Kurzpuls Laserquellen

Ursula Keller

ETH Zurich, Physics Department, Switzerland

Power Lasers: Clean Tech Day
swisslaser-net (SLN), www.swisslaser.net

ETH Zurich
2. Juli 2009

Applications of ultrafast lasers

- **Good time resolution (short pulses)**
  measurements of fast processes

- **High pulse repetition rates**
  optical communication
  clocking and interconnects

- **High peak intensity at moderate energies**
  nonlinear optics
  precise material processing
  high field physics

- **Broad optical spectrum**
  frequency metrology (frequency comb)
  optical coherence tomography (OCT)

Ultrafast Laser Oscillators in the Thin Disk Geometry

A Power-Scalable Concept for Compact and Cost-Efficient fs and ps Lasers

One of the major technology trends in laser research is the progress of ultrafast laser sources from complicated laboratory systems towards compact and reliable instruments. SESAM-modelocked ultrafast lasers using the thin disk geometry are a promising technology for this task.

THE AUTHORS

URSULA KELLER

Ursula Keller became an ETH professor in 1993, received the Ph. D. from Stanford University in 1989 and the Physics "Diplom" from ETH in 1984. She was a Member of Technical Staff (MTS) at AT&T Bell Laboratories in New Jersey from 1989 to 1993. She has

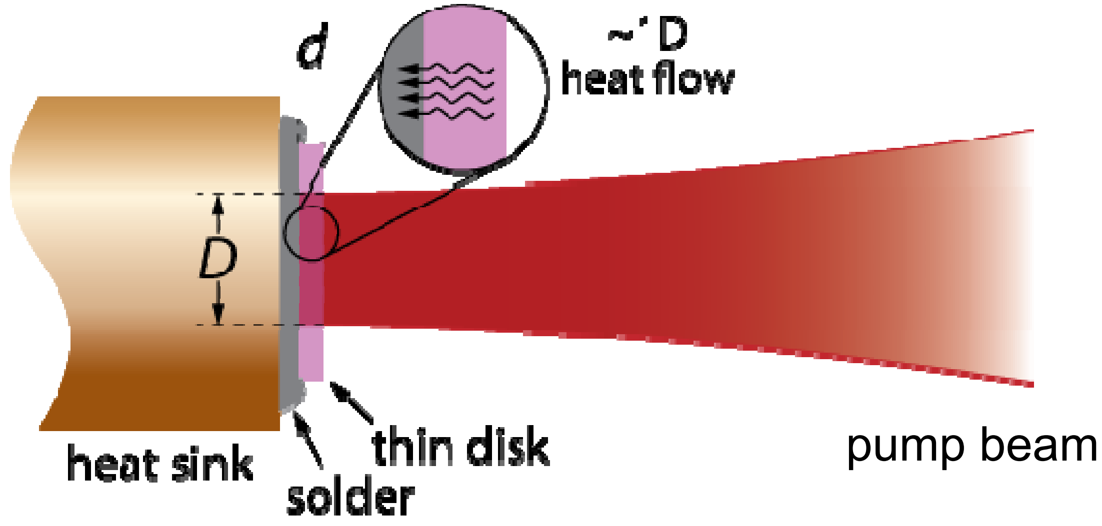
THOMAS SÜDMEYER

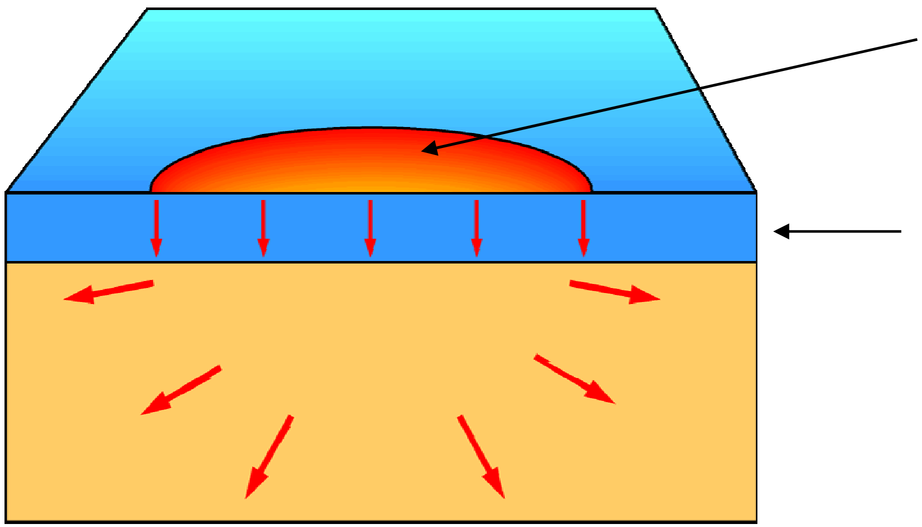
Thomas Südmeyer is head of the ultrafast laser section in Prof. Ursula Keller's group at ETH since 2005. He studied Physics at the University of Hanover and the Ecole Normale Supérieure, Paris, and obtained his Ph. D. from ETH in 2003 for his research on high

Introduction

Since the early 90s, the unique properties of

Thermal management with thin disk geometry





pump beam diameter *2w*

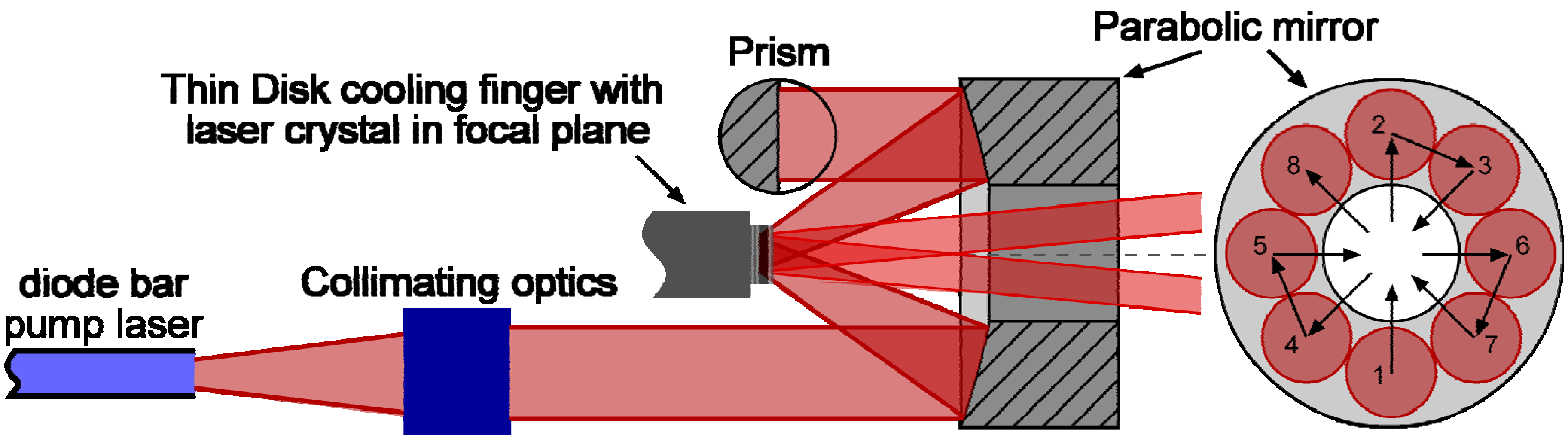
thin disk with 1D heat flow
thickness *d*
d << *w*

Power scaling with mode size

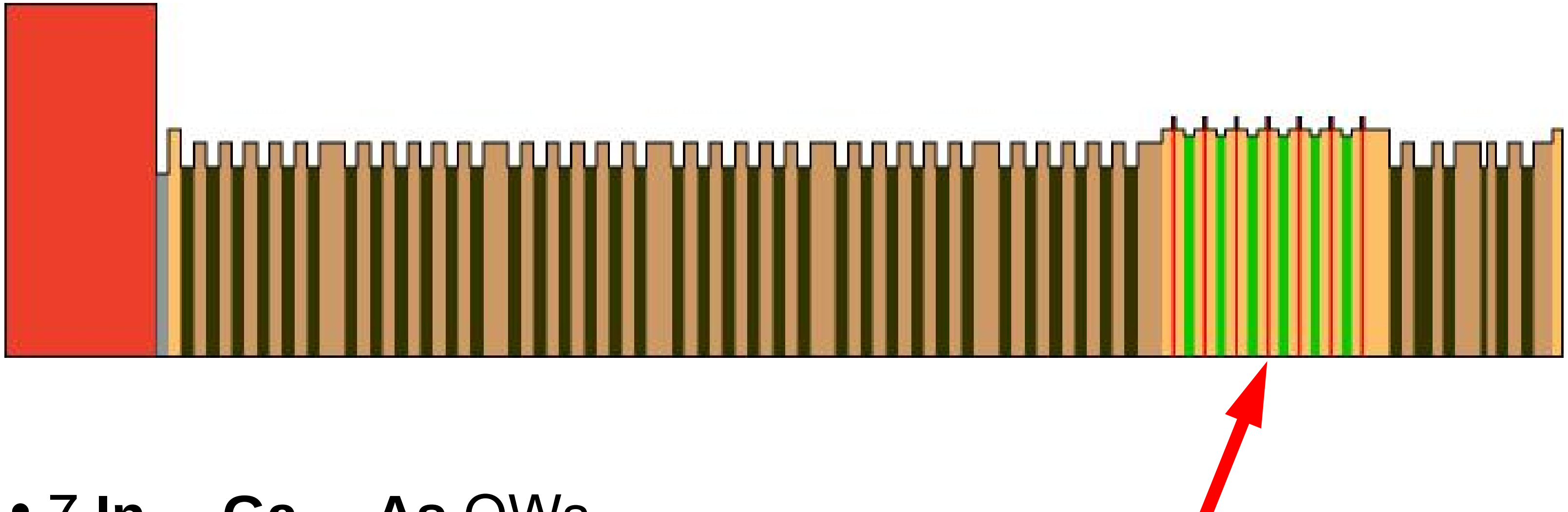
Yb:YAG Thin-Disk Laser Head

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

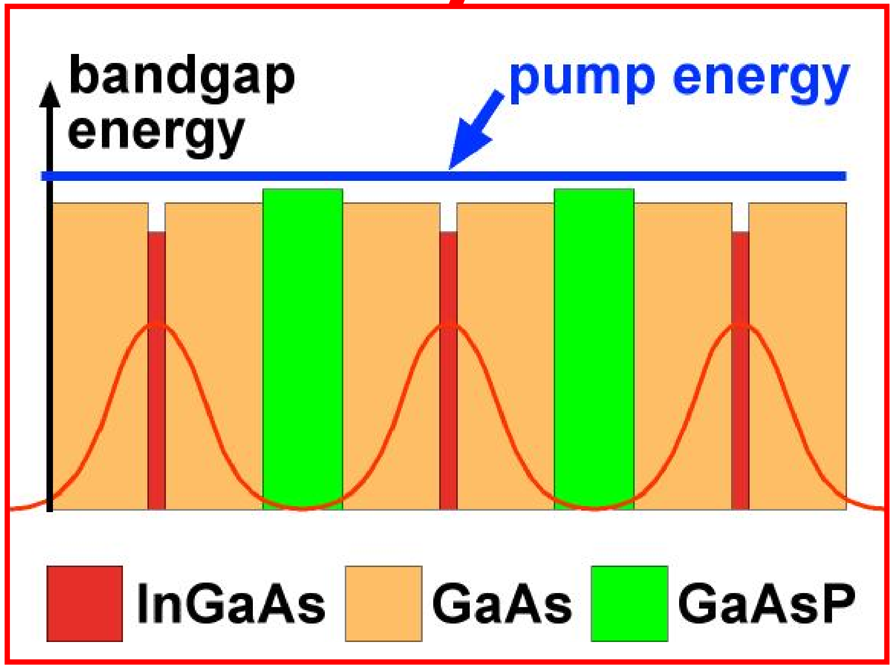
- Thickness of Yb:YAG disk: 100 µm (absorption length a few mm - need multiple passes of pump for efficient absorption)
- Diameter of pump spot: 2.8 mm
- Pump power: up to 370 W @ 940 nm
- 16 passes of pump radiation through disk



VECSEL gain structure: active region



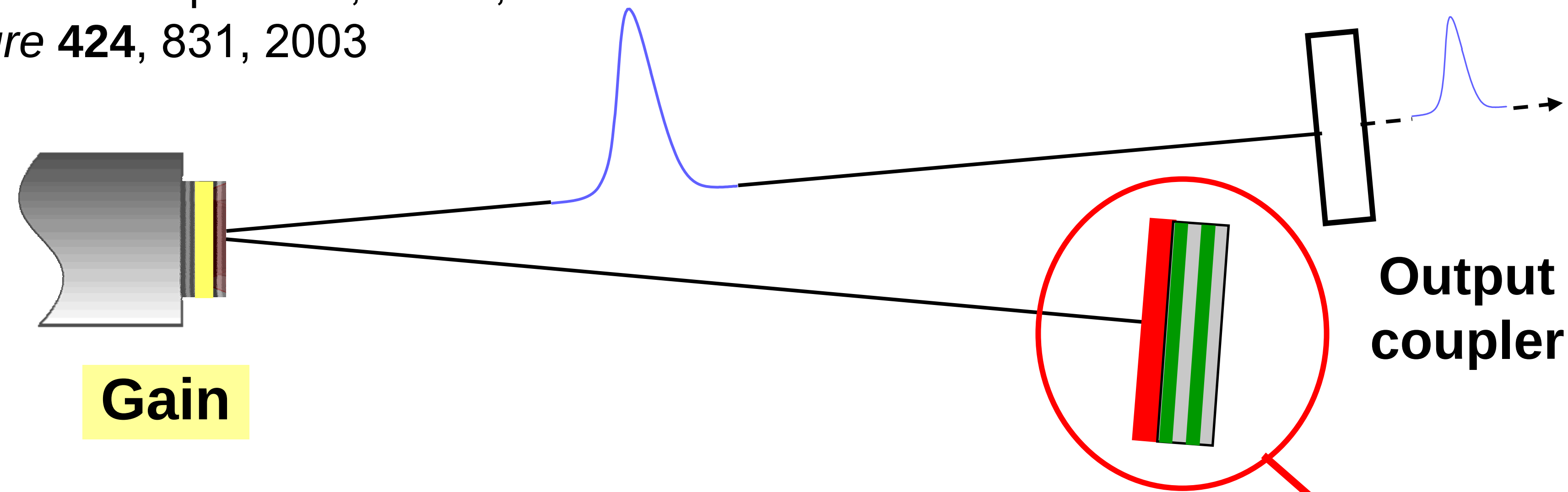
- 7 **$In_{0.13}Ga_{0.87}As$** QWs (8 nm) in anti-nodes of standing-wave pattern, designed for gain at ≈950 nm
- **GaAs** spacer layers
- Strain-compensating **$GaAs_{0.94}P_{0.06}$** layers
- Pump at 808 nm

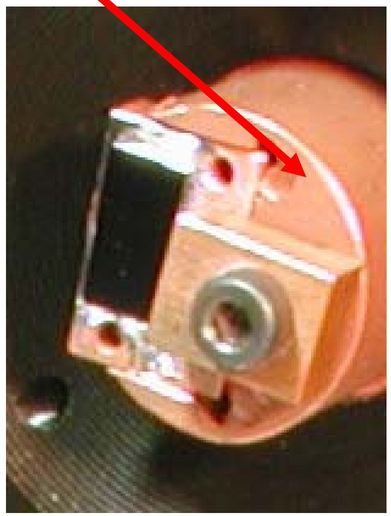


SESAM technology – ultrafast lasers for industrial application

U. Keller et al. *Opt. Lett.* **17**, 505, 1992
IEEE JSTQE **2**, 435, 1996
Progress in Optics **46**, 1-115, 2004
Nature **424**, 831, 2003

SESAM solved Q-switching problem for diode-pumped solid-state lasers



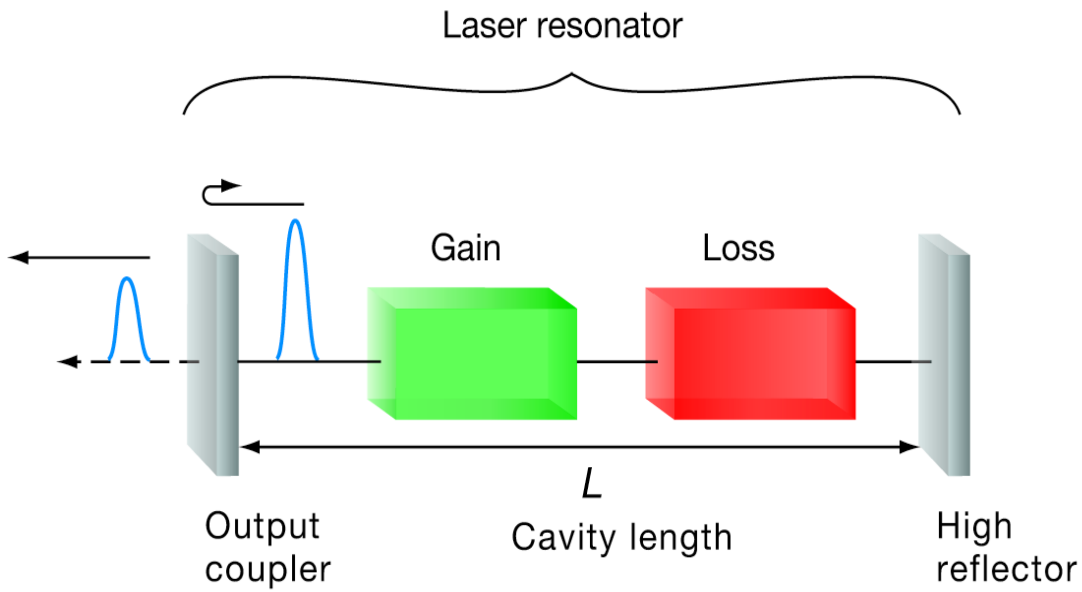


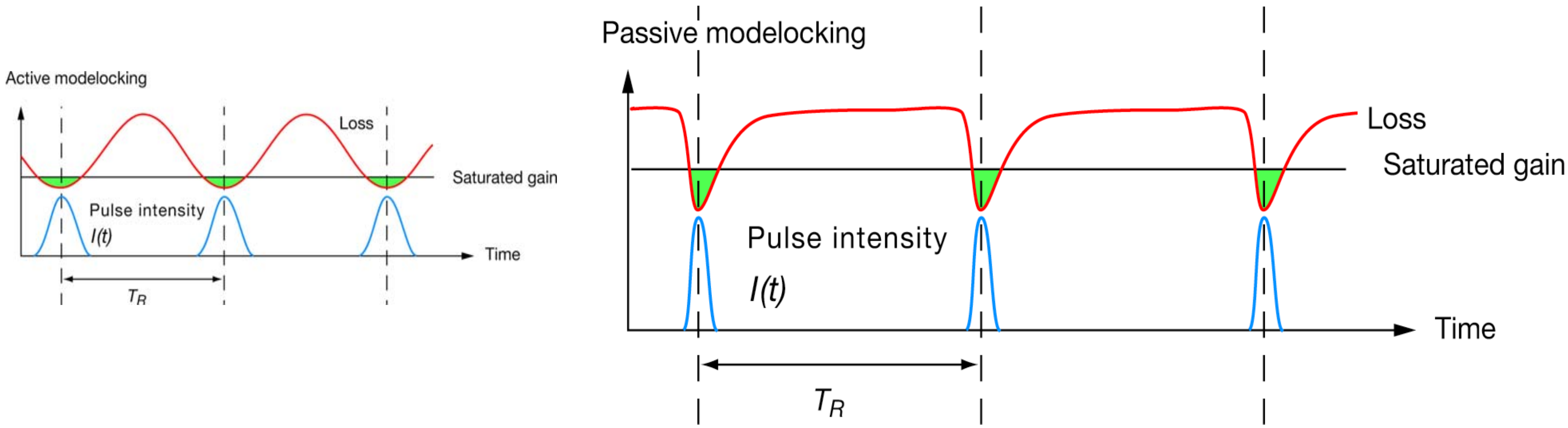
SESAM

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

self-starting, stable, and reliable modelocking of diode-pumped ultrafast solid-state lasers

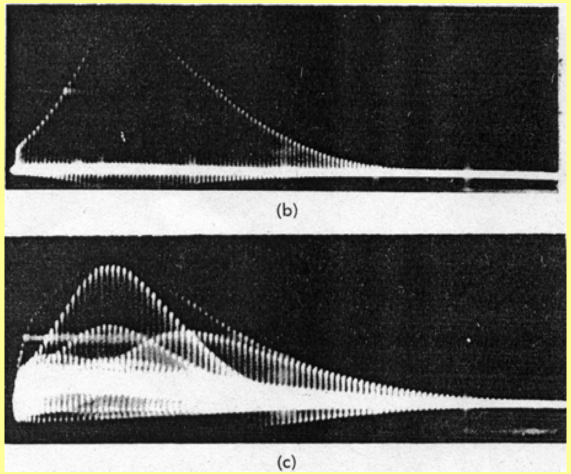
Passive Modelocking





Ultrashort pulse generation with modelocking

A. J. De Maria, D. A. Stetser, H. Heynau
Appl. Phys. Lett. **8**, 174, 1966



200 ns/div

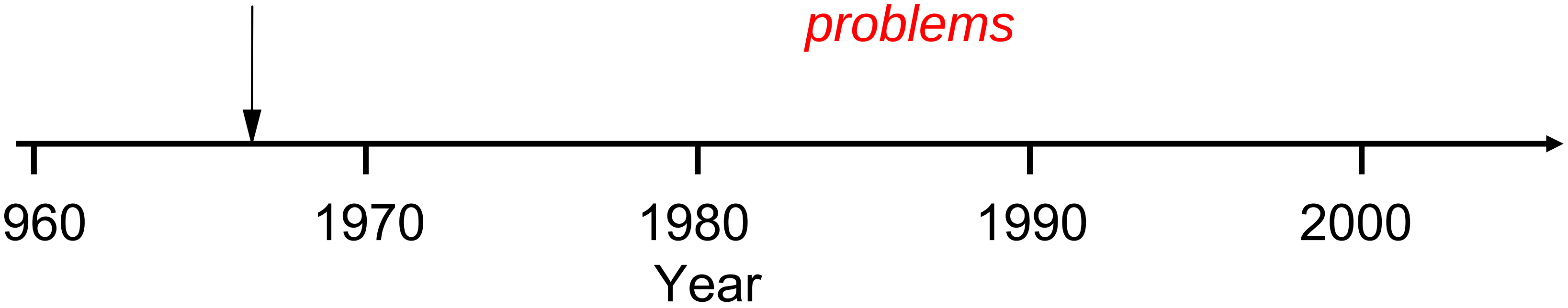
50 ns/div

Nd:glass
first passively modelocked laser
Q-switched modelocked

Q-switching instabilities continued to be a problem for solid-state lasers until 1992 (i.e. for 26 years!)

Theoretical investigations in the 1970th confirmed:
" … such solid-state lasers cannot be passively modelocked …"

Dye lasers do not have Q-switching problems

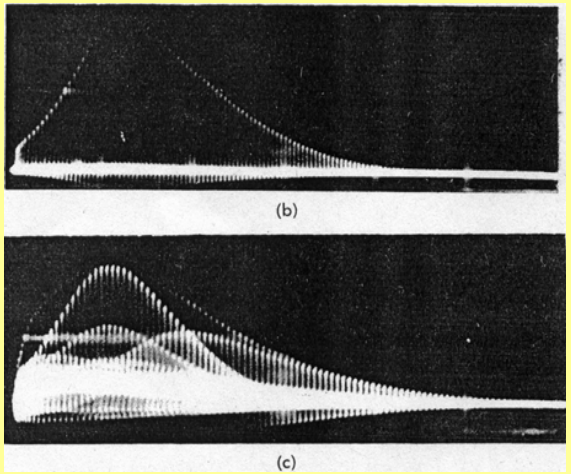


Flashlamp-pumped solid-state lasers

Diode-pumped solid-state lasers
(first demonstration 1963)

Ultrashort pulse generation with modelocking

A. J. De Maria, D. A. Stetser, H. Heynau
Appl. Phys. Lett. **8**, 174, 1966



200 ns/div

50 ns/div

Nd:glass
first passively modelocked laser
Q-switched modelocked

Q-switching instabilities continued to be a problem until 1992

SESAM

First passively modelocked (diode-pumped) solid-state laser without Q-switching

U. Keller et al.
Opt. Lett. **17**, 505, 1992

IEEE JSTQE **2**, 435, 1996
Nature **424**, 831, 2003

KLM

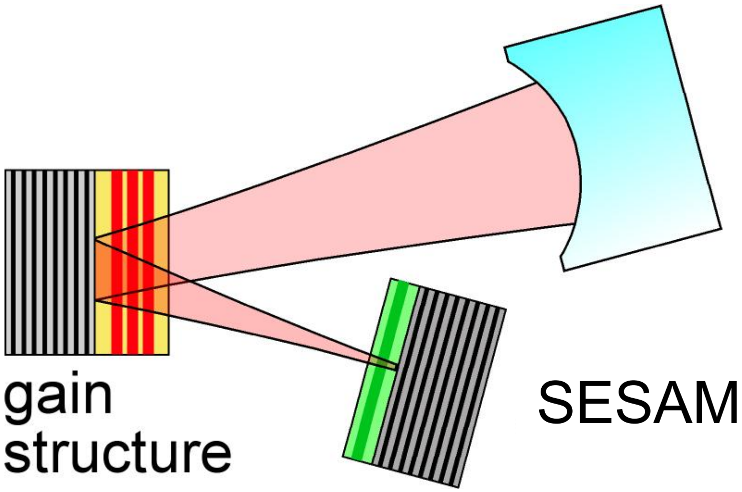
1960 1970 1980 1990 2000
Year

Flashlamp-pumped solid-state lasers

Diode-pumped solid-state lasers
(first demonstration 1963)

Motivation for semiconductor lasers: Wafer scale integration

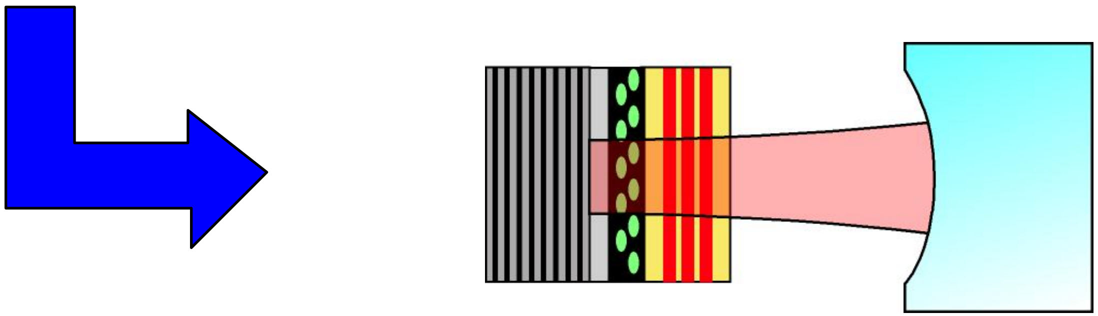
D. Lorenser et al., *Appl. Phys. B* **79**, 927, 2004



Passively modelocked VECSEL

vertical **e**xternal **c**avity **s**urface **e**mitting **l**aser

Review: *Physics Reports* 429, 67-120, 2006

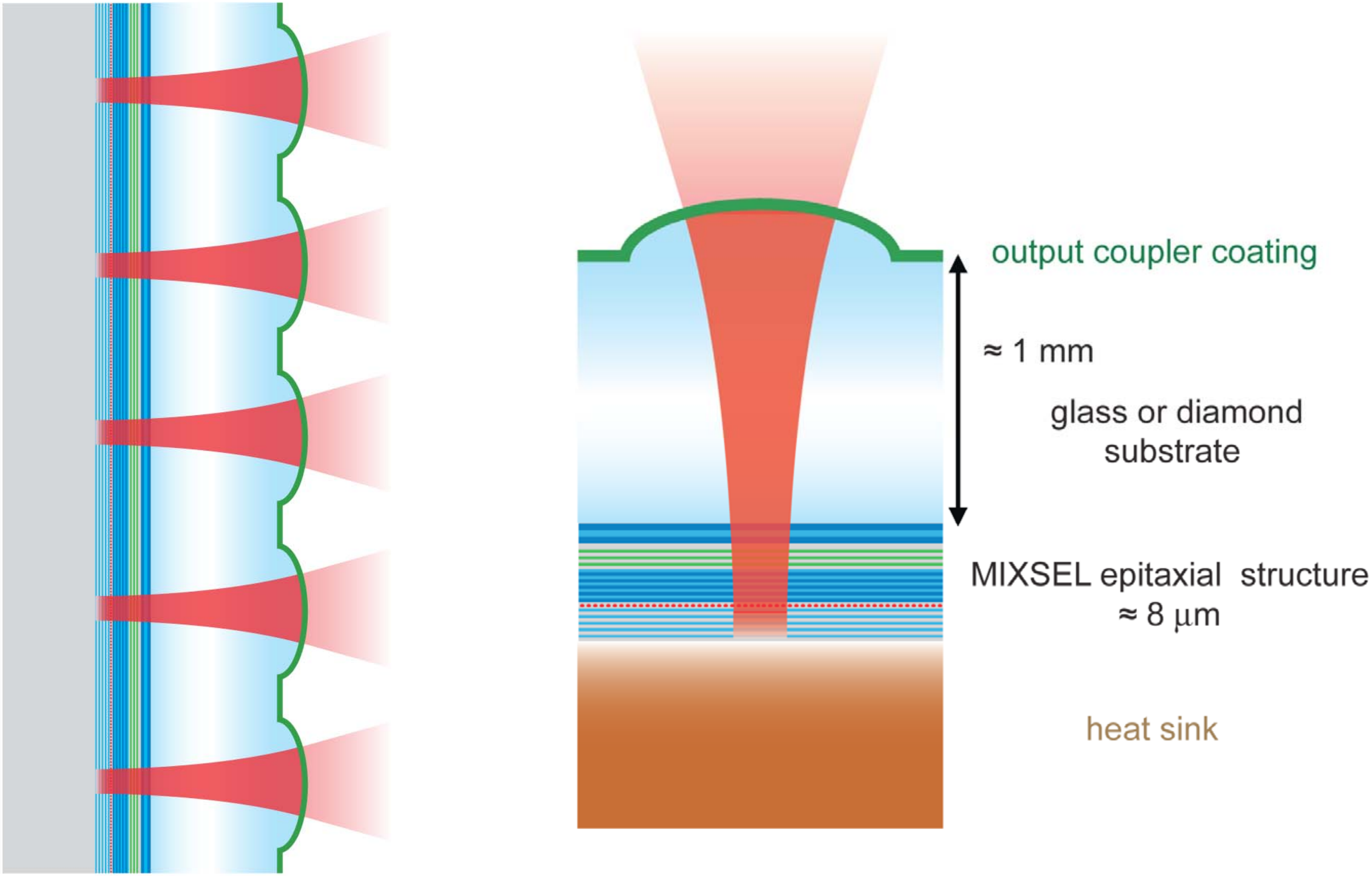


MIXSEL

modelocked **i**ntegrated e**x**ternal-cavity **s**urface **e**mitting **l**aser

D. J. H. C. Maas et al., *Appl. Phys. B* **88**, 493, 2007

MIXSEL wafer scale integration



A. R. Bellancourt et al., "Modelocked integrated external-cavity surface emitting laser"
IET Optoelectronics, vol. 3, Iss. 2, pp. 61-72, 2009 (invited paper)

Optical amplifier

Laser oscillator

pulse energy: typically nanojoule level (≈1 nJ)
pulse repetition rate: typically 100 MHz

Laser amplifier

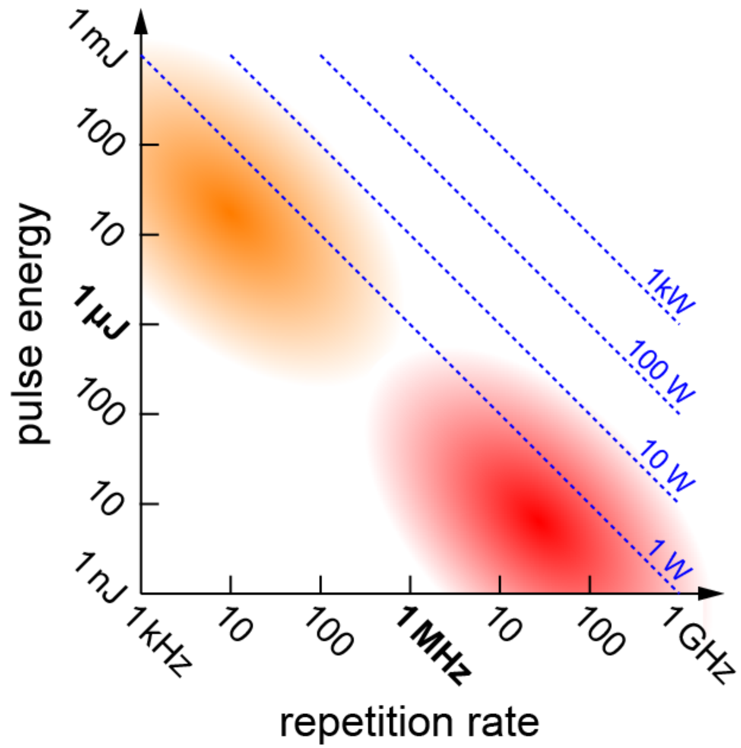
pulse energy: mJ to J
pulse repetition rate: Hz to 1 kHz (10 kHz)

$$P_{av} = E_p f_{rep}$$

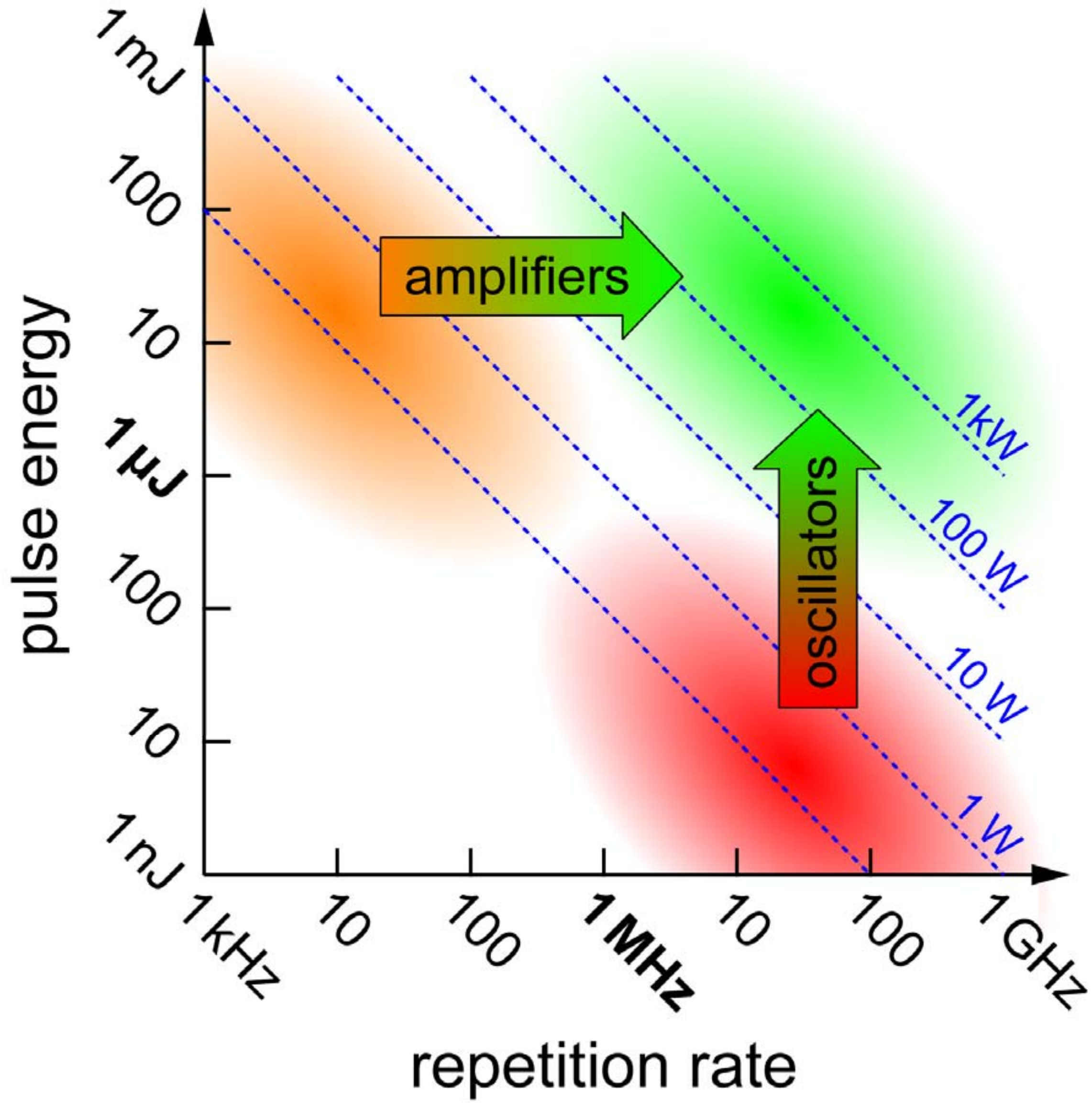
$$E_p = 10 \text{ nJ} \quad \Rightarrow \quad 1 \text{ mJ} \qquad \left(\times 10^5\right)$$

$$f_{rep} = 100 \text{ MHz} \quad \Rightarrow \quad 1 \text{ kHz} \qquad \left(\times 10^{-5}\right)$$

$$P_{av} = 1 \text{ W} \quad \Rightarrow \quad 1 \text{ W}$$

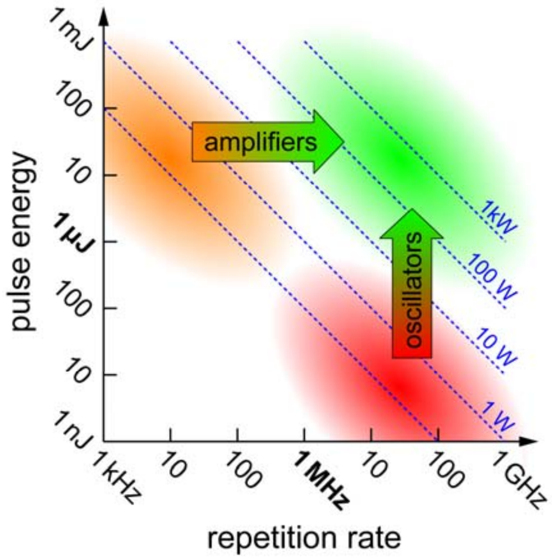


High energy and high pulse repetition rates

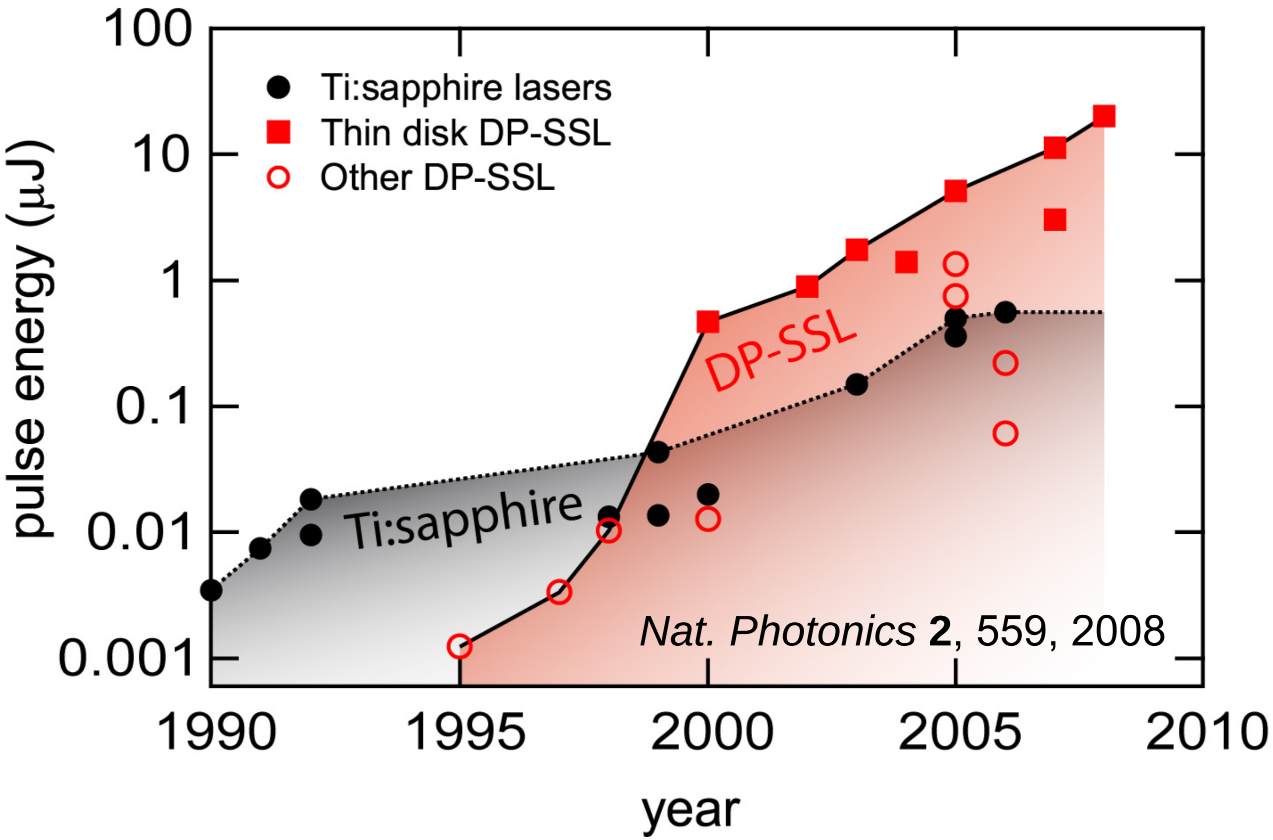


T. Südmeyer et al., *Nature Photonics* 2, 599, 2008

High average power lasers



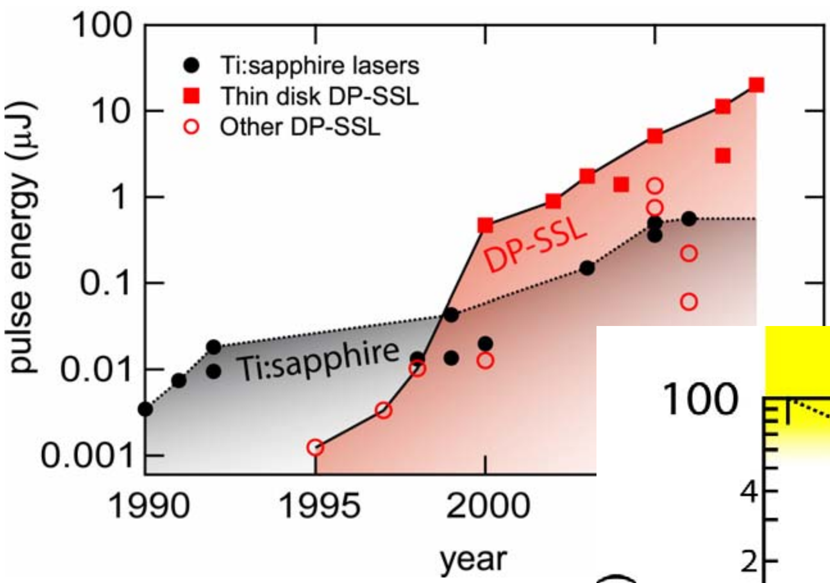
DP-SSL: diode-pumped solid-state lasers



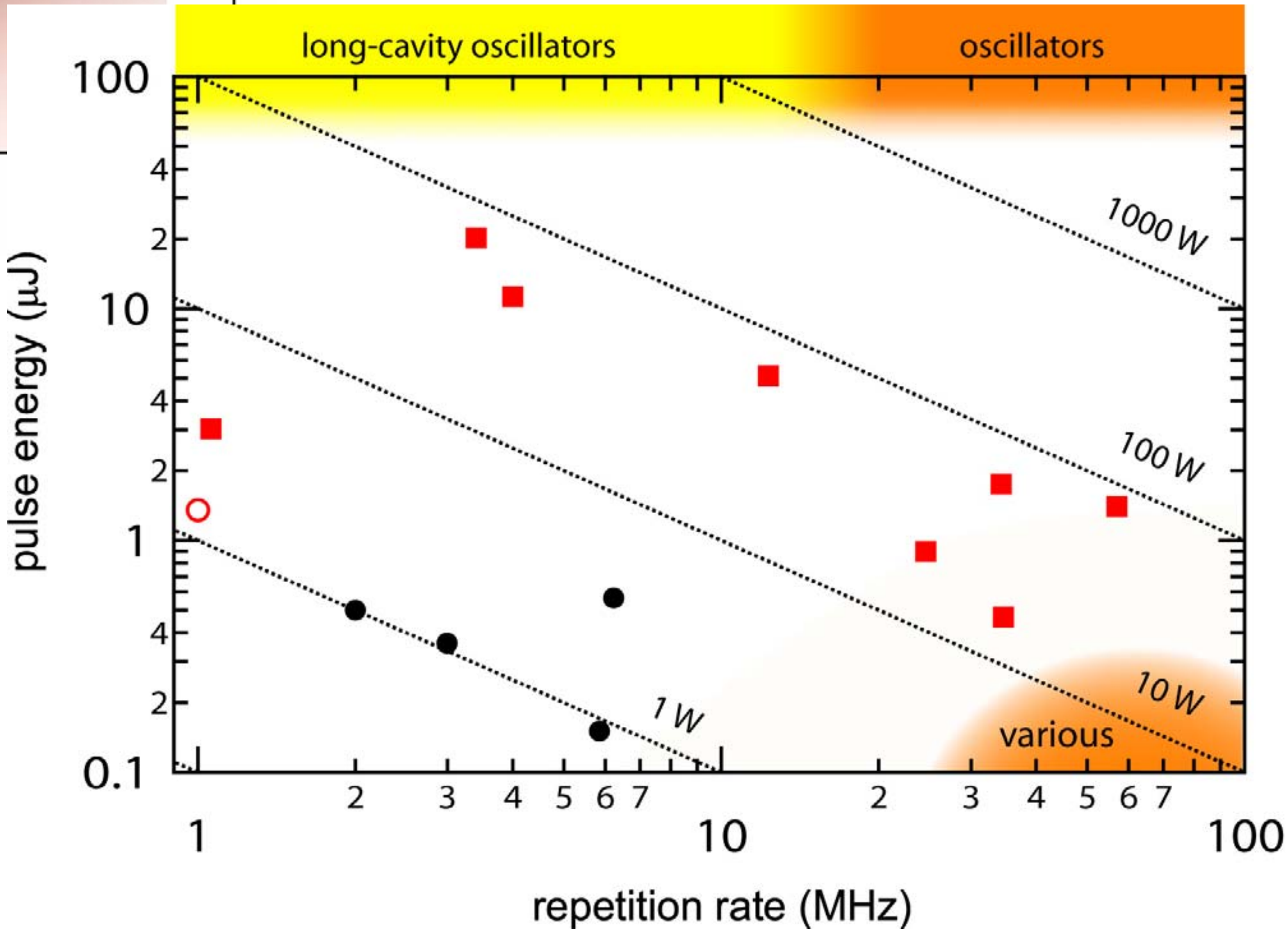
First time >10 µJ pulse energy from a SESAM modelocked Yb:YAG thin disk laser: *Opt. Express* **16**, 6397, 2008 and *CLEO Europe* June 2007

26 µJ with a multipass gain cavity and larger output coupling of 70% (Trumpf/Konstanz) *Opt. Express* **16**, 20530, 2008

High average power lasers



QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.



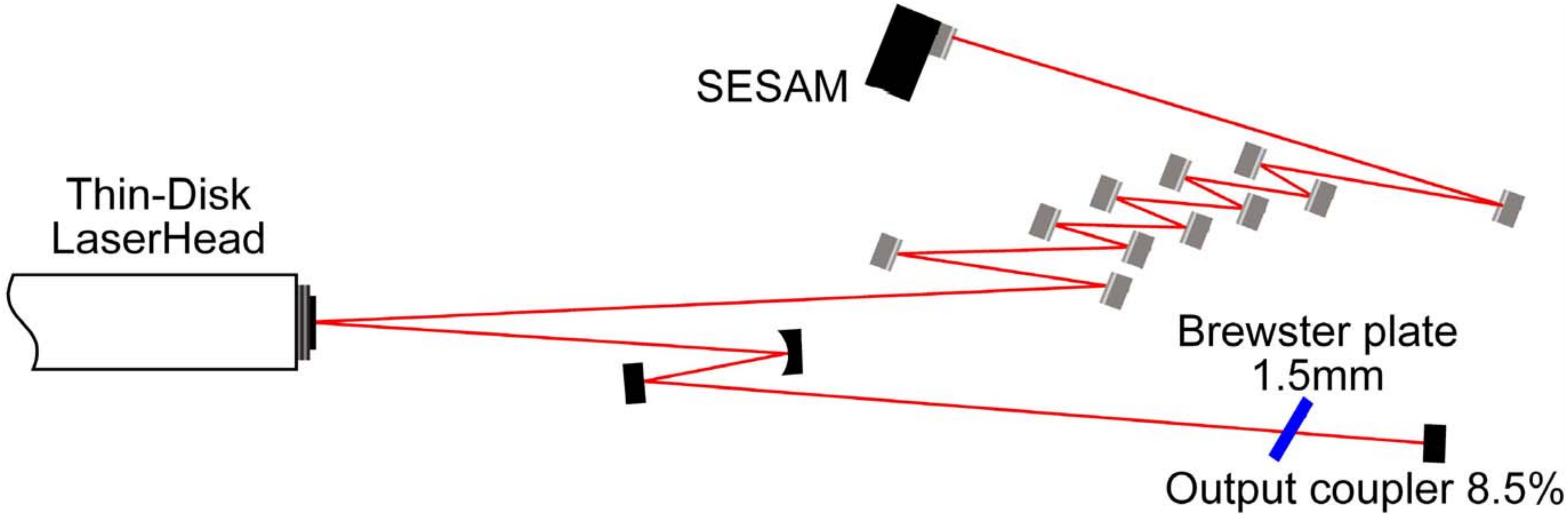
Progress in high power modelocked lasers

First cw modelocked thin-disk laser (Yb:YAG):
16 W, 730 fs, 0.5 MW
J. Aus der Au et al., *Opt. Lett.* **25**, 859 (2000)

Power scaling

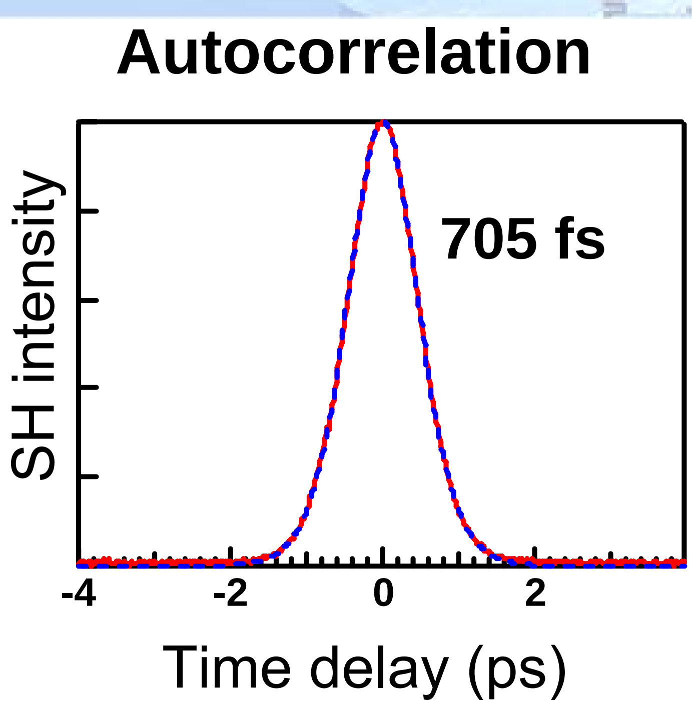
80 W, 705 fs, 1.75 MW
E. Innerhofer et al.,
Laser Phys. Lett. ***1**, 1 2004*

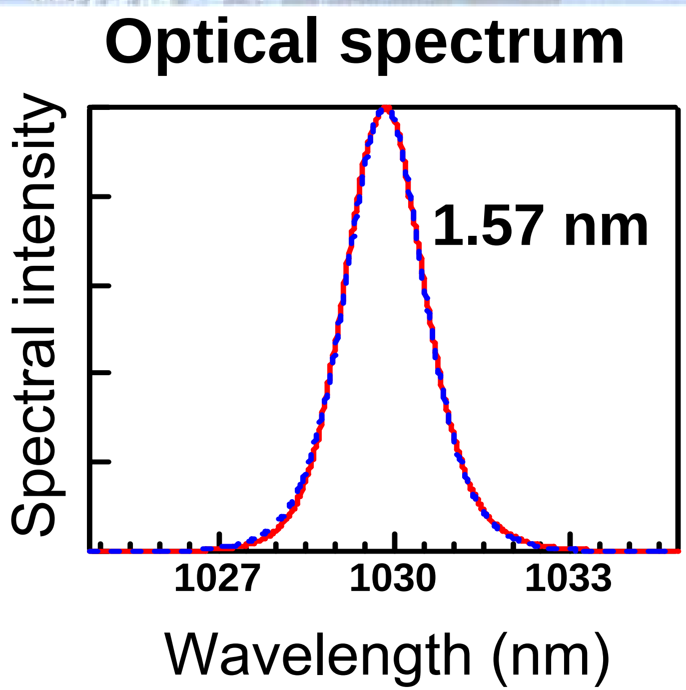
Thin disk laser: 57-MHz setup



- Thin disk **as folding mirror**
- SESAM and output coupler **as end mirror**
- **Brewster plate for** linear polarization
- **Negative group delay dispersion from** GTI-type dispersive mirrors

80 W from Yb:YAG Laser





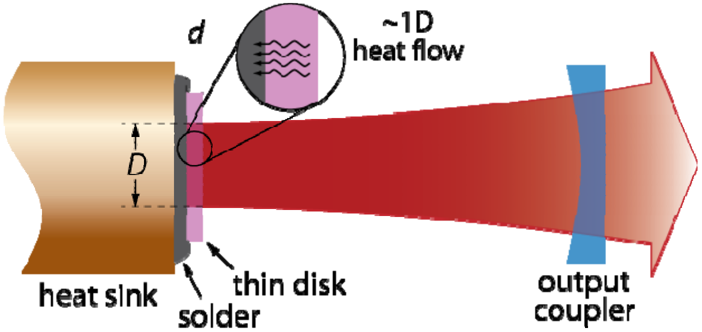
P_{avg}	= 80 W
τ_p	= 705 fs
f_{rep}	= 57 MHz

E_p	= 1.4 µJ
P_{peak}	= 1.75 MW
$\Delta\nu\,\tau_p$	= 0.32

First modelocked (ML) thin-disk, 16 W: *Optics Lett.* **25**, 859, 2000
60 W ML Thin Disk: E. Innerhofer et al., *Optics Lett.* **28**, 367, 2003
80 W ML Thin Disk: F. Brunner et al., *Optics Lett.* **29**, 1921, 2004

The passively mode-locked thin disk laser

Thin disk laser



+

SESAM

semiconductor saturable absorber mirror

A power scalable concept:

Scale output power by equally increasing the pump power and mode sizes on disk and SESAM.

→ no increase of the temperature, no increase of the tendency for QML

16 W, 35 MHz, 730 fs, 0.47 µJ, 0.6 MW
J. Aus der Au, et al., *Opt. Lett.* **25**, 859 (2000)

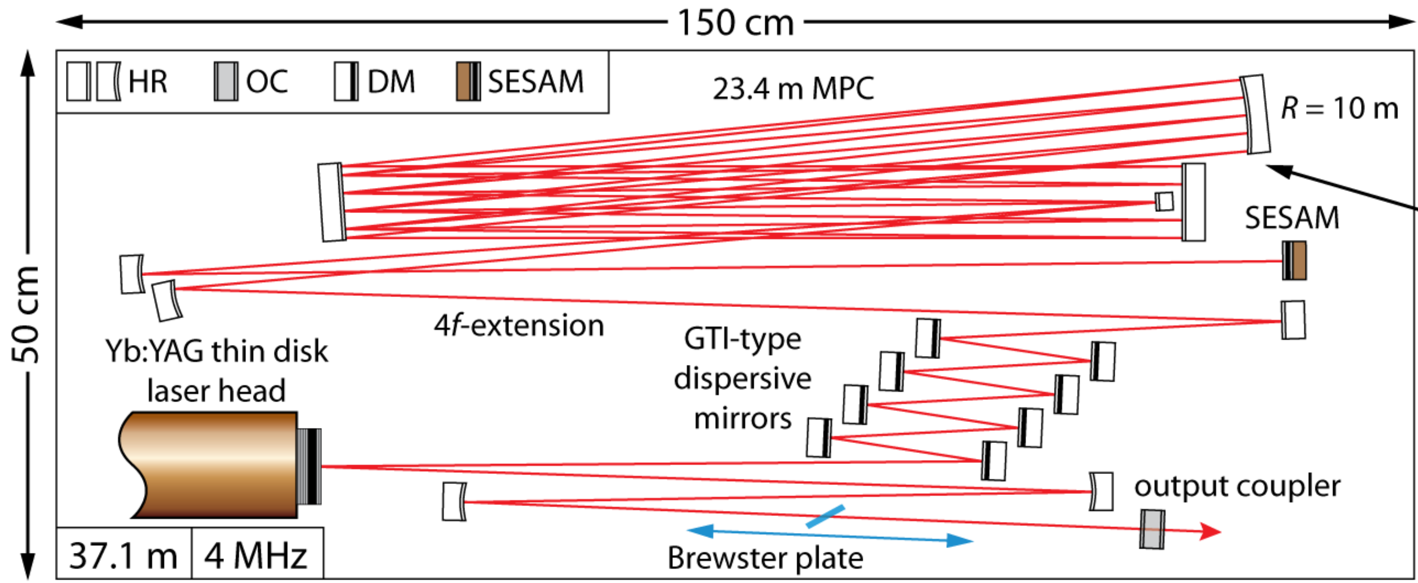
- 1st ML thin disk laser (Yb:YAG)
- pump diameter 1.2 mm

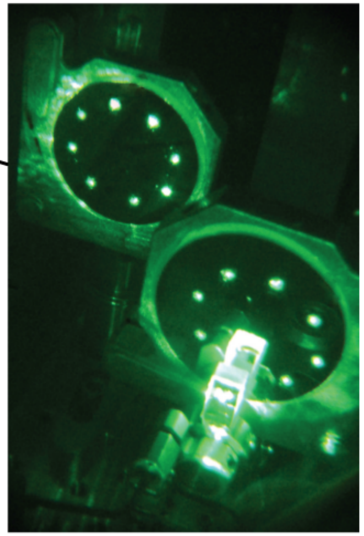
⬇ **power scaling** ⬇

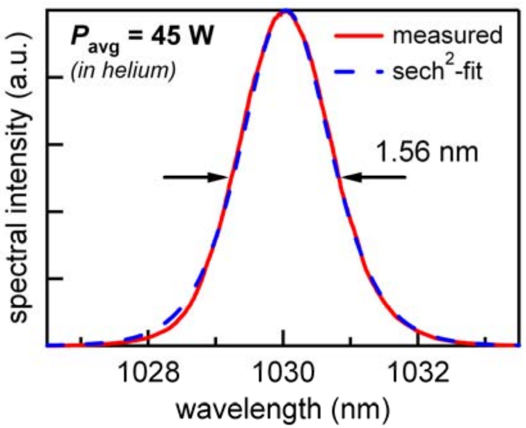
80 W, 57 MHz, 705 fs, 1.4 µJ, 1.75 MW
F. Brunner, et al., *Opt. Lett.* **29**, 1921 (2004)

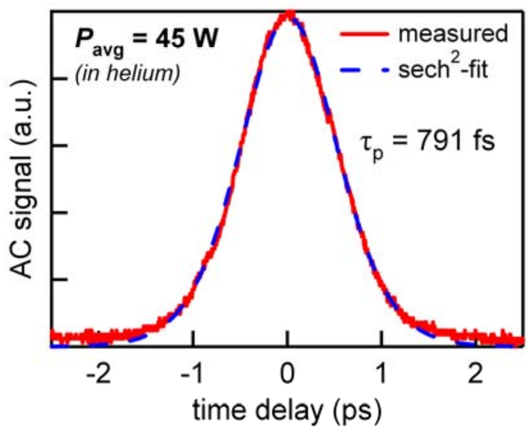
- pump diameter 2.8 mm

11 µJ SESAM modelocked Yb:YAG thin disk laser









Opt. Express **16**, 6397, 2008

P_{avg} = 45 W
f_{rep} = 4 MHz

E_p = 11.3 µJ

λ = 1030 nm
$\Delta\lambda$ = 1.56 nm

M^2 = 1.1
P_{peak} = 12.5 MW

τ_p = **791 fs**
$\tau_p \cdot \Delta\nu$ = 0.35 (ideal 0.315)

Progress in high power modelocked lasers

First cw modelocked thin-disk laser (Yb:YAG):
16 W, 730 fs, 0.5 MW
J. Aus der Au et al., *Opt. Lett.* **25**, 859 (2000)

Power scaling

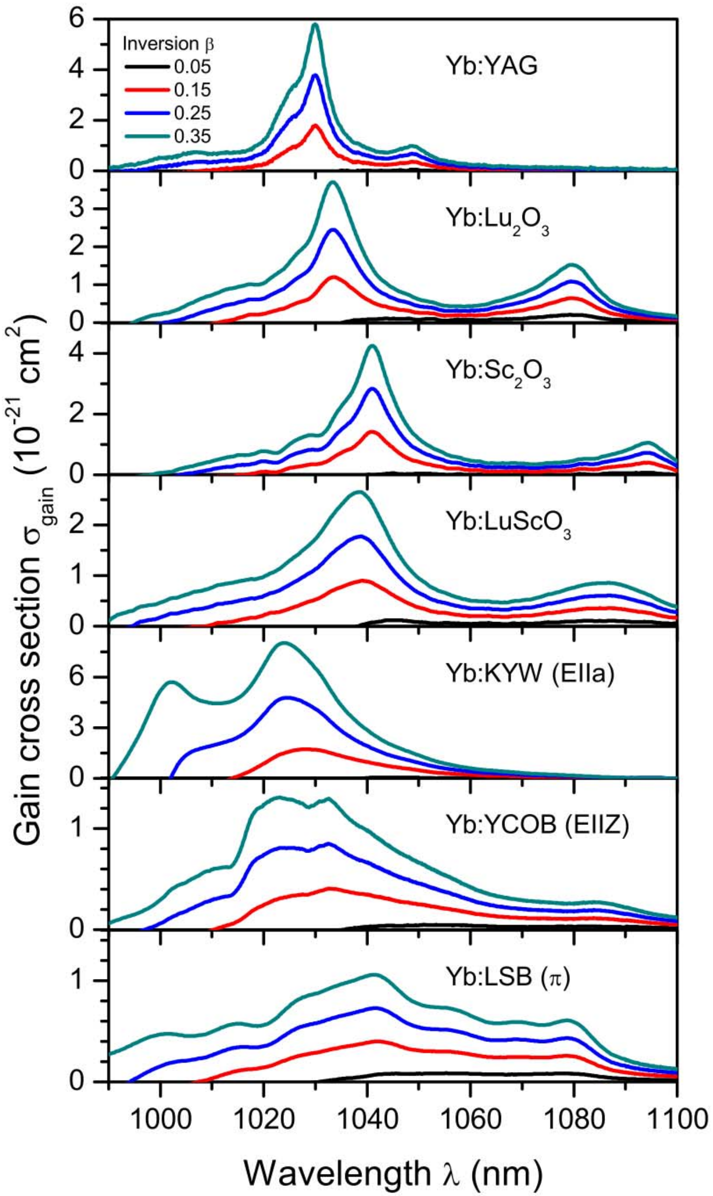
80 W, 705 fs, 1.75 MW
E. Innerhofer et al.,
Laser Phys. Lett. ***1**, 1 2004*

Pulse duration reduced with different laser materials:

Yb:KYW
22 W, 240 fs, 3.3 MW
F. Brunner et al.,
Opt. Lett. **27**, 1162 (2002)

Yb:Lu_2O_3
20.5 W, 370 fs, 0.75 MW
S. V. Marchese et al.,
Opt. Exp. **15**, 16966 (2007)

Novel Yb-doped laser materials



$$\sigma_{gain} = \beta\sigma_{em} - (1-\beta)\sigma_{abs}$$

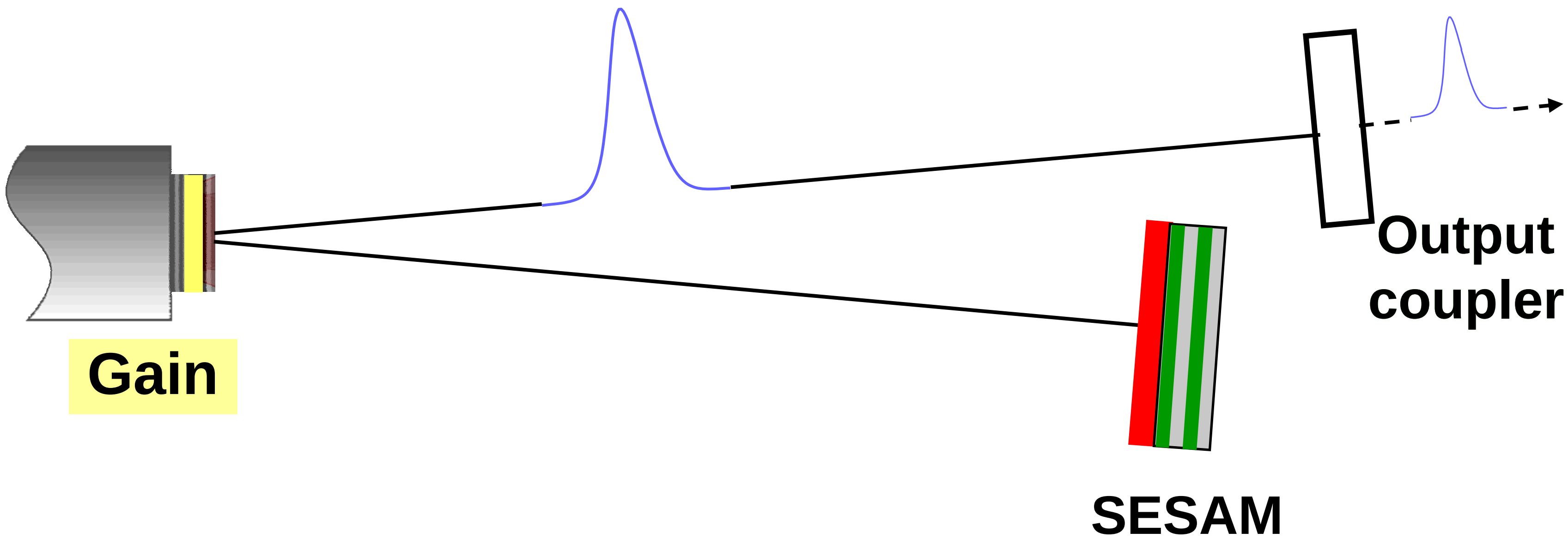
Yb:garnets: Yb:YAG, Yb:LuAG …
relatively small gain bandwidth

Yb:sesquioxides: Yb:RE$_2$O$_3$
RE = Y, Sc or Lu
difficult crystal growth resolved
Yb:Lu$_2$O$_3$ 63 W, 535 fs (CLEO 09)
Yb:Sc$_2$O$_3$
Yb:LuScO$_3$ 7.2 W, 227 fs (CLEO 09)

Yb:tungstates: ARE(WO$_4$)$_2$
A = alkali ion, e.g. K, Na
RE = Gd, Lu and Y
"Yb:KYW, Yb:NYW, Yb:NGW"
strong anisotropy of thermo-mechanical prop.

Yb:borates (disordered crystal structure)
Yb:YCOB, Yb:LSB

High pulse repetition rate



Short cavity length = high pulse repetition rate

Pulse repetition rate is given by the cavity round trip time.

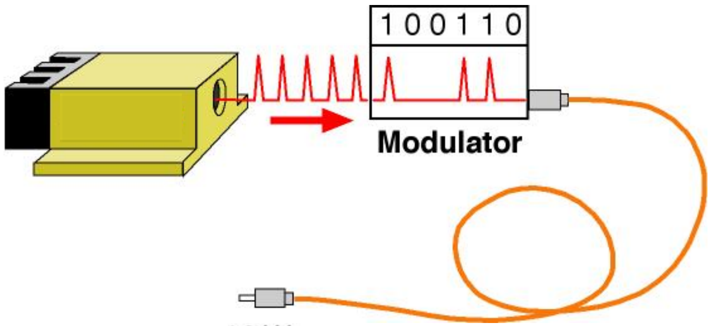
1 GHz: cavity round trip time 1 ns and a cavity length **15 cm**.

1 THz: cavity round trip time 1 ps and a cavity length **150 µm**.

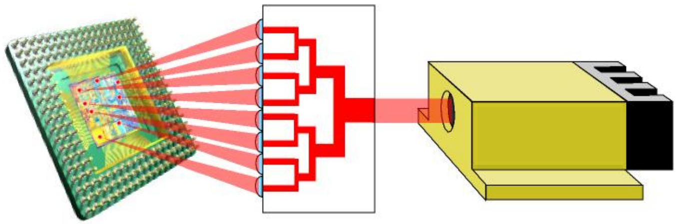
No high speed electronics needed.

Compact ultrafast lasers for "real world application"

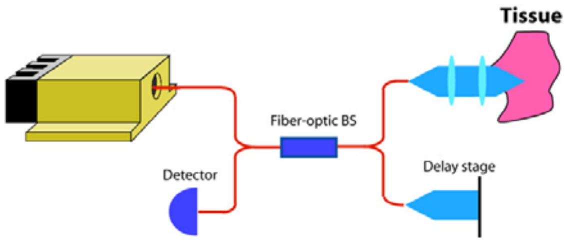
Telecom

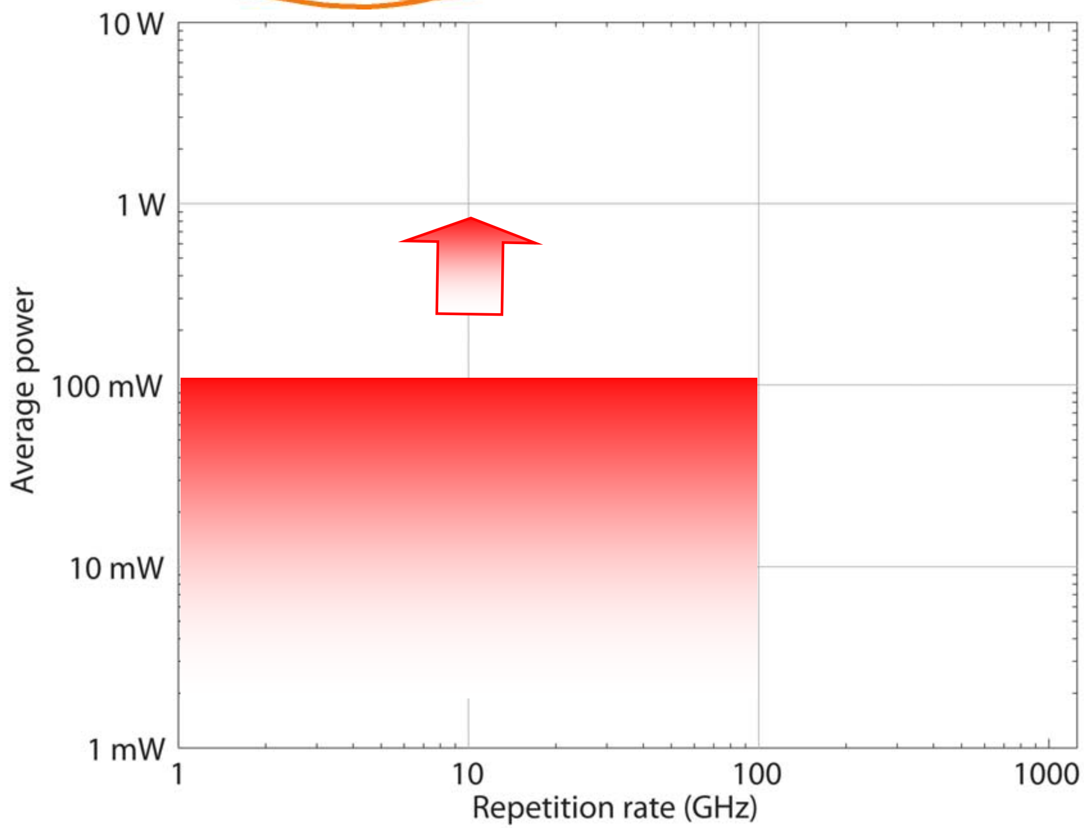


Optical Clocking

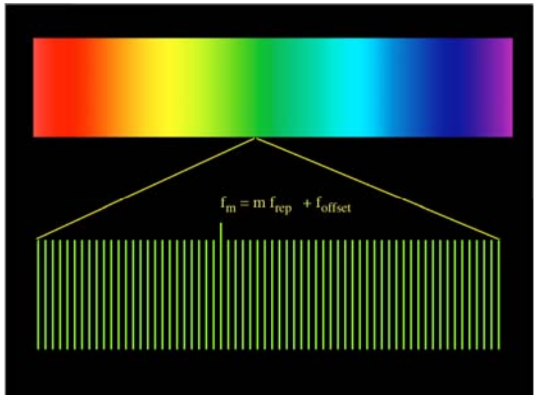


Biomedical applications



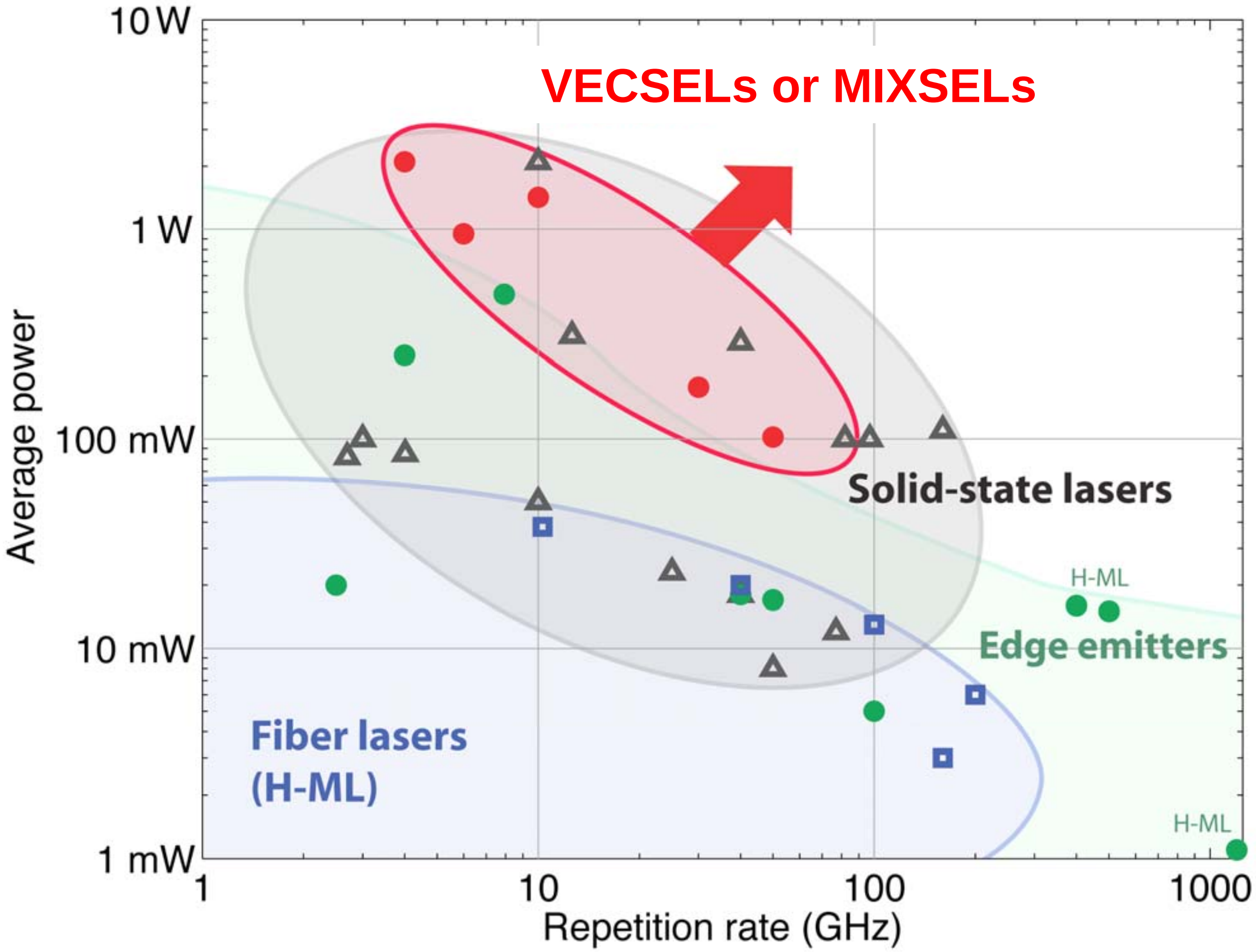


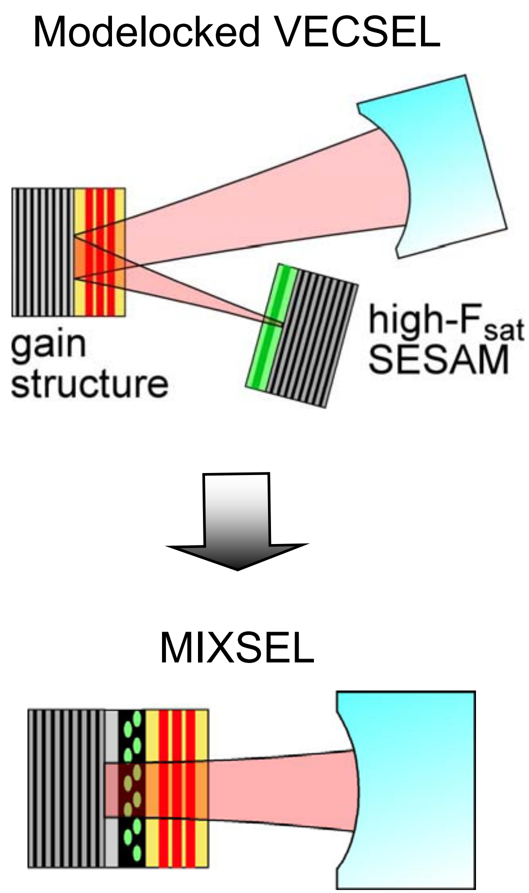
Frequency comb



Comparison of Ultrafast GHz Lasers

Vertical external cavity surface emitting laser (VECSEL) or semiconductor thin disk laser



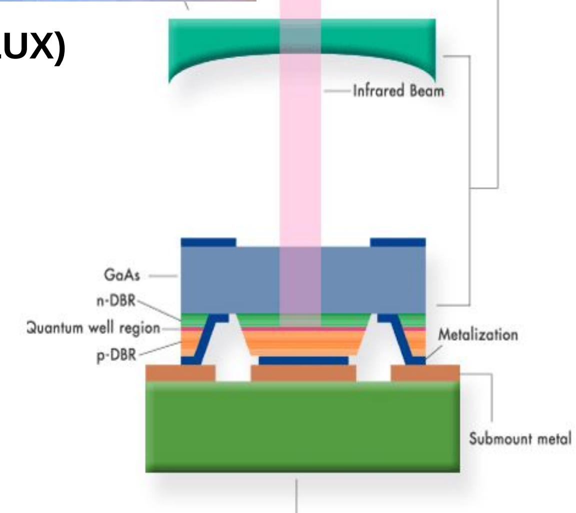


Review article: U. Keller and A. C. Tropper, Physics Reports, vol. 429, Nr. 2, pp. 67-120, 2006

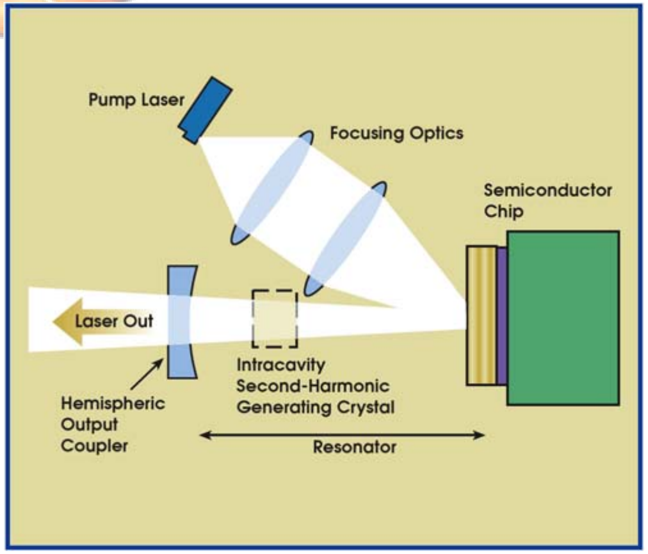
Electrical or optical pumping ?

Medium to high powers with good beam quality

(NOVALUX)



(COHERENT)



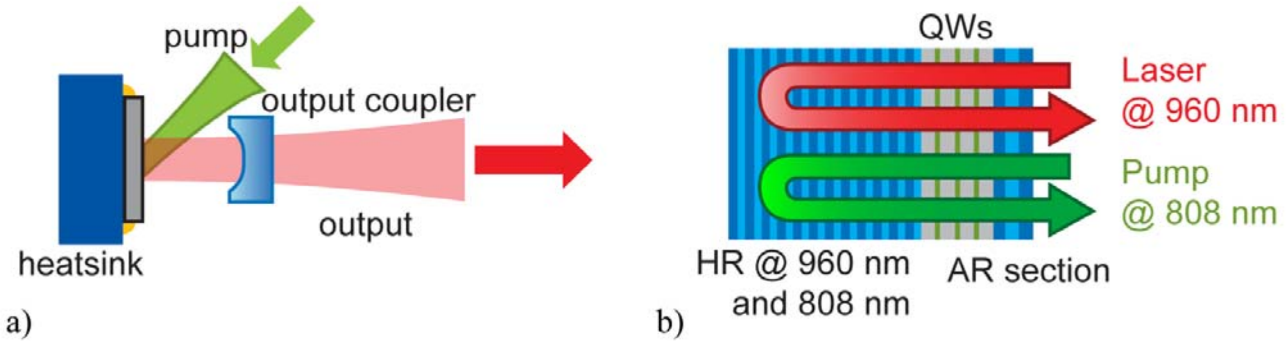
Electrically pumped

Medium power:
up to 500 mW (TEM_{00})

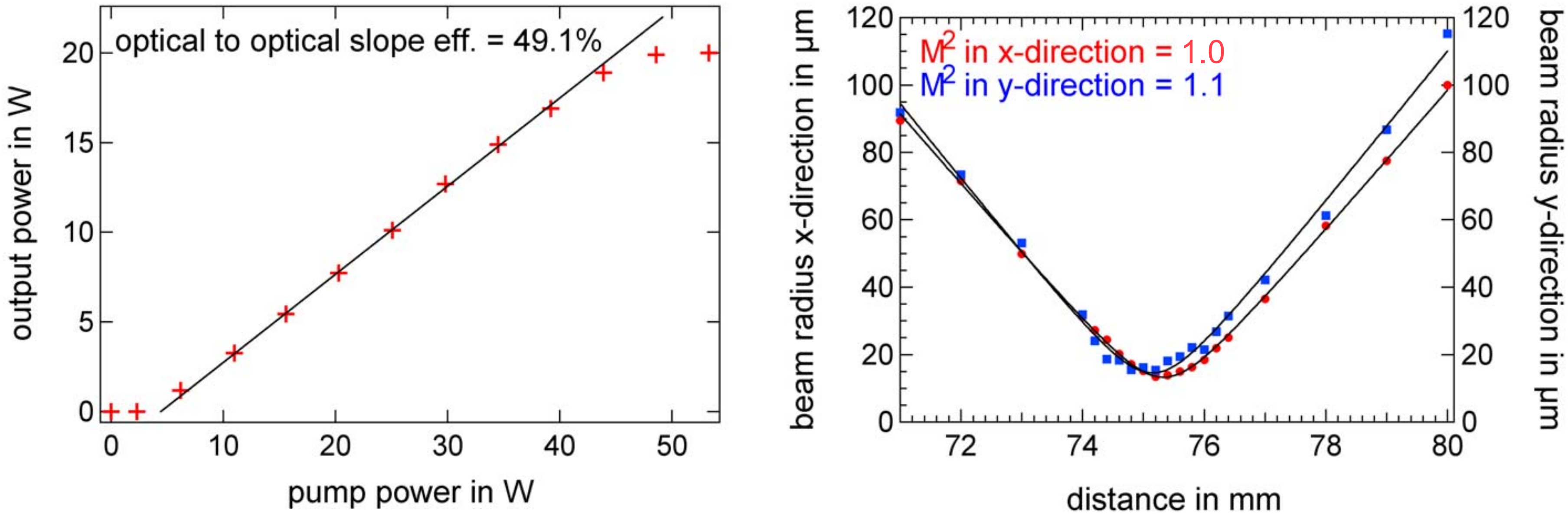
Optically pumped

High power:
up to 30 W (M^2 = 3)

20 W cw OP-VECSEL ($M^2 \approx 1$)

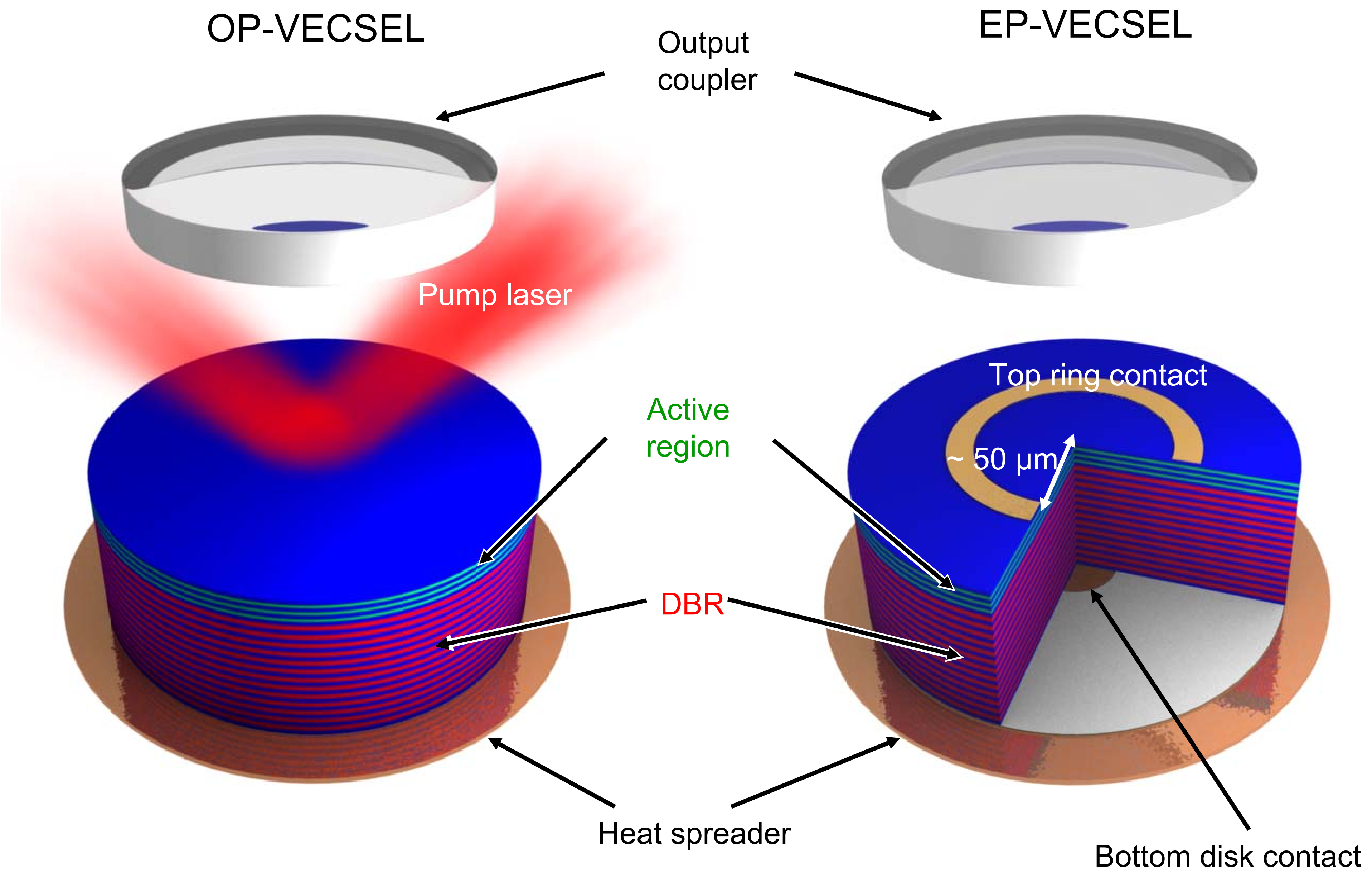


20.2 W cw at 50 W pump power

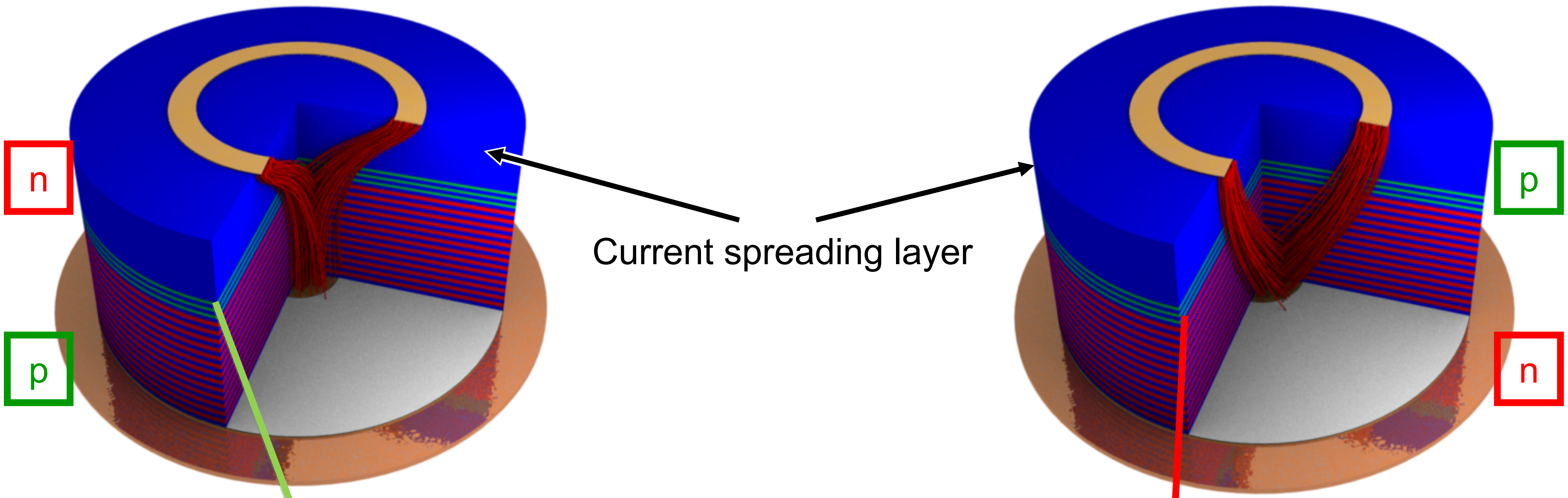


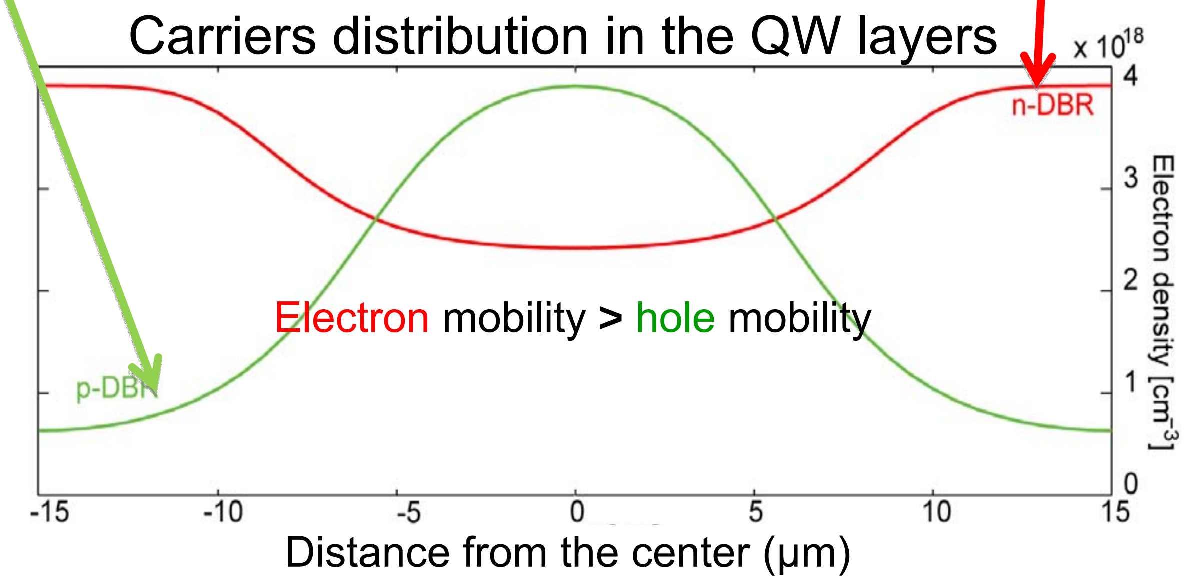
B. Rudin, A. Rutz, M. Hoffmann, D. J. H. C. Maas, A.-R. Bellancourt, E. Gini, T. Südmeyer, U. Keller
Optics Lett. **33**, 2719, 2008

Electrical vs. optical pumping



Simulations for EP-VECSEL Design



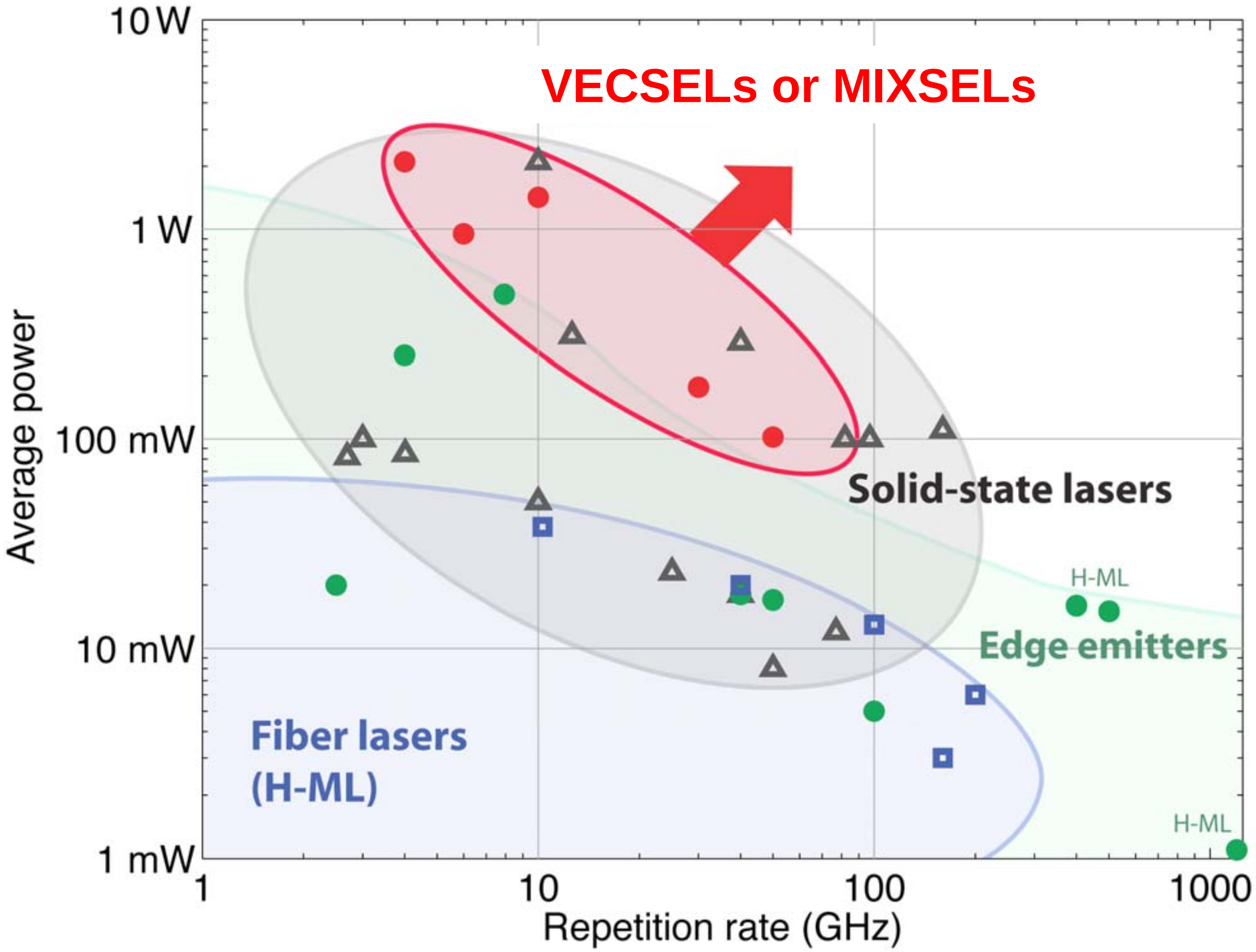


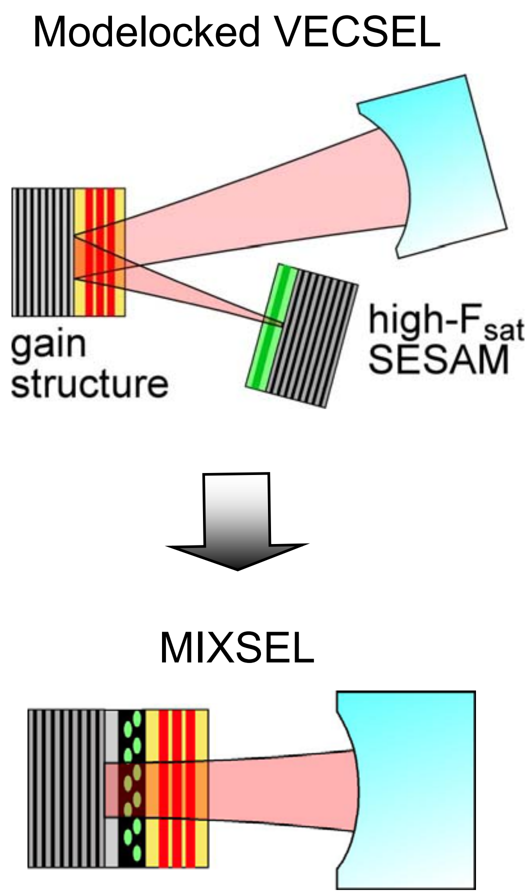
p-DBR design favorable for large output beam with fundamental transverse mode

P. Kreuter et al., *Appl. Phys. B*, **91**, 257, 2008

Comparison of Ultrafast GHz Lasers

Vertical external cavity surface emitting laser (VECSEL) or semiconductor thin disk laser





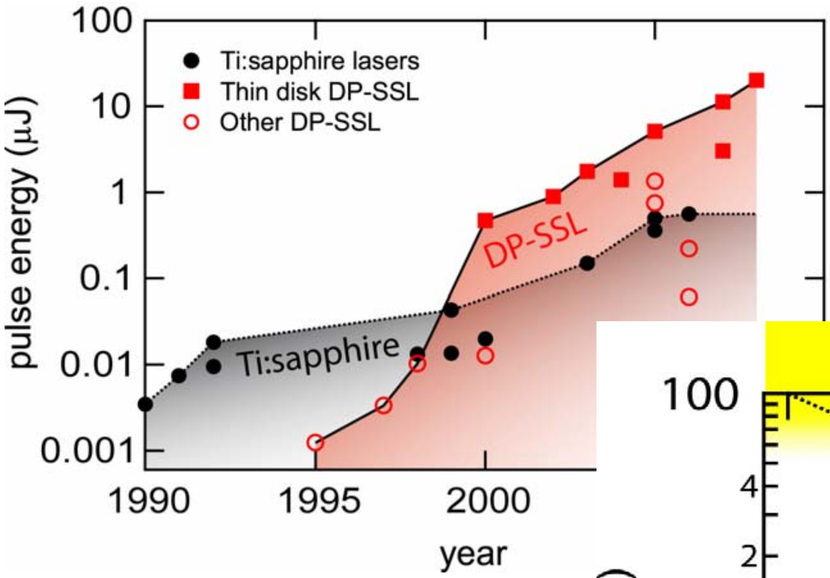
Review article: U. Keller and A. C. Tropper, Physics Reports, vol. 429, Nr. 2, pp. 67-120, 2006 fast-dot.eu **Fast Dot Project** June 2008, 4 years

Project funding: 10.1 Mio Euro
Consortium: 10 Uni, 7 Industries

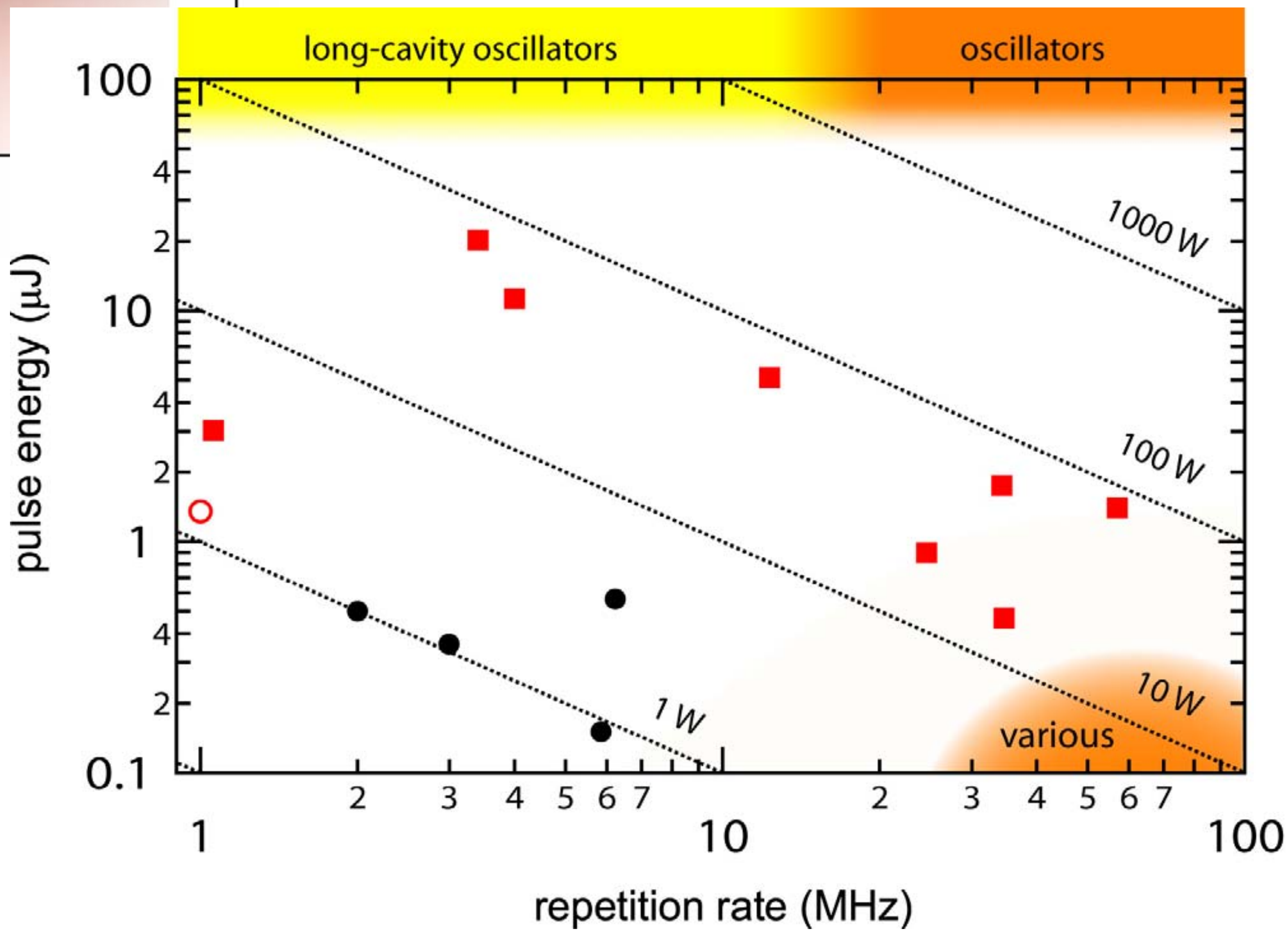
nano-tera.ch June 2009, 4 years

MIXSEL Project funding: 2.3 Mio CHF
Consortium: 4 Uni

High average power lasers - moving towards 100 µJ



QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.



100 µJ

5 MHz

500 W average power

$$P_{av} = E_p f_{rep}$$

Keller group

Ultrafast solid-state lasers: High average power (ML thin-disk laser)
Sergio Marchese, Cyrill Bär, Anna Enquist, Oliver Heckl, **Dr. Thomas Südmeyer** and *new: Clara Saraceno, Dr. Christian Kränkel*

Ultrafast solid-state lasers: High pulse repetition rate
Max Stumpf, Andreas Oehler, Selina Pekarek, **Dr. Thomas Südmeyer**

Ultrafast surface-emitting semiconductor lasers (ultrafast VECSELs and MIXSELs)
Deran Maas, Aude-Reine Bellancourt, Benjamin Rudin, Andreas Rutz, Martin Hoffmann, Dr. Yohan Barbarin, **Dr. Thomas Südmeyer** *and new: Valentin Wittwer, Oliver Sieber*

MBE growth in ETH clean room facility (FIRST-lab)
Dr. Matthias Golling

High field laser physics, attosecond pulse generation and science
Dr. Lukas Gallmann, Dr. Amelle Zair, Dr. Claudio Cirelli, Dr. Thomas Remetter, *new: Dr. Mathias Smolarski*
Christian Erny, Petrissa Eckle, Mirko Holler, Florian Schlapper, Matthias Weger, Adrian Pfeiffer, Clemens Heese

end