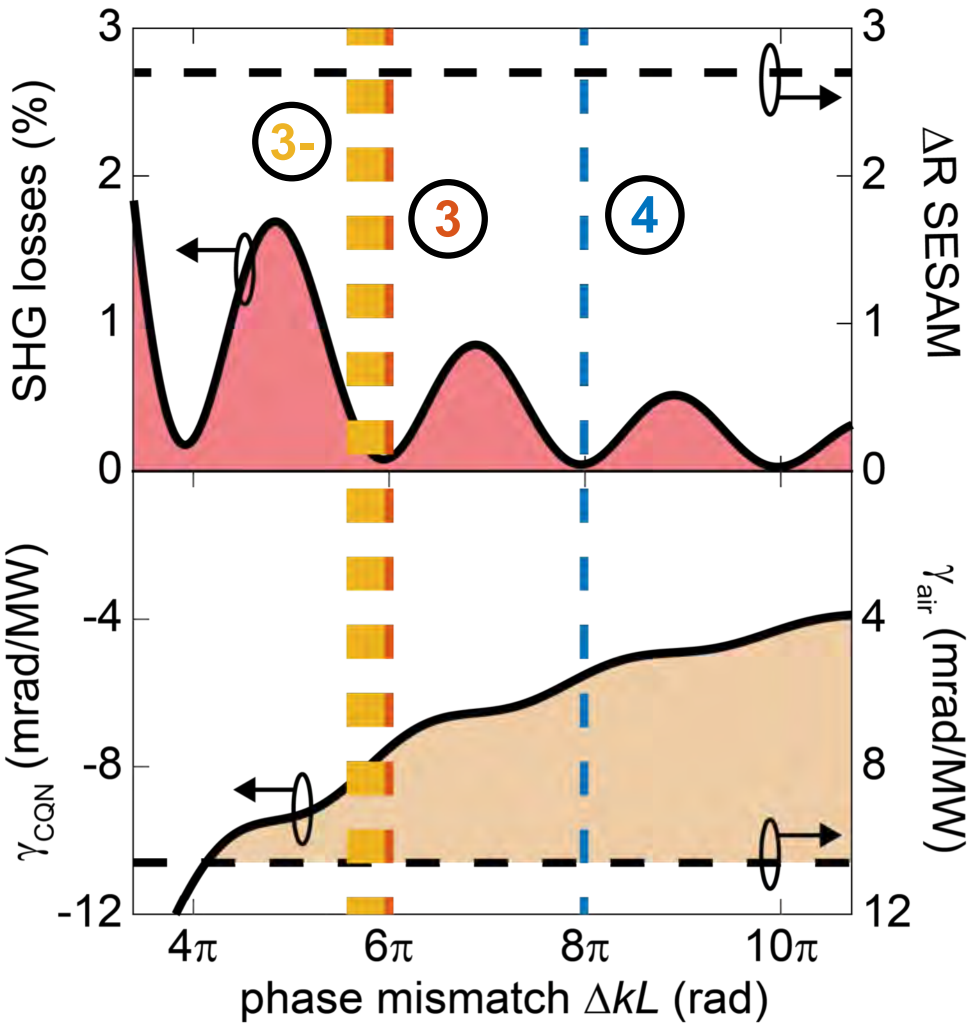


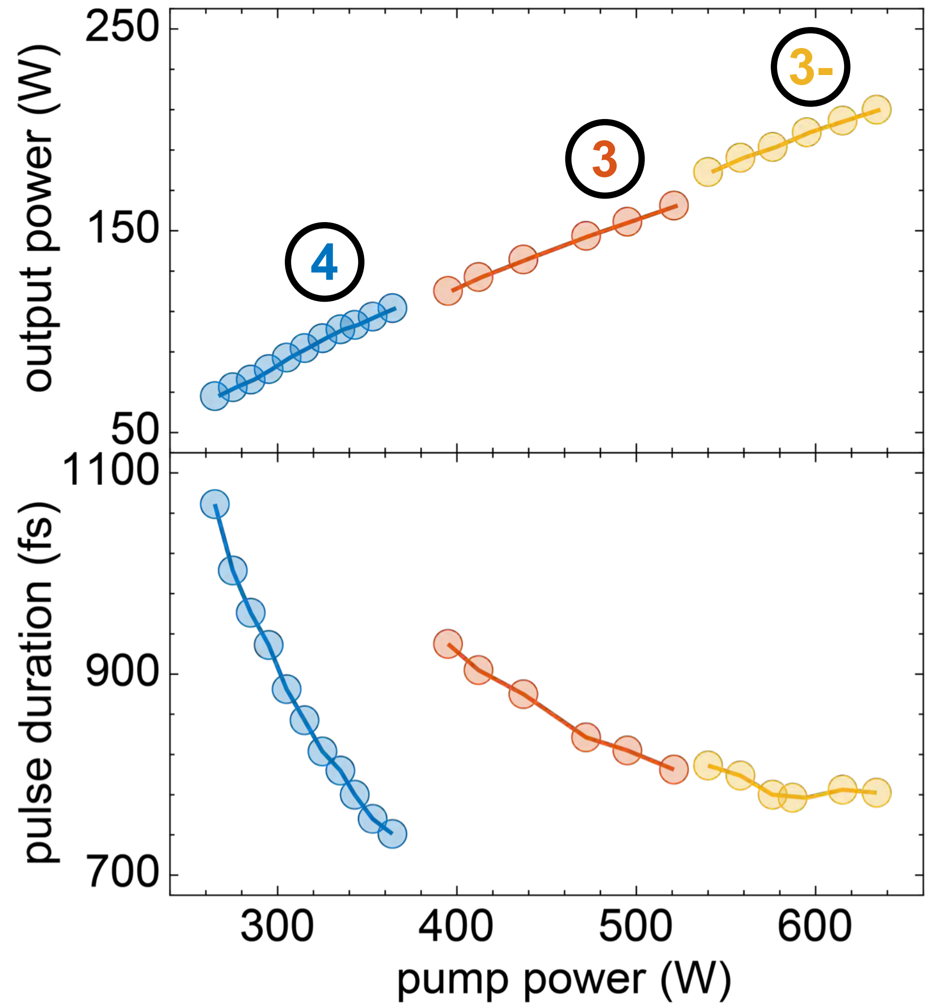


- SPM from air cancelled:

④ ≈ 60% ③ ≈ 75%

Cascaded $\chi^{(2)}$ – SPM on demand

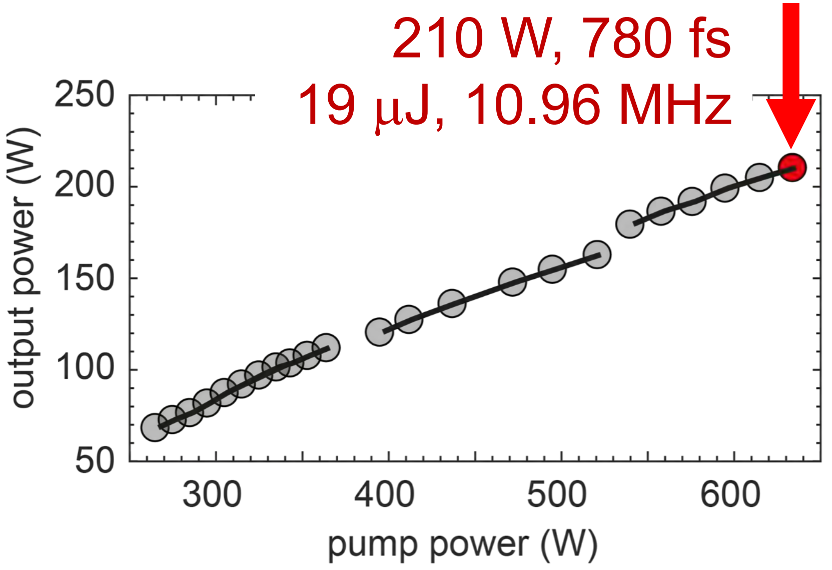




- SPM from air cancelled:

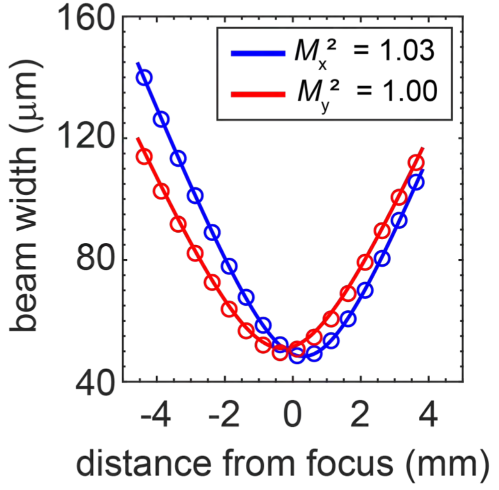
④ ≈ 60% ③ ≈ 75% 3- Up to ≈ 80%

Diagnostics

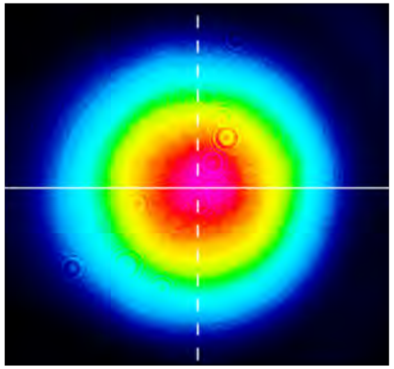


210 W, 780 fs
19 μJ, 10.96 MHz

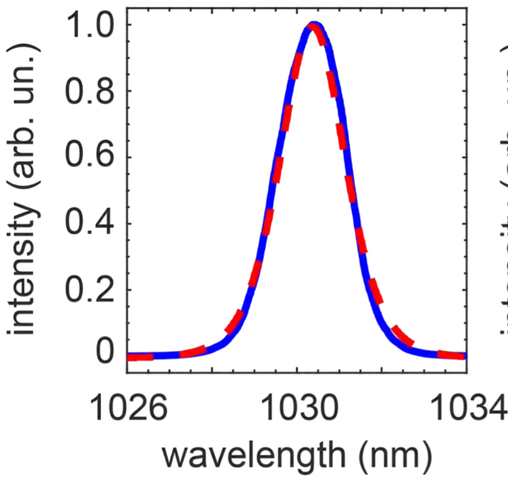
M^2 measurements
$\langle M^2\rangle = 1.01$



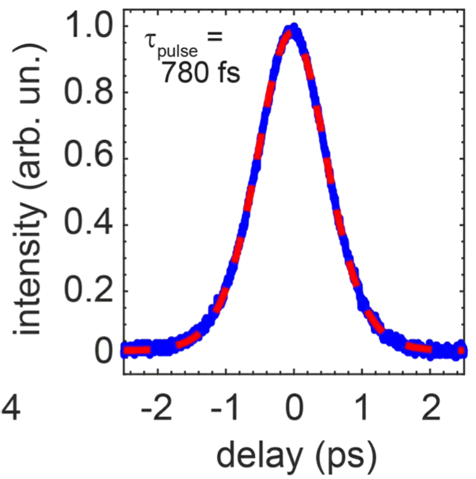
Output power
210 W



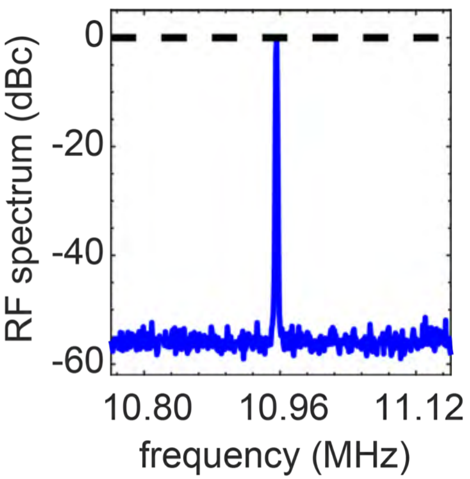
Optical spectrum
FWHM = 1.80 nm



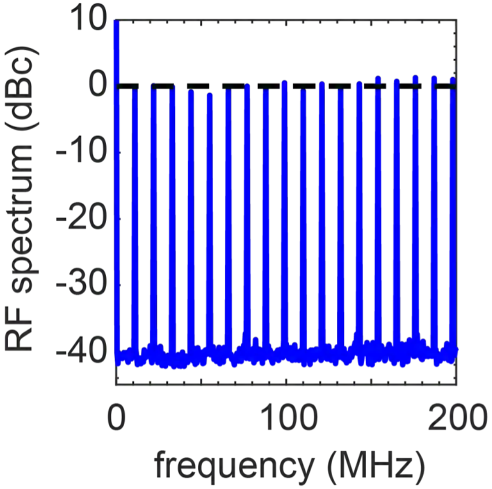
Autocorrelator
τ_{pulse} = 780 fs



RF, RBW 300 Hz
f_{rep} = 10.96 MHz

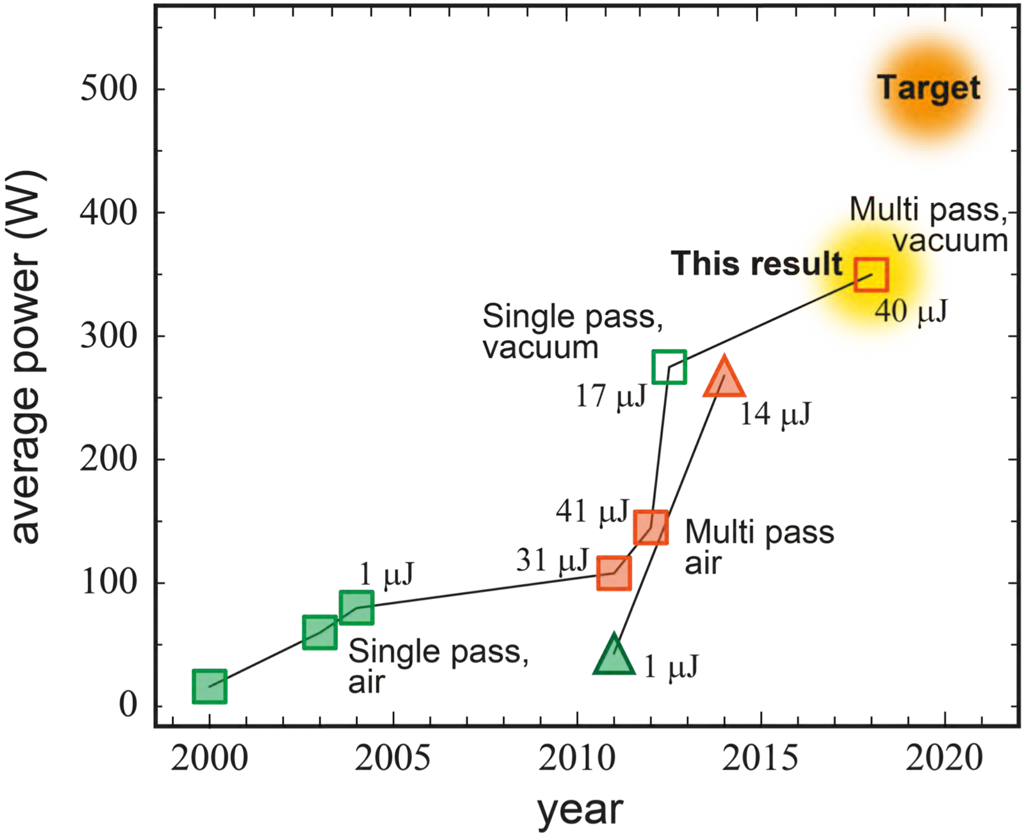


RF, RBW 30 kHz
Harmonics



F. Saltarelli et al., *Optica* **5**, 1603, 2018 (December 2018)

Towards 500-W ultrafast thin-disk oscillators



SESAM modelocked thin-disk lasers:

- 🟩 Single-pass cavity, Air
- ☐ Single-pass cavity, Vacuum
- ☐ Multi-pass cavity, Vacuum

Kerr-lens modelocked thin-disk lasers:

- ▲ Single-pass cavity, Air
- ▲ Multi-pass cavity, Air

C. J. Saraceno, et. al., Opt. Express 20, 23535 (2012)
Dominik Bauer, et. al., Opt. Express 20, 9698 (2012)
Pronin et al, Opt. Lett. 36, 4746 (2011)
J. Brons, et. al., Opt. Lett. 39, 6442 (2014)

F. Saltarelli et al., *Optics Express* **27**, 31465 (2019)

- **350 W –** new record average output power from an ultrafast oscillator
- **Vacuum** operation ➔ mitigates disk's thermal lensing and reduces overall SPM
- **Multi-pass** cavity ➔ minimizes the intracavity power
- Modelocking in the **500-W** average-output-power regime looks feasible